

# Optimal Allocation of Wind Power DG in Power Systems

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**Abstract** - Renewable energy based Distributed Generators (DGs) play a dominant role in electricity production with increase in the global warming. Wind energy is one of the most available and feasible forms of renewable energy due to their advantages. The integration of Distributed Generation (DG) into the distribution system brings technical and economic benefits to the grid. Yet installation of non optimized sizes of DGs at arbitrary locations can result in degraded voltage profile and increased system losses. Therefore it is expedient that the sizing and location of DG units should be deliberately planned and determined. DG unit sizing and siting are calculated using a sensitivity index that combines the exact loss formula and voltage sensitivity coefficients.

In this paper the Squirrel Cage Induction Generator (SCIG) is considered as wind generator. This paper provides the comparison between the economic load dispatch by conventional method and economic load dispatch by non conventional method by using PSO. Gives an analytical technique to determine the optimal siting and size of DGs in a distribution system for power loss reduction. Also the system performance at different penetration levels of wind DG is observed. The proposed model is implemented in MATLAB/SIMULINK.

**Key Words:** Distributed Generation (DG), optimum size, optimum location, power loss, voltage profile, Power system, Squirrel Cage Induction Generator (SCIG), Wind Penetration, Distribution System (DS), Optimal Power Flow (OPF).

## 1. INTRODUCTION

The increase in need for electrical power generation, steady progress in the power deregulation, utility restructuring, tight constraints over the construction of new transmission lines for long distance power transmission, the problem of global warming and fatigue of fossil fuel have increased the usage of Distributed Generation (DG) sources closer to load demands in the distribution system. These include cogeneration of thermal efficiency, clean natural energy generation, and many others. Most especially the DGs are variable

Renewable Generation (RG) which imposes new challenges to the distribution system over centralized expected production due to their intermittency and variable characteristics [2]. The integration of DGs into the DS that is close to the consumer point of common coupling (PCC), changes the traditional flow from a unidirectional flow (Generation, transmission and distribution) to a bidirectional flow that may bring imbalance to energy production and consumption [3]. Therefore, it is required that the whole network operational system should be revisited and managed in a more new way than with the usual manner.

In order to minimize the negative impact and bring benefits, technical constraints concerning the integration of DG units and their penetration levels are being gradually adopted. The optimal sizing and siting of DG units are used in order to decrease the power loss, increase the power transfer capability, increase system power quality, reliability, and improve the voltage profile [4]. Inappropriate installation of DGs at random locations can result in a rise in system losses and poor voltage profile. Optimal sized DG units should be located properly in the system in order to obtain wide benefits.

Integrating wind generator to the power system will have a big impact on the system safety and economical operation. By the use of Optimal Power Flow (OPF) calculation we can find out the impact of wind power on the systems. The OPF is an important tool that system operator require in order to operate the grid with high penetration of wind power more efficiently while maintaining all constraints within restricted limits.

The Optimal Power Flow (OPF) optimizes the operating condition of a power system. The main benefits of Optimal Power Flow (OPF) are:

- To ensure the security of quality of service by imposing limits on system operation,
- To optimize reactive-power/voltage scheduling
- To improve economy of operation through the full utilization of the system's feasible operating range and by the accurate coordination of transmission losses.

Mostly wind generators are used in coastal areas and hilly areas. As wind energy is not constant the wind power generated is not constant all the time. The OPF

minimizes the cost of the thermal plants and the system losses at different levels of the wind power generated.

As modern power systems are more complex planning, operation and control of such systems by conventional methods leads to many difficulties. Intelligent system has been developed and applies for solving such problems.

In order to avoid the effects of the conventional methods, Evolutionary techniques have been proposed; they are Expert System (ES), Genetic Algorithm (GA), Tabu Search (TS), Evolution Strategy (ES), Particle Swarm Optimization (PSO), etc.

In this paper, Particle Swarm Optimization (PSO) method is proposed to solve the optimal power flow problem. Particle swarm optimization (PSO) is a population-based optimization method first proposed by Kennedy and Eberhart in 1995, inspired by social behavior of bird flocking or fish schooling[5].

## **2. DISTRIBUTED GENERATORS (DG):-**

*"Distributed Generation (DG) is the generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in a power system".*

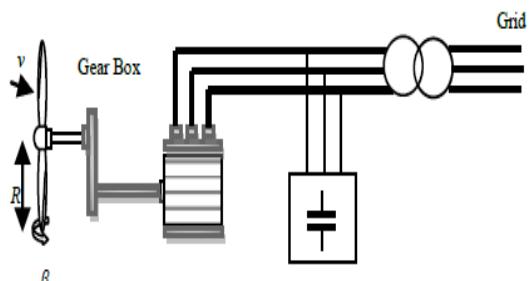
Generally, Distributed Generation (DG) is located at the point where the energy is essentially needed. The DGs are classified mainly based on the type of resources and based on interfacing technologies to the power system.

The different types of DGs base on the power penetration given as follows:

- **Type 1 DG:** is capable of injecting both real and reactive power (e.g., synchronous generators).
- **Type 2 DG:** is capable of injecting real power but consuming reactive power (e.g., induction generators).
- **Type 3 DG:** is capable of injecting real power only (e.g., PV and fuel cells).
- **Type 4 DG:** is capable of delivering reactive power only (e.g., synchronous compensators, capacitor).

## **3. WIND GENERATOR MODELING**

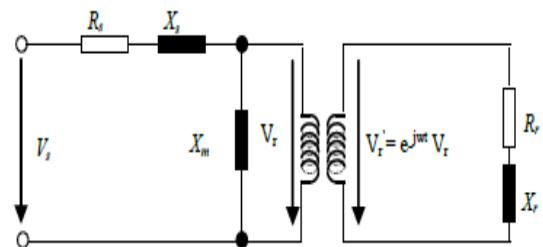
The fixed-speed, Squirrel Cage Induction Generator (SCIG) is connected directly to the distribution grid through a transformer. Representation of fixed speed Induction Generator is shown in Fig 1.



**Fig.1** Representation of the fixed speed induction generator

There is a gear box which scepters the generator's speed to the frequency of the grid. During high wind speeds, the power extracted from the wind is limited by the stall effect of the generator. This prevents the mechanical power extracted from the wind from becoming too large. In most cases, a capacitor bank is connected to the fixed speed wind generator for reactive power compensation purposes. The capacitor bank minimizes the amount of reactive power that the generator draws from the grid [6].

The Squirrel Cage Induction generator model is shown in Fig. 2. Where  $R_s$  represents the stator resistance,  $X_s$  represents the stator reactance;  $X_m$  is the magnetizing reactance, while  $R_r$  and  $X_r$  represent the rotor resistance and reactance, respectively.



**Fig.2** Equivalent circuit of the Squirrel Cage Induction generator

A standard detailed two-axis induction machine model is used to represent the induction generator. The relationship between the stator voltage, rotor voltage, the currents and the fluxes are given by the following equations [7].

$$V_{ds} = -R_s * i_{ds} - \omega_s * \lambda_{qs} + \frac{d}{dt} \lambda_{ds} \quad (1)$$

$$V_{qs} = -R_s * i_{qs} + \omega_s * \lambda_{ds} + \frac{d}{dt} \lambda_{qs} \quad (1)$$

$$V_{dr} = R_r * i_{dr} - g * \omega_s * \lambda_{qr} + \frac{d}{dt} \lambda_{dr} \quad (2)$$

$$V_{qr} = R_r * i_{qr} + g * \omega_s * \lambda_{dr} + \frac{d}{dt} \lambda_{qr} \quad (2)$$

Where  $V_s$  is the stator voltage while  $V_r$  represents the rotor voltage,  $\lambda_s$  and  $\lambda_r$  are the stator and rotor flux respectively, while  $\omega_s$  is the synchronous speed. The rotor voltage is zero because the rotor has been short-circuited in the Squirrel cage induction generator. The model is completed by the mechanical equation as given below [7].

$$\frac{d\omega_r}{dt} = \frac{1}{2H} * (T_m - T_e) \quad (3)$$

Where,  $H$  represents the inertia constant,  $T_m$  represents the mechanical torque,  $T_e$  represents the electrical torque and  $\omega_r$  represents the generator speed.

#### 4. ECONOMIC LOAD DISPATCH

The basic OPF problem can described mathematically as a minimization of problem of minimizing the total fuel cost of all committed plants subject to the constraints.

$$\text{Minimize } \sum_{i=1}^n F_i(P_i) \quad (4)$$

Where,  $F_i(P_i)$  represents the fuel cost equation of the  $i^{th}$  plant. It is the variation of fuel cost (\$) or Rs) with generated power (MW). Normally it is expressed as continuous quadratic equation.

$$F_i(P_i) = a_i P_i^2 + b_i P_i + c_i, \quad P_i^{\min} \leq P_i \leq P_i^{\max} \quad (5)$$

The total generation should meet the total demand and transmission loss. The transmission loss can be determined from power flow.

$$\sum_{i=1}^n P_i = D + R \quad (6)$$

$$R = \text{real} \left( \sum_j^n V_i Y_{ij} V_j \right), \quad i = 1, 2, 3, \dots, n \quad (7)$$

$$Q_i = \text{imag} \left( \sum_j^n V_i Y_{ij} V_j \right), \quad i = 1, 2, 3, \dots, n \quad (8)$$

$$V_i^{\min} \leq V_i \leq V_i^{\max} \quad (9)$$

#### 5. QUADRATIC PROGRAMMING

Quadratic Programming is an effective optimization method to find the global solution if the objective functions is quadratic and the constraints are linear. It can be applied to optimization problems having non-quadratic objective and nonlinear constraints by

approximating the objective to quadratic function and the constraints as linear. For all the four problems the objective is quadratic but the constraints are also quadratic so the constraints are to be made linear.

$$\begin{aligned} & \text{Minimize } 0.5 (X.H.X^T) + F^T X, \\ & \text{Subject to } KX \leq R, \\ & X^{\min} \leq X \leq X^{\max} \\ & X = [x_1, x_2, x_3, \dots, x_n]^T \\ & f = [f_1, f_2, f_3, \dots, f_n]^T \\ & R = [R_1, R_2, R_3, \dots, R]^T \end{aligned} \quad (10)$$

Where,  $H$  represents Hessian matrix of size  $n \times n$   
 $A$  is an  $m \times n$  matrix representing inequalities.

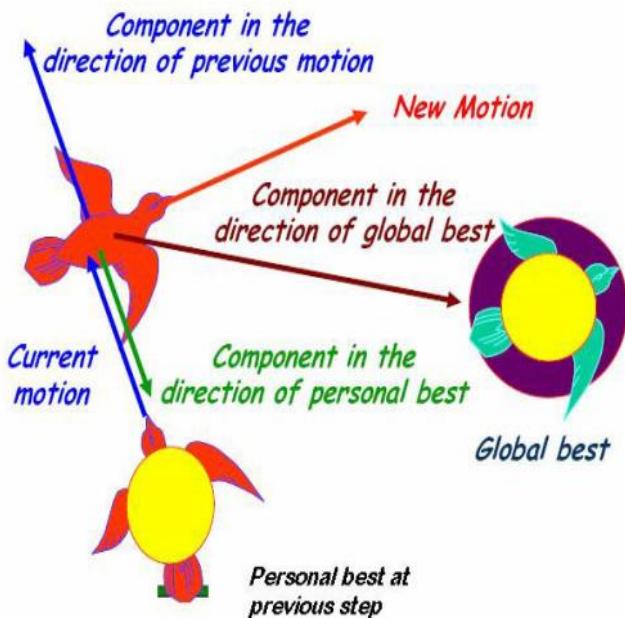
To solve the economic dispatch with losses the Quadratic Programming can be effectively implemented by defining the matrices  $H$ ,  $f$ ,  $K$  and  $R$ .

$$\begin{aligned} H &= \text{diag} \left[ \frac{a_1}{x_1}, \frac{a_2}{x_2}, \dots, \frac{a_n}{x_n} \right], \\ f &= \text{diag} \left[ \frac{b_1}{x_1}, \frac{b_2}{x_2}, \dots, \frac{b_n}{x_n} \right] \\ K &= [1, 1, 1, \dots, 1] \quad 1 \times n \text{ matrix} \\ R &= D + P_i^{\text{old}} \end{aligned}$$

#### 6. OPTIMAL POWER FLOW

Optimal Power flow (OPF) is allocating loads to plants for minimum cost while meeting the network constraints. It is formulated as an optimization problem of minimizing the total fuel cost of all committed plant while meeting the network (power flow) constraints.

The PSO as an optimization tool provides a population-based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience (this value is called **Pbest**), as well as according to the experience of its neighboring particle (this value is called **Gbest**), from the best position encountered by itself and its neighbor. The basic concept of PSO lies in accelerating each particle toward its **pbest** and the **gbest** locations, with a random weighted acceleration at each time step as shown in Fig.3. Initially, the algorithm randomly generates the particle positions representing the variable adopted. Each particle moves from its current position using the velocity and the distance from current best local and global solutions attained. The velocity consists of inertia of the particle, memory, and cooperation between particles.



**Fig 3:** Concept of searching mechanism of PSO

The velocity of each agent is updated by the following equation:

$$V_{id}^{k+1} = \omega V_{id}^k + c_1 r_1 * (pbest_{id} - S_{id}^k) + c_2 r_2 * (gbest_{id} - S_{id}^k) \quad (11)$$

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest, is calculated.  $c_1$  and  $c_2$  take the values ranging between 1 & 2.  $r_1$  and  $r_2$  are two different random numbers in the range 0 to 1. The current position (searching point in the solution space) is modified by the following equation:

$$S_{id}^{k+1} = S_{id}^k + V_{id}^{k+1} \quad (12)$$

$i=1, 2, 3 \dots n \quad d=1, 2, 3 \dots m$

Where,  $S^k$  the current searching point,  
 $s^{k+1}$  the modified searching point,  
 $v^k$  the current velocity,  
 $v^{k+1}$  the modified velocity of agent i,  
 $\omega_i$  the weight function for velocity of agent i,  
 $c_i$  the weight coefficients for each term.

The following weight function is used:

$$\omega_i = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{k_{max}} k \quad (13)$$

Where,  $\omega_{min}$  and  $\omega_{max}$  are the minimum and maximum weights respectively.  $k$  and  $k_{max}$  are the current and

maximum iteration. Appropriate values for  $\omega_{min}$  and  $\omega_{max}$  are 0.2 and 0.9 respectively.

## 7. OPTIMAL LOCATION AND SIZING

There are lots of benefits in installing distributed energy resources in Distribution systems. The major technical benefits are as follows:

- Line-loss reduction
- Voltage profile improvement
- Improvement in the reliability and continuity of power supply
- Modularity

Though interaction of DG units into distribution systems has got the above mentioned advantages, they need to be placed in appropriate location as well as of appropriate sizing. If DG units are improperly located and sized, there can be a steep increase in power losses as well as voltage constraint at the buses would be violated. Hence, to minimize losses, it is important to find the best location and size, given the option of resources availability.

### 7.1 OPTIMAL LOCATION

Optimal location of can be given by using sensitivity index. Sensitivity index is of many types. In this paper power loss of the system is to be reduced, sensitivity index of exact loss formula [8] is considered to determine the optimal location of DG.

Whereas the exact loss formula is as follows,

$$R = \sum_{i=1}^n \sum_{j=1}^n A_{ij} (P_i P_j + Q_i Q_j) + B_{ij} (Q_i - Q_j P_i) \quad (14)$$

Where,

$$A_{ij} = \frac{R_{ij}}{V_i V_j} \cos(\delta_i - \delta_j)$$

$$B_{ij} = \frac{R_{ij}}{V_i V_j} \sin(\delta_i - \delta_j)$$

Sensitivity index is given by,

$$\frac{\partial P_i}{\partial P_i} = 2(A_{ii} P_i) + 2 \sum_{j=1, j \neq i}^n (A_{ij} P_j - B_{ij} Q_j) \quad (15)$$

### 7.2 OPTIMAL SIZING

In this paper wind generator has been used. And the sizing of wind DG is given by

$$P_{DGi} = \frac{A_{ii}(P_{Di} + aQ_{Di}) + B_{ii}(aP_{Di} - Q_{Di}) - X_i - aY_i}{a^2 A_{ii} + A_{ii}}$$

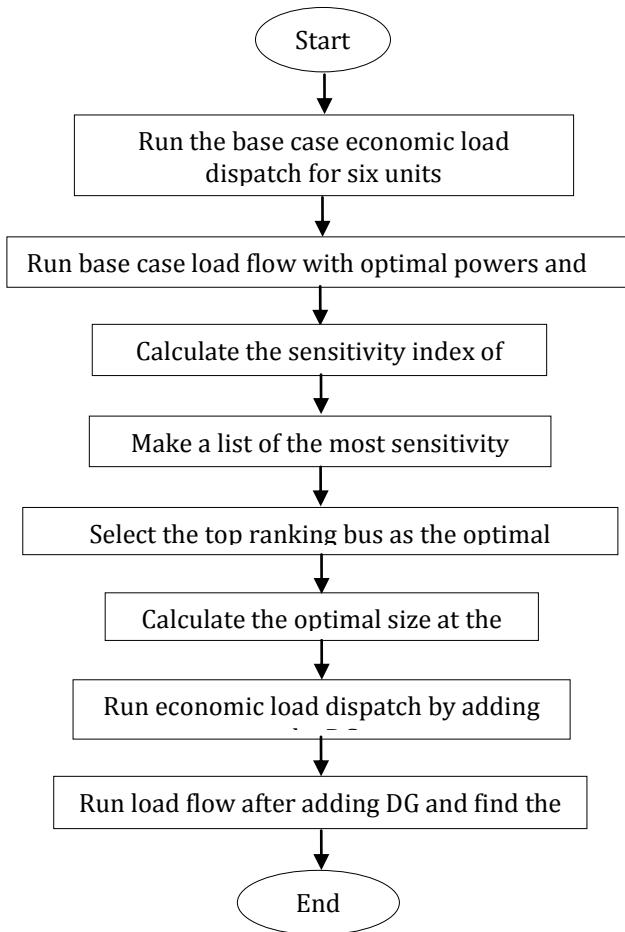
$$Q_{DGi} = aP_{DGi} \quad (16)$$

Where,  $a = (\text{sign}) \tan(\cos^{-1}(PF_{DG}))$   
 Sign=(-1), DG injecting reactive power

$$X_i = \sum_{\substack{j=1 \\ j \neq i}}^n (A_{ij} P_j - B_{ij} Q_j)$$

$$Y_i = \sum_{\substack{j=1 \\ j \neq i}}^n (A_{ij} Q_j - B_{ij} P_j)$$

From equation (15) sensitivity index at each bus is calculated. Select the top ranking bus as the optimal location for the installation of DG in the system. Figure 3. gives the detailed procedure for determining the optimal location and sizing of wind DG.

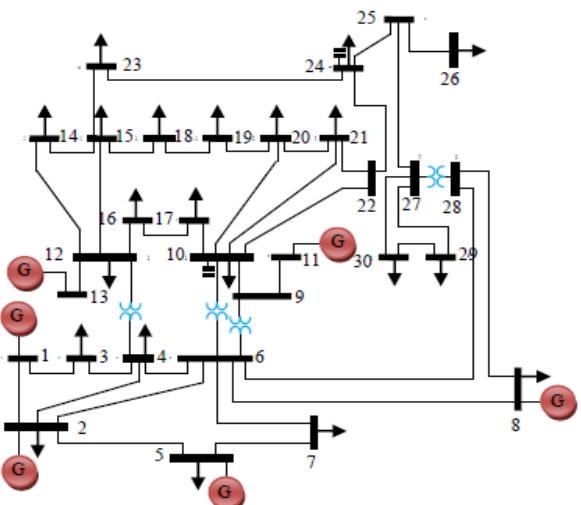


**Fig.3.** Flow chart

## 8. SYSTEMS UNDER STUDY

The system under study is a typical 30-bus distribution system, contains 30 buses and 41 branches as shown in Figure 4. It is a system with a total load of 2.834 MW and 1.262 MVAR [9]. A computer program is written in

MATLAB 7.8 to find the economic load dispatch for the six units by using quadratic programming and PSO.



**Fig.4.** Single line diagram of the IEEE 30-bus system

**Table - 1.** Power Generation Limits and Cost coefficients

Bus No	Pmin (MW)	Pmax (MW)	Cost Coefficients		
			A	B	C
1	50	200	0.00375	2	0
2	20	80	0.0175	1.75	0
5	15	50	0.0625	1	0
8	10	35	0.0083	3.25	0
11	10	30	0.025	3	0
13	15	40	0.025	3	0

## 9. SIMULATION RESULTS

This section presents computer simulation studies with programs developed in MATLAB software version 7.8 to give the comparison between the conventional method by quadratic programming and non-conventional method by PSO. Table.2. gives the optimal powers, cost and power loss of the system without DG.

**Table - 2.** Comparison for Quadratic programming and PSO without DG

	Quadratic Programming	PSO
Pg 1 (p.u)	1.96	1.9676
Pg 2 (p.u)	0.4668	0.4687
Pg 5 (p.u)	0.1907	0.1912
Pg 8 (p.u)	0.1109	0.1
Pg 11 (p.u)	0.1	0.1
Pg 13 (p.u)	0.12	0.12
Cost (\$/h)	767	767.6

P loss (MW)	10.8	10.88
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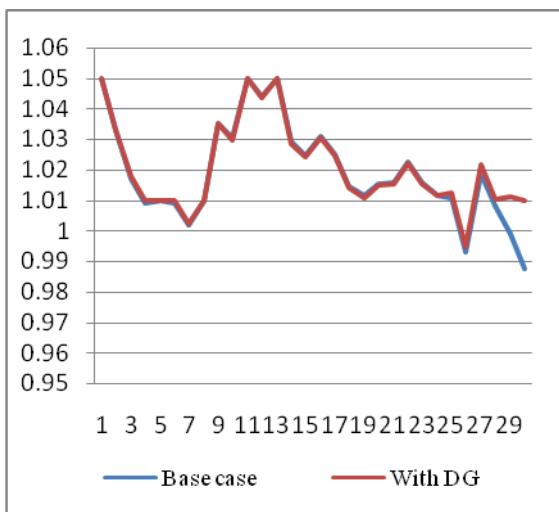
From equations (15), (16) the optimal location of wind DG is given as 30<sup>th</sup> bus and the optimal sizing is given as 15MW. Table.3. gives the optimal powers, cost and power loss of the system by installing DG.

**Table - 3.** Comparison for Quadratic programming and PSO with DG

	Quadratic Programming	PSO
Pg 1 (p.u)	1.8356	1.8356
Pg 2 (p.u)	0.4435	0.4435
Pg 5 (p.u)	0.1842	0.1842
Pg 8 (p.u)	0.1	0.1
Pg 11 (p.u)	0.1	0.1
Pg 13 (p.u)	0.12	0.12
DG (p.u)	0.15	0.15
Cost (\$/h)	716	716
P loss (MW)	9.61	9.61

From Table.2. and Tale.3. the cost obtained by conventional and non-conventional method is almost same. After adding the DG at 30<sup>th</sup> bus of 15MW cost is reduced by 5.9% and power loss reduced by 11.9% and are almost same in two methods are same. This paper proposes the PSO method is best.

Fihure.4. shows the voltage profile of the system with DG and without DG. Voltage profile is increased by installing the DG.



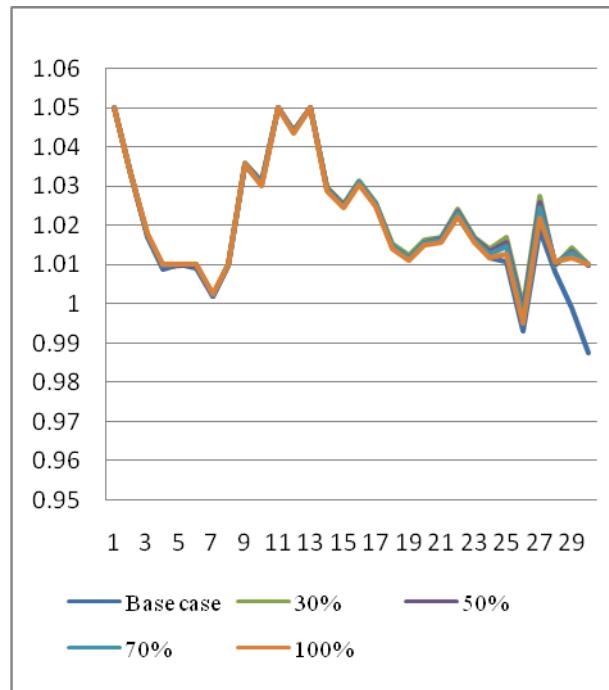
**Fig.4.** Voltage profiles of the system with and without DG

As the speed of wind is not constant the power penetrated into the system by DG also varies. Table.4. gives the optimal powers, cost and power loss at different penetration levels.

**Table - 4.** Penetration level of wind DG

	30%	50%	70%	100%
Pg 1(p.u)	1.94	1.93	1.87	1.8356
Pg 2(p.u)	0.4662	0.462	0.4511	0.4435
Pg 5(p.u)	0.1905	0.15	0.1863	0.1842
Pg 8(p.u)	0.1	0.1	0.1	0.1
Pg11(p.u)	0.1	0.1	0.1	0.1
Pg13(p.u)	0.12	0.12	0.12	0.12
DG (p.u)	0.045	0.075	0.105	0.15
Cost(\$/h)	62.5	743	732.32	716
Plos(MW)	10.6	10.47	9.8	9.61

From Table.4. cost and Power loss decreases with the increase in the penetration level of DG. Figure.5. shows the voltage profile at different penetration levels.



**Fig.5.** Voltage profiles at different penetration levels

## 10. CONCLUSION

In this paper economic load dispatch is done by Quadratic programming and PSO. And proposed that PSO is also better than Quadratic programming. After installing the DG of 15MW at 30<sup>th</sup> bus the power losses are reduced by 11.9% and cost is reduced by 5.9%. By increasing the penetration levels of DG the voltage profile increases, cost and power losses are reduced.

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