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*

Abstrak

      Studi aliran daya yang optimal (OPF) dilakukan untuk mencapai salah satu tujuan yang diantaranya untuk meminimalisasi biaya atau kerugian melalui perhitungan kemampuan transfer daya yang tersedia (ATC) dalam lingkungan yang terderegulasi. Pembangkitan terdistribusi (DG) jenis non-konvensional dan pembangkit terdistribusi hibrida merupakan cara yang paling hemat biaya dan dapat diandalkan untuk menghasilkan tenaga listrik. Variabel kontrol optimal dan nilai minimum fungsi objektif dalam OPF akan berubah ketika pembangit terdistribusi terhubung ke jala-jala. Perubahan ini akan berkaitan dengan jumlah, lokasi dan kombinasi daya yang diinjeksikan oleh pembangkit terdistribusi. Di sisi lain, keberadaan pengendali saluran transmisi arus bolak balik yang fleksibel (FACTS) akan memanfaatkan jaringan transmisi yang ada. Pengontrol aliran daya terpadu (UPFC), yang merupakan generasi kedua pengendali FACTS, dikenal dengan kemampuannya untuk meminimalkan biaya pembangkitan/kerugian dengan menghasilkan profil tegangan yang baik dan peningkatan kinerja ATC. Tulisan ini melakukan penelaahan rinci OPF pada sistem 9 bus dengan tujuan untuk menganalisis pengaruh dari pembangkit terdistribusi dengan dan tanpa keberadaan UPFC. Dari hasil penelitian, ditemukan bahwa dalam banyak aspek, pembangkit terdistribusi hibrida bersama dengan UPFC menghasilkan kinerja yang lebih baik.

Kata kunci: aliran daya optimal (OPF), kemampuan transfer daya yang tersedia (ATC), optimasi particle swarm (PSO), pengontrol aliran daya terpadu (UPFC)

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 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 (HRES) 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 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 $|V_{cR}|$ provides voltage regulation and phase angle θ_{cR} determines the mode of power flow control [10].The UPFC power flow model presented uses the equivalent circuit shown in Figure 1.

$$V_{VR} = |V_{VR}|(\cos\theta_{VR} + j\sin\theta_{VR}) \tag{1}$$

$$V_{CR} = |V_{CR}|(\cos\theta_{CR} + j\sin\theta_{CR}) \tag{2}$$

$$\mathrm{Re}\{-V_{VR}I_{VR}^{*} + V_{CR}I_{m}^{*}\} = 0 \tag{3}$$

For the shunt converter, the voltage magnitude and phase angle limits are:

$$V_{VR}^{min} \leq V_{VR} \leq V_{VR}^{max} \tag{4}$$

$$0 \leq \theta_{VR} \leq 2\pi \tag{5}$$

The corresponding limits for series converter are:

$$V_{CR}^{min} \leq V_{CR} \leq V_{CR}^{max} \tag{6}$$

$$0 \leq \theta_{CR} \leq 2\pi \tag{7}$$

Where,
V_{CR} : Series converter voltage magnitude
Θ_{CR} : Series converter voltage angle
V_{VR} : Shunt converter voltage magnitude
Θ_{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]

$$S_{CR} = P_{CR} + jQ_{CR} = V_{CR}I_m^* = V_{CR}\{Y_{ml}^*V_l^* + Y_{mm}^*V_m^* + Y_{mm}^*V_{CR}^*\} \tag{8}$$

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

$$S_{VR} = P_{VR} + jQ_{VR} = V_{VR}I_{VR}^* = V_{VR}Y_{VR}^*\{V_{VR}^* - V_l^*\} \tag{9}$$

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

$$P_{VR} + P_{CR} = 0 \tag{10}$$

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 \theta_l} & \frac{\partial P_l}{\partial \theta_m} & \frac{\partial P_l}{\partial |V_{vR}|} & \frac{\partial P_l}{\partial |V_m|} & \frac{\partial P_l}{\partial \theta_{cR}} & \frac{\partial P_l}{\partial |V_{cR}|} & \frac{\partial P_l}{\partial \theta_{vR}} \\ \frac{\partial P_m}{\partial \theta_l} & \frac{\partial P_m}{\partial \theta_m} & 0 & \frac{\partial P_m}{\partial |V_m|} & \frac{\partial P_m}{\partial \theta_{cR}} & \frac{\partial P_m}{\partial |V_{cR}|} & 0 \\ \frac{\partial Q_l}{\partial \theta_l} & \frac{\partial Q_l}{\partial \theta_m} & \frac{\partial Q_l}{\partial |V_{vR}|} & \frac{\partial Q_l}{\partial |V_m|} & \frac{\partial Q_l}{\partial \theta_{cR}} & \frac{\partial Q_l}{\partial |V_{cR}|} & \frac{\partial Q_l}{\partial \theta_{vR}} \\ \frac{\partial Q_m}{\partial \theta_l} & \frac{\partial Q_m}{\partial \theta_m} & 0 & \frac{\partial Q_m}{\partial |V_m|} & \frac{\partial Q_m}{\partial \theta_{cR}} & \frac{\partial Q_m}{\partial |V_{cR}|} & 0 \\ \frac{\partial P_{ml}}{\partial \theta_l} & \frac{\partial P_{ml}}{\partial \theta_m} & 0 & \frac{\partial P_{ml}}{\partial |V_m|} & \frac{\partial P_{ml}}{\partial \theta_{cR}} & \frac{\partial P_{ml}}{\partial |V_{cR}|} & 0 \\ \frac{\partial Q_{ml}}{\partial \theta_l} & \frac{\partial Q_{ml}}{\partial \theta_m} & 0 & \frac{\partial Q_{ml}}{\partial |V_m|} & \frac{\partial Q_{ml}}{\partial \theta_{cR}} & \frac{\partial Q_{ml}}{\partial |V_{cR}|} & 0 \\ \frac{\partial P_{bb}}{\partial \theta_l} & \frac{\partial P_{bb}}{\partial \theta_m} & \frac{\partial P_{bb}}{\partial |V_{vR}|} & \frac{\partial P_{bb}}{\partial |V_m|} & \frac{\partial P_{bb}}{\partial \theta_{cR}} & \frac{\partial P_{bb}}{\partial |V_{cR}|} & \frac{\partial P_{bb}}{\partial \theta_{vR}} \end{bmatrix} \begin{bmatrix} \Delta \theta_l \\ \Delta \theta_m \\ \Delta |V_{vR}| \\ \Delta |V_m| \\ \Delta \theta_{cR} \\ \Delta |V_{cR}| \\ \Delta \theta_{vR} \end{bmatrix} \tag{11}$$

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

$$F = K_p \sum_{j=1}^{NL} P_{LOSSj} + K_v \sqrt{\{\sum_{i=1}^{NVB} \left(V_{Li} - V_{LiLIM}\right)^2 / N\}}$$

(12)

Case 2: Minimization of cost
Minimize

$$F = \sum_{j=1}^{NG} C_{gpi}(P_{gi}) + K_v \sqrt{\{\sum_{i=1}^{NVB} \left(V_{Li} - V_{LiLIM}\right)^2 / N\}}$$

(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
$C_{gpi}(P_{gi})$ is the cost function of ith generator

Equality Constraints [12]:

$$(P_G - P_D) - (|V_l| \sum_{m=1}^{n} V_m | \{G_{lm} \cos(\theta_l - \theta_m) + B_{lm} \sin(\theta_l - \theta_m)\}) = 0$$

(14)

$$(Q_G - Q_D) - (|V_l| \sum_{m=1}^{n} V_m | \{G_{lm} \sin(\theta_l - \theta_m) + B_{lm} \cos(\theta_l - \theta_m)\}) = 0$$

(15)

Where,
P_D and Q_D and P_G and Q_G are the active and reactive power demand and generation respectively.
V and Θ are the voltage magnitude and voltage angle.
n is the number of buses connected to bus l

Inequality Constraints:

$$P_{g(k)}^{\min} \leq P_{g(k)} \leq P_{g(k)}^{\max} \quad \text{k=1-NG}$$

(16)

$$Q_{g(k)}^{\min} \leq Q_{g(k)} \leq Q_{g(k)}^{\max} \quad \text{k=1-NG}$$

(17)

$$V_{(k)}^{\min} \leq V_{(k)} \leq V_{(k)}^{\max} \quad \text{k=1-N}$$

(18)

Case 3: Maximization of ATC
The objective function for the ATC is taken as
Maximize

$$ATC = \sum_{i=1}^{NL} \Delta P_{ij}$$

(19)

Where, 'i' is the sending end bus number
    'j' is the receiving end bus number
Additional Inequality constraint:

$$P_{ij} < TL_{ij}$$

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).
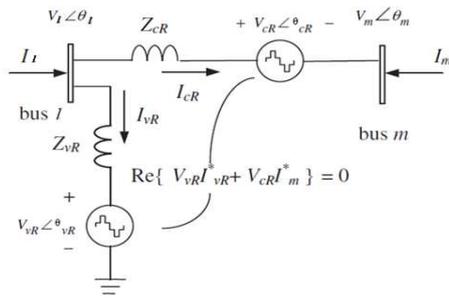
Figure 1. Equivalent circuit of UPFC based on solid-state voltage sources
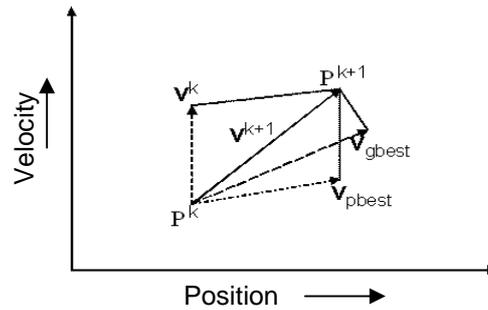
Figure 2. Concept of modification of a searching point

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

$$w = w_{max} - \left[\left(w_{max} - w_{min} \right) * iter \right] / iter_{max} \tag{21}$$

$$V_{i(k+1)} = w V_{i(k)} + C_1 rand()*(Pbest_i - P_{i(k)})$$
$$+ C_2 rand()*(Gbest_i - P_{i(k)}) \tag{22}$$

$$P_{i(k+1)} = P_{i(k)} + V_{i(k+1)} \tag{23}$$

where,

w_{max}	: initial weight
w_{min}	: final weight
$iter_{max}$	: maximum iteration number
iter	: current iteration number
Vi(k)	: velocity of agent i at iteration k
w	: inertia weight factor
Cj	: weighting factor (j = 1, 2)
rand	: uniformly distributed random number between 0 and 1
Pi(k)	: current position of agent i at iteration k
Pbesti	: best position of agent i
Gbest	: best position among all particles in the swarm

Vi(k) must lie in the range Vmin ≤ Vi(k) ≤ Vmax. The constants C1and C2 pull each particle towards P-best and 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 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 iter < maximum iteration (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.
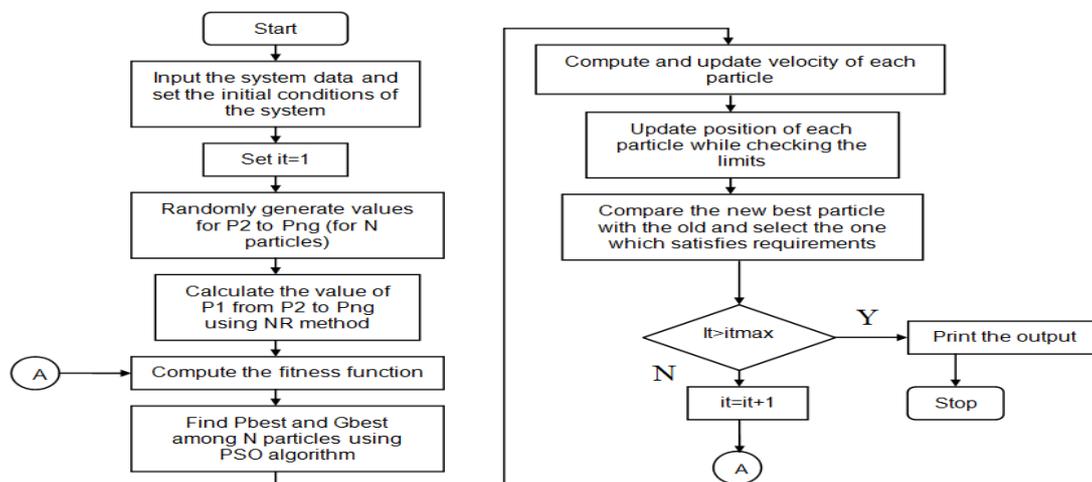
Figure 3. PSO based OPF-flowchart

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 1. Base Case OPF-Optimum Results

Case	PG1 (MW)	PG2 (MW)	PG3 (MW)	Loss/Cost/ATC
Loss minimization	56.39	187.9	104.6	4.03 MW
Cost minimization	69.3	186.9	92.9	3194.9 $/Hr
Max. of ATC G-2;L-9	62.1	204.3	95.4	22.8 MW
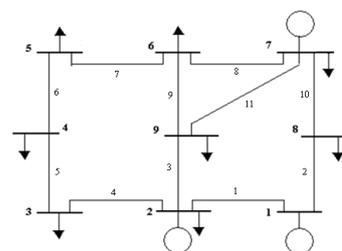
Figure 4. Nine Bus Test System

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.
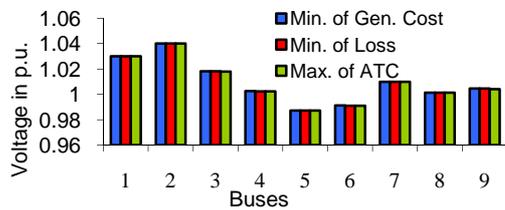
Figure 5. Voltage profile for base case OP
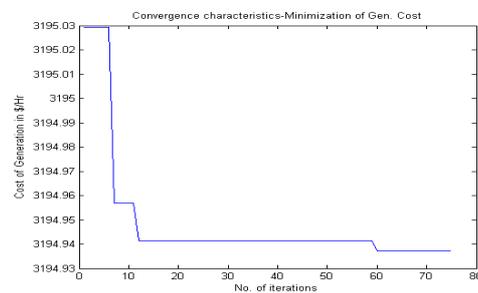
Figure 6. Convergence characteristics of cost objective function

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]

$$Q_{DG} = -\left(0.5 + 0.04 * P_{DG}{}^{2}\right)$$

(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 mthod) 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

Case	DG2 At	PG1 (MW)	PG2 (MW)	PG3 (MW)	Loss/ Cost/ ATC
Min. of Loss	5	56.4	181.1	100.9	3.85 MW
Min. of Gen. Cost	5	66.5	181.9	90.4	3114.0 $/Hr
Max. of ATC	8	106.0	105.3	147.1	18.43 MW

Table 3. OPF with PV generators

Case	DG1 at	PG1 (MW)	PG2 (MW)	PG3 (MW)	Loss/Cost/ ATC
Min. of Loss	5	56.1	185.5	102.2	3.90 MW
Min. of Gen. Cost	5	68.2	183.9	91.7	3154.1 $/Hr
Max. of ATC	9	72.7	192.8	87.7	16.17 MW

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

Case	Location DG1	Location DG2	PG1 (MW)	PG2 (MW)	PG3 (MW)	Loss/Cost/ATC
Min. of Loss	5	5	56.4	176.7	100.6	3.79 MW
Min. of Gen. Cost	5	5	65.9	179.3	88.5	3073.5 $/Hr
Max. of ATC	9	8	91.26	133.9	118.0	10.9 MW
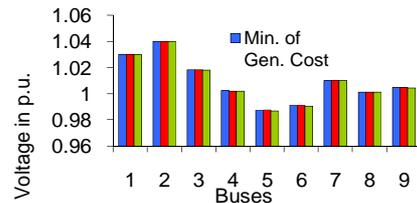
Figure 7. Voltage profile for OPF with hybrid DGs

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.

$$UPFC_{cost} = S * 150\$ \ / \ kVAR \tag{25}$$

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 the 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

| Case | DG Location | | UPFC Location | PG1 (MW) | PG2 (MW) | PG3 (MW) | Loss/ Cost |
	DG1	DG2					
Min. of Loss	5	9	6	152.5	124.3	58.5	5.45 MW
Min. of Gen. Cost	3	4	6	185.3	72.2	78.8	3173.1 $/Hr

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

| Load | For Generator at Bus 2 | | | | |
	PG1 (MW)	PG2 (MW)	PG3 (MW)	ATC (MW)	UPFC Location
Bus 3	153.4	124.4	82.2	59	7
Bus 4	173.7	81.4	83.1	4.3	7
Bus 5	166.2	83.7	88.3	1.8	7
Bus 6	183.0	67.9	88.7	1.7	7
Bus 8	186.3	113.2	74.4	35.2	7
Bus 9	135.8	192.6	96.9	90	7

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

| Load | For Generator at Bus 3 | | | | |
	PG1 (MW)`	PG2 (MW)	PG3 (MW)	ATC (MW)	UPFC Location
Bus 3	180.0	69.9	98.2	28.01	7
Bus 4	191.8	50.8	98.8	22.09	7
Bus 5	149.4	119.1	74.9	10.3	7
Bus 6	155.1	81.8	105.9	8.64	7
Bus 8	168.2	109.6	93.2	27.6	7
Bus 9	162.2	151.1	110.1	50.69	7
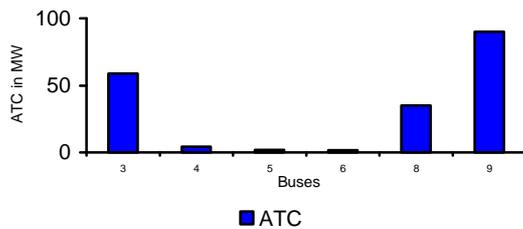
Figure 8. ATC margin for case (a)
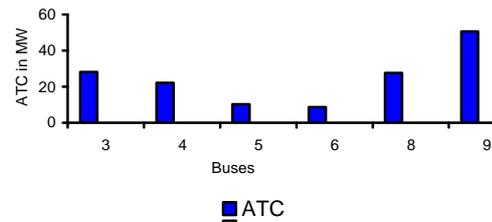
Figure 9. ATC margin for case (b)
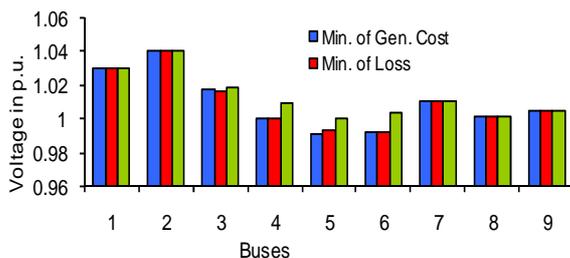
Figure 10. Voltage profile for OPF with hybrid DGs and UPFC
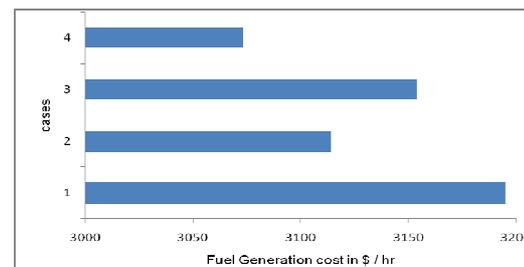
Figure 11. Effects of DG on fuel cost
Case 1: Base case; case 2: only wind; case 3: only PV; case 4: hybrid wind-PV; case 5: case 4 with UPFC

- **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).
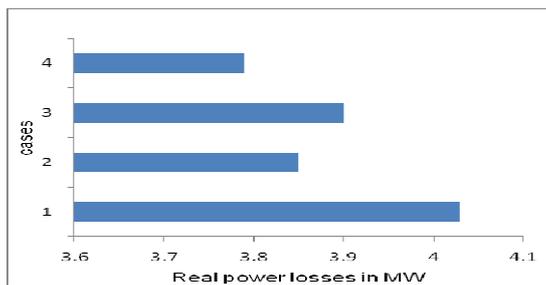
Figure 12.Effect of DG on real power loss
Case 1: Base case; case 2: only wind; case 3: only PV; case 4: hybrid wind-PV; case 5: case 4 with UPFC
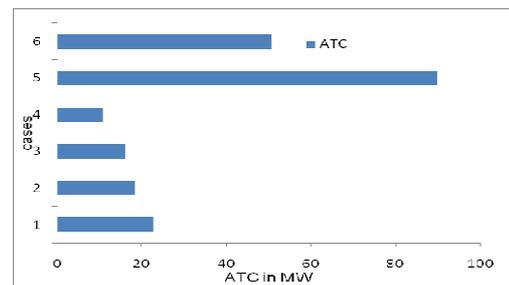
Figure 13.Effect of DG on ATC
Case 1: Base case; case 2: only wind; case 3: only PV; case 4: hybrid wind-PV; case 5: case 4 with UPFC-case (a), case 6: case 4 with UPFC-case (b)

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

[1] Hadi Saadat, Power System Analysis. 2nd edition. New Delhi: Tata McGraw Hill publications.2002
[2] F. Capitanescu, J. L. Martinez Ramos, P. Panciatici, D. Kirschen, A. Marano Marcolini, L. Platbrood, L. Wehenkel. *State-of-the-art, challenges, and future trends in security constrained optimal power flow*. Elsevier, Electric power system research. 2011:1731-1741
[3] Mithun M. Bhaskar, Sydulu Maheswarapu. A Hybrid Genetic Algorithm Approach for OptimalPower Flow.*TELKOMNIKA*. August 2011; 9(2): 211-216.
[4] S. G. Bharathi Dasan, Selvi Ramalakshmi, R. P. K. Devi. *Optimal siting and sizing of hybrid distributed generation using EP*. IEEE International Conference on Power Systems. 2009: 27-29.
[5] L. Gyugi, C. D. Schauder. The Unified Power Flow Controller: A new approach to power transmission control. *IEEE Transactions on power delivery*. 1995; 10(2): 1085-1097.
[6] M. Basu. *Optimal power flow with FACTS devices using Differential Evolution*. Elsevier, Electrical Power and Energy Systems. 2008: 150-156.
[7] M. Noroozian, L. Angquist, M. Ghandhari, G. Anderson. Use of UPFC for optimal power flow control. *IEEE Transactions on Power Delivery*. 1997; 12(4): 1629-1634.
[8] H. Farahmand, M. Rashidinijad, A. A. Gharaveisi, G. A. Shahriary. *Optimal location of UPFC for ATC enhancement in restructured power systems.* 2007: 176-181
[9] Sandip Chanda, Abhinandan De. *Congestion Relief of Contingent Power Network with Evolutionary Optimization Algorithm. TELKOMNIKA*. March 2012; 10(1): 1-8.
[10] Enrique Acha, Claudio R. Fuerte-Esquivel, Hugo Ambriz-Perez, Cesar Angeles-Camacho. FACTS: Modelling and Simulation in Power Networks. New Delhi. John Wiley and Sons Ltd.2004.
[11] M. A. Abido. *Optimal Power Flow using Particle Swarm Optimization*. Elsevier, Electrical Power and Energy Systems. 2001: 563-571.
[12] John J. Grainger, William D. Stevenson Jr., Power System Analysis. 4th Edition. McGraw Hill publications. 1982.