Optimal Power Flow with Hybrid Distributed Generators and Unified Controller

Lakshmi Ravi, Vaidyanathan R, Shishir Kumar D, Prathika Appaiah, S.G. Bharathi Dasan*
Department of EEE, Sri Venkateswara College of Engineering, Pennalur, Sriperumbudur, Chennai, India, Ph: 914427152000
e-mail: lakshmi.ravi29@gmail.com, vaigaibharathi@rediffmail.com*

Abstract
Optimal power flow (OPF) study is conducted on a power system to achieve one of the following objectives: cost/loss minimization or available transfer capability (ATC) calculation in a deregulated environment. Distributed generation (DG) is a small source of electric power conversion from non-conventional energy sources and Hybrid DGs which is often the most cost-effective and reliable way to produce power. The optimality of control variables and minimum value of objective functions in OPF study would definitely change when DGs are interconnected to the grid. The change would be respect to the location, quantity and combination of power injection by DGs. On the other hand, FACTS controllers are effective in utilizing the existing of transmission network which is very important especially in a deregulated system. Unified power flow controller (UPFC), a second generation FACTS controller, is well known for minimizing the cost of generation/losses with a good voltage profile as well as for ATC improvement. This paper conducts a detailed OPF study on a 9 bus system for the above mentioned three objectives to analyze the effect of DGs with and without UPFC. From the results, it is found that hybrid DGs along with UPFC yields better performance in many aspects.

Keywords: available transfer capability (ATC), optimal power flow (OPF), particle swarm optimization (PSO), unified power flow controller (UPFC).

1. Introduction
OPF is carried out to optimize the power flow solution of a large scale power system by minimizing one of the selected objective functions: economic costs or system losses. While maintaining an acceptable system performance in terms of generator capability limits and the output of the compensating devices, optimized control parameters are determined [1]. Capitanecu [2] addresses the main challenges to the security constrained Optimal Power Flow computations. The state of the art computational solution for the problem is reviewed and the challenges and the approaches to face them are identified. Bhaskar [3] proposed a hybrid genetic algorithm for solving OPF problem to minimize the fuel cost.
With the on-going expansion and the growth of industries in developing countries, the demand for electric power is increasing globally. Distributed Generation is gaining popularity in the present day world of increasing power demand as a reliable and clean approach to energy generation. It reduces the amount of energy lost in electricity transmitting as it is located close to the load center. Hybrid renewable energy system (HR ES) is often the most cost-effective and reliable way to produce power. A system using a combination of different sources has the advantage of balance and stability which offers the strengths of each type of sources that complement one another.

The placement of distributed generation (DG) at non-suitable places can result in increasing in system losses, implying an increase in costs and therefore having an effect opposite to the desired. To find the location, quantity and combination of power injection by DGs, OPF study should be conducted with DGs. Dasan et al. [4] presented the optimal siting and sizing of DGs to achieve minimum losses in system.

Flexible AC transmission systems (FACTS) have been mainly used for solving various power system steady state control problems such as voltage regulation, power flow control, and transfer capability enhancement. FACTS assure maximum utilization of existing transmission lines. Basu [6] applied thyristor controlled series capacitor (TCSC) to minimize the generator fuel cost. In recent times, FACTS devices have exploited the concept of converter based devices. Gyugi [5] introduced the concept of UPFC. The Unified power flow controller is a combination of a SSSC and STATCOM controller which able simultaneously compensate reactive power, control active and reactive power flow of the line. Noroozian [7] conducted optimal power flow study using UPFC.

On the other side, in a deregulated power system, one of the main objectives is ATC enhancement. According to the NERC definition, available transfer capability (ATC) is a measure of the transfer capability remaining in the physical transmission network for future commercial activity over and above already committed uses. Farahmand and Rashidinejad [8] proposed a novel technique to identify the optimal location of UPFC. Based on repeated AC power flow method, the ATC enhancement using UPFC was calculated. Chanda et al. [9] applied differential evolution for solving congestion management problem in a deregulated environment.

So, it is very important to study the effect of distributed generators addition in many aspects. This paper presents the effect of a wind turbine addition or a PV system or both together in the power system in steady state. A detailed OPF study is conducted to achieve three different objective functions- (a) minimization of real power losses (b) minimization of generation cost (c) maximization of ATC margin. The constraints considered are equality constraints (power flow equations) and inequality constraints (operating limits on control variables (real power generation and ATC margin) and dependent variables (bus voltages, the generator reactive powers and the line flows)). The best location to include fixed size (power model) DGs: wind, PV individual and hybrid wind-PV is identified by direct method. Then UPFC is incorporated in the OPF study by considering the location of UPFC as an additional control variable. OPF problem is solved by using a non-conventional mathematical technique called particle swarm optimization (PSO).

2. Research Method
2.1. Modeling of UPFC

The UPFC consists of one STATCOM and one SSSC sharing a common capacitor on their DC side. The active power demanded by the series converter is drawn by the shunt converter from the AC network and supplied via the DC link. The voltage magnitude of the inverter voltage $|V_{in}|$ provides voltage regulation and phase angle $\theta_{in}$ determines the mode of power flow control [10].The UPFC power flow model presented uses the equivalent circuit shown in Figure 1.

\[ V_{IK} = |V_{IR}| (\cos \theta_{IR} + j \sin \theta_{IR}) \]  
\[ V_{CR} = |V_{CR}| (\cos \theta_{CR} + j \sin \theta_{CR}) \]  
\[ \text{Re}\{-V_{IR}I_{IR}^* + V_{CR}I_{IR}^*\} = 0 \]
For the shunt converter, the voltage magnitude and phase angle limits are:

\[ V_{VR}^{\text{min}} \leq V_{VR} \leq V_{VR}^{\text{max}} \]
\[ 0 \leq \theta_{VR} \leq 2\pi \]  

The corresponding limits for series converter are:

\[ V_{CR}^{\text{min}} \leq V_{CR} \leq V_{CR}^{\text{max}} \]
\[ 0 \leq \theta_{CR} \leq 2\pi \]  

Where,

- \( V_{CR} \): Series converter voltage magnitude
- \( \theta_{CR} \): Series converter voltage angle
- \( V_{VR} \): Shunt converter voltage magnitude
- \( \theta_{VR} \): Shunt converter voltage angle

2.2. Power Flow Model of UPFC

The active and reactive powers for the series converter are as follows [10]

\[ S_{cr} = P_{cr} + jQ_{cr} = V_{cr} I_{cr} = V_{cr} \left( Y_{cm} V_{m} + Y_{cr} V_{r} \right) \]  

The active and reactive powers for the shunt converter are as follows

\[ S_{vr} = P_{vr} + jQ_{vr} = V_{vr} I_{vr} = V_{vr} \left( V_{m} - V_{r} \right) \]  

Assuming lossless converters, the UPFC neither absorbs nor injects active power with respect to the AC system. Hence, the following constraint must be followed

\[ P_{VR} + P_{CR} = 0 \]  

If nodes \( l \) and \( m \) are the nodes where the UPFC and the power network join together and the UPFC is set to control voltage magnitude at node \( l \), active power flowing from node \( m \) to node \( l \) and reactive power injected at node \( m \), then the following linearized equation shows the relevant portion of the overall system of equations.

\[
\begin{bmatrix}
\Delta P_l \\
\Delta P_m \\
\Delta Q_l \\
\Delta Q_m \\
\Delta P_{ml} \\
\Delta Q_{ml} \\
\Delta P_{bb}
\end{bmatrix}
= \begin{bmatrix}
\frac{\partial P_l}{\partial V_{l}} & \frac{\partial P_l}{\partial V_{m}} & \frac{\partial P_l}{\partial V_{b}} & \frac{\partial P_l}{\partial \theta_{l}} & \frac{\partial P_l}{\partial \theta_{m}} & \frac{\partial P_l}{\partial \theta_{b}} & 0 \\
\frac{\partial P_m}{\partial V_{l}} & \frac{\partial P_m}{\partial V_{m}} & 0 & \frac{\partial P_m}{\partial \theta_{l}} & \frac{\partial P_m}{\partial \theta_{m}} & \frac{\partial P_m}{\partial \theta_{b}} & 0 \\
\frac{\partial Q_l}{\partial V_{l}} & \frac{\partial Q_l}{\partial V_{m}} & \frac{\partial Q_l}{\partial V_{b}} & \frac{\partial Q_l}{\partial \theta_{l}} & \frac{\partial Q_l}{\partial \theta_{m}} & \frac{\partial Q_l}{\partial \theta_{b}} & 0 \\
\frac{\partial Q_m}{\partial V_{l}} & \frac{\partial Q_m}{\partial V_{m}} & 0 & \frac{\partial Q_m}{\partial \theta_{l}} & \frac{\partial Q_m}{\partial \theta_{m}} & \frac{\partial Q_m}{\partial \theta_{b}} & 0 \\
\frac{\partial P_{ml}}{\partial V_{l}} & \frac{\partial P_{ml}}{\partial V_{m}} & \frac{\partial P_{ml}}{\partial V_{b}} & \frac{\partial P_{ml}}{\partial \theta_{l}} & \frac{\partial P_{ml}}{\partial \theta_{m}} & \frac{\partial P_{ml}}{\partial \theta_{b}} & 0 \\
\frac{\partial Q_{ml}}{\partial V_{l}} & \frac{\partial Q_{ml}}{\partial V_{m}} & \frac{\partial Q_{ml}}{\partial V_{b}} & \frac{\partial Q_{ml}}{\partial \theta_{l}} & \frac{\partial Q_{ml}}{\partial \theta_{m}} & \frac{\partial Q_{ml}}{\partial \theta_{b}} & 0 \\
\frac{\partial P_{bb}}{\partial V_{l}} & \frac{\partial P_{bb}}{\partial V_{m}} & \frac{\partial P_{bb}}{\partial V_{b}} & \frac{\partial P_{bb}}{\partial \theta_{l}} & \frac{\partial P_{bb}}{\partial \theta_{m}} & \frac{\partial P_{bb}}{\partial \theta_{b}} & 0
\end{bmatrix}
\begin{bmatrix}
\Delta V_{l} \\
\Delta V_{m} \\
\Delta V_{b} \\
\Delta \theta_{l} \\
\Delta \theta_{m} \\
\Delta \theta_{b}
\end{bmatrix}
\]

2.3 Optimal Power Flow

The primary goal of a generic OPF is to minimize the costs of meeting the load demand for a power system while maintaining the security of the system. In a deregulated power system, maximization of ATC is one of the major objectives. This paper considers the minimization of cost or loss and maximization of ATC margin.
Case 1: Minimization of Loss

Minimize

\[ F = K_p \sum_{j=1}^{NL} P_{Loss} + K_v \left( \sum_{j=1}^{NL} \left[ V_{Li} - V_{LILIM} \right]^2 / N \right) \]  \hspace{1cm} (12)

Case 2: Minimization of cost

Minimize

\[ F = \sum_{j=1}^{NG} C_{pg}(P_g) + K_v \left( \sum_{j=1}^{NL} \left[ V_{Li} - V_{LILIM} \right]^2 / N \right) \]  \hspace{1cm} (13)

Where,

- \( K_p \), \( K_v \) are penalty factors
- \( NL \) is the number of lines in the system
- \( P_{Loss} \) is the real power loss in the given line in MW
- \( V_{Li} \) is the voltage magnitude in \( i^{th} \) bus in p.u.
- \( V_{LILIM} \) is the voltage limit set at \( i^{th} \) bus in p.u.
- \( NVB \) is the number of buses violating the voltage limit
- \( N \) is the total number of buses
- \( NG \) is the number of generators in the system
- \( C_{pg}(P_g) \) is the cost function of \( i^{th} \) generator

Equality Constraints [12]:

\[ (P_D - P_G) - \left( \sum_{i=1}^{n} V_i \sum_{a=1}^{a} V_i \right) (G \cos(\theta - \theta) + B \sin(\theta - \theta)) = 0 \] \hspace{1cm} (14)

\[ (Q_D - Q_G) - \left( \sum_{i=1}^{n} V_i \sum_{a=1}^{a} V_i \right) (G \sin(\theta - \theta) + B \cos(\theta - \theta)) = 0 \] \hspace{1cm} (15)

Where,

- \( P_D \) and \( Q_D \) are the active and reactive power demand respectively.
- \( P_G \) and \( Q_G \) are the active and reactive power generation respectively.
- \( V \) and \( \theta \) are the voltage magnitude and voltage angle.
- \( n \) is the number of buses connected to bus \( l \)

Inequality Constraints:

\[ P_{g(k)}^{min} \leq P_{g(k)} \leq P_{g(k)}^{max} \] \hspace{1cm} (16)

\[ Q_{g(k)}^{min} \leq Q_{g(k)} \leq Q_{g(k)}^{max} \] \hspace{1cm} (17)

\[ V_{g(k)}^{min} \leq V_{g(k)} \leq V_{g(k)}^{max} \] \hspace{1cm} (18)

Case 3: Maximization of ATC

The objective function for the ATC is taken as

Maximize

\[ ATC = \sum_{i=1}^{NL} \Delta P_{ij} \] \hspace{1cm} (19)

Where, \( 'i' \) is the sending end bus number

\( 'j' \) is the receiving end bus number

Additional Inequality constraint:

\[ P_{ij} < TL_{ij} \] \hspace{1cm} (20)

Where, \( TL \) is the thermal limit of the line

\( 'i' \) is the sending end bus number

\( 'j' \) is the receiving end bus number
2.4 Particle Swarm Optimization

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling. The PSO algorithm is generally used to solve non-linear equations. The algorithm initializes a group of random particles (solutions) and then searches for optima by updating generations.

In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience (called particle memory influence) and the experience of neighboring particles (called swarm influence), making use of the best position encountered by its self (Pbest) and its neighbors (Gbest).

The modification of the particle's position can be mathematically modeled according to the following equations:

\[ w = w_{\text{max}} - \left( w_{\text{max}} - w_{\text{min}} \right) \times \frac{\text{iter}}{\text{iter}_{\text{max}}} \]

\[ V_{i(k+1)} = wV_{i(k)} + C_1 \cdot \text{rand}(\cdot) \times \left( \text{Pbest}_i - P_{i(k)} \right) + C_2 \cdot \text{rand}(\cdot) \times \left( \text{Gbest} - P_{i(k)} \right) \]

\[ P_{i(k+1)} = P_{i(k)} + V_{i(k+1)} \]

where,
- \( w_{\text{max}} \) : initial weight
- \( w_{\text{min}} \) : final weight
- \( \text{iter}_{\text{max}} \) : maximum iteration number
- \( \text{iter} \) : current iteration number
- \( V_{i(k)} \) : velocity of agent \( i \) at iteration \( k \)
- \( w \) : inertia weight factor
- \( C_j \) : weighting factor (\( j = 1, 2 \))
- \( \text{rand} \) : uniformly distributed random number between 0 and 1
- \( P_{i(k)} \) : current position of agent \( i \) at iteration \( k \)
- \( \text{Pbest}_i \) : best position of agent \( i \)
- \( \text{Gbest} \) : best position among all particles in the swarm

\( V_{i(k)} \) must lie in the range \( V_{\text{min}} \leq V_{i(k)} \leq V_{\text{max}} \). The constants \( C_1 \) and \( C_2 \) pull each particle towards \( \text{P-best} \) and \( \text{G-best} \) positions and often set to be 2.0 according to past experiences. Suitable selection of inertia weight \( w \) provides a balance between global and local explorations, thus requiring less iteration on average to find a sufficient optimal solution.

2.5 Algorithm

**Step 1** : Input system data (generator cost functions, real power generation limits, transmission line data, bus data and inertia weight factor, and weighting factor of PSO algorithm).

**Step 2** : Generate ‘N’ number of population. Each particle in the algorithm is defined by a set of control variables. The particles are \( [P_{2, P_{3},..., P_{ng}}] \) for minimization of cost/loss and \( [P_{2, P_{3},..., P_{ng}, x}] \) for maximization of ATC problem, \( (P_{2, P_{3},..., P_{ng}}) \) are the generator bus real
powers and x is percentage (ATC margin) by which real power generation and
demand is increased in generator bus and load bus respectively.)

**Step 3**: Set iteration count \( \text{iter} = 1 \).

**Step 4**: Initialize the population generated as Pbest.

**Step 5**: Discard particles that violate the inequality constraints (equations (16) to (18) and (20)).

**Step 6**: Evaluate the fitness function for each particle (equation (12) or (13) or (19)) and determine the value of Gbest among all particles.

**Step 7**: Modify the position of each particle based on the PSO algorithm (equation (21) to (23)) and discard particles which violate the limits.

**Step 8**: Compare the fitness function of modified population with that of Pbest.

**Step 9**: Particle with lower/higher (min/max problem) value of fitness function is assigned as Pbest.

**Step 10**: If \( \text{iter} < \) maximum iteration (\( \text{itermax} \)) then go to step 5 else go to step 11.

**Step 11**: Print the value of Gbest which gives the optimum solution.

### 2.6 Flowchart

The flowchart for PSO based OPF is shown in Figure 3.

![Flowchart](image_url)

**Figure 3. PSO based OPF-flowchart**

### 3. Result and Analysis

#### 3.1. Simulation Study 1

The algorithm explained in the previous section is tested on a 9 bus network [5] shown in Figure 4.

<table>
<thead>
<tr>
<th>Case</th>
<th>PG1 (MW)</th>
<th>PG2 (MW)</th>
<th>PG3 (MW)</th>
<th>Loss/Cost/ATC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss minimization</td>
<td>56.39</td>
<td>187.9</td>
<td>104.6</td>
<td>4.03 MW</td>
</tr>
<tr>
<td>Cost minimization</td>
<td>69.3</td>
<td>186.9</td>
<td>92.9</td>
<td>3194.9 $/Hr</td>
</tr>
<tr>
<td>Max. of ATC G-2;L-9</td>
<td>62.1</td>
<td>204.3</td>
<td>95.4</td>
<td>22.8 MW</td>
</tr>
</tbody>
</table>

**Figure 4. Nine Bus Test System**

The following cases were considered in optimal power flow analysis to optimize the three objectives given in Section IV.

a) Base case OPF
b) OPF with DGs
   (i) With only PV
   (ii) With only Wind
   (iii) With hybrid wind-PV

c) OPF with hybrid DGs and UPFC

3.1.1 Base Case OPF

The optimum results of basic OPF conducted on 9 bus system using PSO are tabulated in Table 2. It is found that minimized system loss and cost are 4.03 MW and $ 3194.6 per hour respectively. For the maximization of ATC problem, the real power generation of generator 2 is gradually increased along with demand at any one of the load busses by a small percentage x to find the ATC margin. In this study, all load busses were considered individually and optimum result with change in load bus 9 is displayed in Table I. The voltage profile of the system for all three objectives is compared in Figure 5. The convergence characteristic of PSO for cost minimization is shown in Figure 6.

![Figure 5. Voltage profile for base case OP](image)

![Figure 6. Convergence characteristics of cost objective function](image)

3.1.2. Optimal Power Flow with Distributed Generators

Distributed Generations (DGs) is a small source of electric power conversion from non-conventional energy sources, typically from less than a kW to tens of MW. The distributed generators considered here are Solar cell and Wind generator. 

DG1: Real power consumption only (PV)

DG2: Supplying real power but consuming proportionately reactive power.

The reactive power consumed by a DG (fixed speed wind turbine generator) in a simple form can be represented by [11]

\[ Q_{DGi} = -0.5 + 0.04 \times P_{DGi} \]  

(24)

This work deals with the effect of PV and wind individually and as a hybrid combination.

- **Case 1: Minimization of Loss**
  This section explains the OPF problem for loss minimization with the inclusion of DG1 as real power generation and DG2 as real power generation and reactive power consumption (equation (24)) at the corresponding buses. Size of DG1 has been chosen as 5MW while for DG2 has been chosen as 10MW. Each of these DGs has been placed at 6 different load buses (direct method) and the optimum results are displayed in Table II and III. It is inferred from the tables that the real power losses of wind (at optimum location bus 5) included system is reduced by 4.5% and PV included system by 3.2%.

- **Case 2: Minimization of Generation Cost**
  A similar case study has been performed on the test system with the objective as minimization of generation cost. The cost of generation varies for different locations of DGs and the minimum cost for wind (at optimum location bus 5) included system is $3114 per hour which is 2.5% lesser than the base case. For the PV included system has also shown a reduction in generation cost.

- **Case 3: Maximization of ATC**
  Using the algorithm proposed in Section VI, the OPF problem has been solved for maximization of ATC after inclusion of DGs at all load buses. It is found from the study that
for the case of DG at bus 8, the generation at bus 2 is increased from 88MW to 105MW and the load at bus 9 is tabulated in Table 2 and Table 3. When DGs are included, ATC margin has reduced compared to base case.

### Table 2. OPF with wind generators

<table>
<thead>
<tr>
<th>Case</th>
<th>DG2 @ (MW)</th>
<th>PG1 @ (MW)</th>
<th>PG2 @ (MW)</th>
<th>PG3 @ (MW)</th>
<th>Loss/Cost/ATC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. of Loss</td>
<td>5</td>
<td>56.4</td>
<td>181.1</td>
<td>100.9</td>
<td>3.85 MW</td>
</tr>
<tr>
<td>Min. of Gen. Cost</td>
<td>5</td>
<td>66.5</td>
<td>181.9</td>
<td>90.4</td>
<td>3114.0 $/Hr</td>
</tr>
<tr>
<td>Max. of ATC</td>
<td>8</td>
<td>106.0</td>
<td>105.3</td>
<td>147.1</td>
<td>18.43 MW</td>
</tr>
</tbody>
</table>

### Table 3. OPF with PV generators

<table>
<thead>
<tr>
<th>Case</th>
<th>DG1 @ (MW)</th>
<th>PG1 @ (MW)</th>
<th>PG2 @ (MW)</th>
<th>PG3 @ (MW)</th>
<th>Loss/Cost/ATC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. of Loss</td>
<td>5</td>
<td>56.1</td>
<td>185.5</td>
<td>100.9</td>
<td>3.90 MW</td>
</tr>
<tr>
<td>Min. of Gen. Cost</td>
<td>5</td>
<td>68.2</td>
<td>183.9</td>
<td>91.7</td>
<td>3154.1 $/Hr</td>
</tr>
<tr>
<td>Max. of ATC</td>
<td>9</td>
<td>72.7</td>
<td>192.8</td>
<td>87.7</td>
<td>16.17 MW</td>
</tr>
</tbody>
</table>

### 3.1.3 Optimal Power Flow with Hybrid DGs (wind and PV)

The optimal locations of DG1 and DG2 taken at a time have been obtained from the previous section for three objectives. In this section, two DGs are placed at a time at the optimum locations so obtained. The algorithm has been performed again with DG1 and DG2 together for minimization of loss/cost and ATC maximization, and the results are given in Table 4. The generation cost and loss for hybrid DG are found to be least due to the optimal location and hybrid combination. On the other hand, ATC margin is lesser than the base case. This emphasizes the needs of a FACTS controller for enhancement. The voltage profile of the system for all three objectives is compared in Figure 7. Voltages at busses 5 and 6 are lesser than 1p.u. and require a suitable reactive power compensator for improvement.

### Table 4. OPF with hybrid wind-PV generators-optimum results

<table>
<thead>
<tr>
<th>Case</th>
<th>Location</th>
<th>PG1 @ (MW)</th>
<th>PG2 @ (MW)</th>
<th>PG3 @ (MW)</th>
<th>Loss/Cost/ATC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. of Loss</td>
<td>5</td>
<td>5</td>
<td>56.4</td>
<td>176.7</td>
<td>100.6</td>
</tr>
<tr>
<td>Min. of Gen. Cost</td>
<td>5</td>
<td>5</td>
<td>65.9</td>
<td>179.3</td>
<td>88.5</td>
</tr>
<tr>
<td>Max. of ATC</td>
<td>9</td>
<td>8</td>
<td>91.26</td>
<td>133.9</td>
<td>118.0</td>
</tr>
</tbody>
</table>

### 3.2. Simulation Study 2

From the detailed OPF study which performed on the system, the need for a compensator to improve the ATC margin and voltage profile is strongly justified. The Unified power flow controller is combinations of a SSSC and STATCOM controller that able to simultaneous compensate reactive power, control active and reactive power flow of the line with a good voltage profile. The objective functions, equation (12) and (13) should be modified to include the operating cost (equation (25)) involved in incorporation of UPFC in the system.

\[
UPFC_{cost} = S \times 150\$/kVAR
\]  

(25)

where, S is the operating range of the UPFC in kVAR.

In addition to the equality and inequality constraints explained in Section IV, the operating voltage and angle of series and shunt converters presented in Section 2.1.1 (equations (4) to (7)) are also considered in this case. Before conducting OPF on the system, initial conditions of the UPFC [10] were calculated using load flow analysis results. In the algorithm given in section 2.5, the location of UPFC is also included as a control variable and applied for system given in Figure 4.

- **Case 1:** Minimization of Cost and Loss:
  The result of minimization of cost and loss are tabulated in Table 5. From the study, the optimal location of UPFC is found as line 6. The optimum cost is lesser than all other cases.
considered in this paper. But the real power loss is higher than other cases. UPFC is not deployed for a single objective. It improved the voltage profile as shown in Figure 10. At the same time, the real and reactive power flow through the transmission line connecting 4th and 5th bus, are maintained at a value equal to receiving end demand.

Table 5. OPF with Hybrid DG’s and UPFC-cost and loss optimization

<table>
<thead>
<tr>
<th>Case</th>
<th>Min. of Loss (MW)</th>
<th>Min. of Gen. Cost (MW)</th>
<th>PG1 (MW)</th>
<th>PG2 (MW)</th>
<th>PG3 (MW)</th>
<th>Loss/ Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 6. OPF with hybrid DG’s and UPFC case (a)

<table>
<thead>
<tr>
<th>Load</th>
<th>PG1 (MW)</th>
<th>PG2 (MW)</th>
<th>PG3 (MW)</th>
<th>ATC (MW)</th>
<th>UPFC Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG1</td>
<td>153.4</td>
<td>124.4</td>
<td>82.2</td>
<td>59</td>
<td>7</td>
</tr>
<tr>
<td>PG2</td>
<td>173.7</td>
<td>81.4</td>
<td>83.1</td>
<td>4.3</td>
<td>7</td>
</tr>
<tr>
<td>PG3</td>
<td>166.2</td>
<td>83.7</td>
<td>88.3</td>
<td>1.8</td>
<td>7</td>
</tr>
<tr>
<td>PG4</td>
<td>183.0</td>
<td>67.9</td>
<td>88.7</td>
<td>1.7</td>
<td>7</td>
</tr>
<tr>
<td>PG5</td>
<td>186.3</td>
<td>113.2</td>
<td>74.4</td>
<td>35.2</td>
<td>7</td>
</tr>
<tr>
<td>PG6</td>
<td>135.8</td>
<td>192.6</td>
<td>96.9</td>
<td>90</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 7. OPF with hybrid DG’s and UPFC case (b)

<table>
<thead>
<tr>
<th>Load</th>
<th>PG1 (MW)</th>
<th>PG2 (MW)</th>
<th>PG3 (MW)</th>
<th>ATC (MW)</th>
<th>UPFC Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG1</td>
<td>180.0</td>
<td>69.9</td>
<td>98.2</td>
<td>28.0</td>
<td>7</td>
</tr>
<tr>
<td>PG2</td>
<td>191.8</td>
<td>50.8</td>
<td>98.8</td>
<td>22.0</td>
<td>7</td>
</tr>
<tr>
<td>PG3</td>
<td>149.4</td>
<td>119.1</td>
<td>74.9</td>
<td>10.3</td>
<td>7</td>
</tr>
<tr>
<td>PG4</td>
<td>155.1</td>
<td>81.8</td>
<td>105.9</td>
<td>8.6</td>
<td>7</td>
</tr>
<tr>
<td>PG5</td>
<td>168.2</td>
<td>109.6</td>
<td>93.2</td>
<td>27.6</td>
<td>7</td>
</tr>
<tr>
<td>PG6</td>
<td>162.2</td>
<td>151.1</td>
<td>110.1</td>
<td>50.6</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 8. ATC margin for case (a)

Figure 9. ATC margin for case (b)

Figure 10. Voltage profile for OPF with hybrid DGs and UPFC

- **Case 2: Maximization** of ATC:

Available transfer capability (ATC) has improved extensively in this case. Since this 9 bus system has 3 generators, the two generators; generator 2 (case (a)) and generator 3 (case (b)), other than the slack generator are considered for analysis. In addition to real powers and ATC margin, line location is also taken as a control variable. For the power increase in each generator, demand at one of the load busses is also increased to find ATC. The OPF results for all the choices of load for each generator are tabulated in Table VI and VII. From Table VII, it is inferred that ATC margin (generator 3) is 50.69 MW whereas it is only 22.8 MW in base case. Similarly, when real power of generator 2 is varied, ATC margin is 90 MW which is a very high improvement compared to base case. Figure 8 and 9 show the ATC margin for cases (a) and (b).
4. Conclusion

This paper studied the effect of DGs on power system by conducting OPF using PSO. Then, the performance analyzed by adding UPFC with the hybrid DG included system. Figures 11-13 depict the important conclusions. From Figure 11, it is inferred that fuel generation cost reduce when DGs are included individually compared to base case. But when hybrid wind-PV is connected in addition to assurance for reliable power, fuel generation cost also reduced by 3.815% from base case. Similarly, real power loss reduction is higher for hybrid wind-PV case than individual DG case i.e. 5.955% from base case. According to ATC improvement, simple DG inclusion does not perform better, but addition of UPFC highly improves ATC as it seen from Figure 13. It is approximately 2 or 3 times greater than base case. At the same time, UPFC maintains the voltage profile at buses 5 and 6 closer to 1 p.u. and the real power generation cost is lesser than base case. This paper concludes that there are many technical advantages when DGs are included in power system apart from real power generation. This study can be expanded for other non-conventional energy sources in future.

References