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Maximization of instantaneous wind penetration using particle swarm optimization

Sasidharan Sreedharan[1*], Weerakorn Ongsakul[2], J G Singh[3]

[1*] *Energy Field of Study, Asian Institute of Technology, Bangkok, THAILAND,*
[2] *Energy Field of Study, Asian Institute of Technology, Bangkok, THAILAND,*
[3] *Energy Field of Study, Asian Institute of Technology, Bangkok, THAILAND,*
[*]*Corresponding Author: e-mail:Sasi.Sreedhar@ait.ac.th, Tel +66(0) 2524-5397(O), Fax +66(0) 2524-5439*

Abstract

In this paper, a new methodology has been proposed for attaining the maximum instantaneous wind penetration by the optimization of grid control parameters. Particle Swarm Optimization (PSO) based algorithm has been developed to obtain the maximum instantaneous penetration. The developed algorithm has been tested on modified IEEE 14-bus test system. The results have shown the maximum instantaneous wind energy penetration limit in percentage and also maximum bus loading point explicitly beyond which system drives into instability.

Keywords: Wind power generation, wind penetration, power system modeling, PSO

1. Introduction

Modern power generating systems are fully integrated with various renewable energy resources for capacity saving, cost reduction, loss reduction, and for decarbonization of the power sector. Among the various renewable energy sources, wind power generation is having lot of advantages and is the most promising source for the future as per by Global Wind Energy Association report (2008). Takur *et al*. (2009) mentioned that the increased penetration of wind power introduces unwanted conditions such as: loss of synchronism, voltage collapse, load shedding, large deviations in voltage and/or frequency, introducing flicker and harmonics, high transmission and distribution losses, over loading and increased power oscillation. The problem is, therefore, how to increase the wind penetration into the grid, and what could be the maximum wind penetration possible at any time.

For the above problem, a number of methodologies and techniques are available depending on the wind availability, grid limitation etc and varies from country to country and region to region as presented in by Hofmann *et al*. (2007) and Estanqueiro *et al*. (2008) . In general, some of the methods for maximizing the wind penetration are to use suitable type of wind turbines in the wind farms, which are connected at suitable buses and to use suitable grid control mechanisms to enable maximum penetration as mentioned by Estanqueiro *et al*. (2007).

Wind Turbine Generators (WTGs) can be classified into two categories – Constant Speed Wind Turbine Generators (CSWTGs) and Variable Speed Wind Turbine Generators (VSWTGs). One of the popular types of VSWTG is Doubly Fed Induction Generator (DFIG), which can be smoothly connected to the grid and can provide reactive power compensation besides excellent speed control. Moreover, studies done by Takur *et al*. (2009) have proved that DFIG based wind turbine does not provide any oscillatory instability problems. The wind farm should be attached to the most suitable bus for maximizing the wind penetration by taking into account the wind availability, closeness to load centre, strength of the grid etc. The strategic grid control mechanisms are suitable optimization algorithm driven control measures to accept various levels of wind penetration.

Wind energy "penetration" refers to the fraction of energy produced by wind compared with the total available generation capacity. The concepts and reviews of instantaneous wind penetration was given in by Weisser *et al*. (2005), where the ratio of total wind power output to the total load at any instant of time and has been termed as instantaneous penetration..

Earlier, the works done in the area of maximum wind penetration were based on stochastic analysis, which depended on the annualized energy yield calculated through the capacity credit and capacity factor as mentioned by Milligan *et al*. (2005) and

Voorspools *et al*. (2006) . A new computational algorithm for the calculation of maximum wind energy penetration in autonomous island of Greece was proposed by Kaldellis *et al.* (2009) and Kaldellis (2008), where the entire algorithm was based on a factor termed as the instantaneous upper wind energy penetration limit (λ), fixed by the network manager of Greek Public Power Corporation. The algorithm for λ was not available. In addition, it was also stated that there were lot of wind energy rejection taking place due to under limiting of λ for maximum grid stability. Moreover, the algorithm was based on stochastic analysis cumulated for yearly average. Another method of maximum wind penetration was explained by Papathanassiou *et al.* (2006) , where the maximum wind turbine output was limited by a constant C_D, dynamic penetration limit factor ; a grid constant and the value was assumed between 15 and 45% but stated normally 30%. Selection of C_D algorithm was not available in the literature. Kaldellis (2008) also proposed a methodology for optimizing the wind in power system, where the optimization was through a local energy storage power electronics buffer via UPS in WTG side and not by optimizing the grid parameters and none of the articles, explained the methodology for instantaneous wind penetration and were treated as constant irrespective of the grid conditions.

Stochastic analysis based on annualized energy yield required the instantaneous wind energy absorption/rejection strategy of the concerned Electricity Authority for accurate analysis. Most of the prevailing approaches as per the literatures assumed a constant value for wind acceptance/rejection factor set by concerned Electricity Authority. In the deregulated electricity market, authorities always underestimate the factor for maximum grid stability and the calculation remains as the trade secret of the electricity authority. Lots of wind energy rejections were taking place because of that; moreover, the factor is quite time varying in nature depending on the dynamic nature of the grid and can no longer be treated as constant and hence, maximum penetration calculations based on annualized energy yield assuming, a constant value of, λ has got inherent limitations of inaccuracy.

Many researchers have made immense contribution as explained above for enhancing the wind share to the grid. However, no significant research focused on the development of a good transparent methodology for increasing the instantaneous wind share in the grid by optimizing the grid control parameters, especially, based on advanced techniques such as Particle Swarm Optimization (PSO).

For increasing the penetration in maximum wind penetration study, the load has to be varied in a fuzzy fashion to reach the maximum penetration strategy, without violation of system parameters as mentioned by Kazantzakis (1985). Among the various meta heuristic optimization methods, particle swarm optimization method seems to be simple in approach, fast in convergence and robust in action and found to be healthy and promising for maximum wind penetration problems as mentioned by Harley (2008) and hence has been incorporated in this paper .

DFIG based wind turbine has been used for the formation of wind farms. The best location for connecting the wind farm was judged by the calculation of Wind Farm Placement Index (WFPI) by taking into account the parameters such as voltage limits and voltage stability, wind speed, interconnecting cable length and bus load absorption capability.

In this paper, a novel concept of maximum safe instantaneous wind energy penetration limit (ψ) have been introduced and the methodology has been proposed by suitable placement of wind farms, considering voltage stability index.

The paper has been organized as follows. In section 2, proposed methodology has been explained with the help of the block diagram. The maximum instantaneous wind penetration problem formulation has been explained in section 3. Section 4 presented some interesting numerical results along with some discussions based on the test systems used. Finally, conclusions and major contributions of the paper have been summarized in section 5.

2. Proposed Methodology and Problem Formulation

The proposed methodology consisted of placing the DFIG based wind farm at suitable location and utilizing a suitable algorithm to enable maximum grid penetration as given in Figure 1. The development of algorithm required detailed problem formulation with dynamic modeling of wind farm and power system and the model details are given in appendix (Table 4).

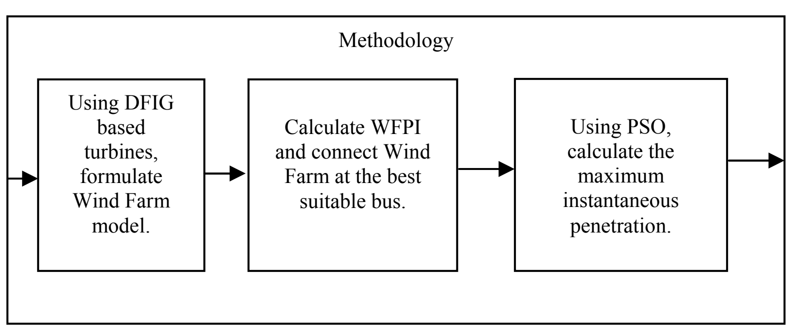

Figure1. Proposed methodology

Wind has been modeled as a Weibull distribution by taking into account its composite nature by including average, ramp, gust and turbulence components. The turbine generator used is DFIG whose stator is directly connected and the rotor was connected through slip rings and assuming lossless power electronic converter and the model details are given in appendix (Table 5).

3. Problem Formulation for Maximum Instantaneous Wind Penetration

The quality of the interconnected operation of DFIG to the grid has been assessed in terms of operational constraints and the normal operation presupposed that a number of constraint parameters are maintained within predetermined limits of which the most significant ones were voltage and frequency. Only fundamental frequency based analysis has been considered and the analysis assumed suitable buffer energy storage to handle the unpredicted power level fluctuations in additional to the adequate spinning reserve. Among the various factors for increasing wind penetration, those considered were, voltage setting of PV buses, synchronous compensators, and the load sharing between the system generators and the wind generator.

3.1. Objective function and constraints:

The objective of the penetration problem is to maximize the wind share into the grid. Accordingly, the objective function has been formulated for any time period (t) as
Maximize

$$P_W = \sum_{wf=1}^{NF} \sum_{wi=1}^{NT} P_{wi}^{\ wf}(V_{wb}, S^{wf}, v_{\omega}) \tag{1}$$

3.1.1 Power balance constraints:

Equality constraints are mainly nodal power equations, which have to be satisfied in each time interval

$$P_i = P_{Gi} - P_{Di} - \sum_{j=1}^{N_b} |V_i|\ |V_j|\ |Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{2}$$

$$Q_i = Q_{Gi} - Q_{Di} - \sum_{j=1}^{N_b} |V_i|\ |V_j|\ |Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \tag{3}$$

3.1.2 Generator and system operating constraints:

$$\left.\begin{array}{l} P_{Gi\ \min} \le P_{Gi} \le P_{Gi\ \max} \\ Q_{Gi\ \min} \le Q_{Gi} \le Q_{Gi\ \max} \\ |V_{i\ \min}| \le |V_i| \le |V_{i,\ \max}| \\ |MVA_{line}| \le |MVA_{line\ \max}| \end{array}\right\} \tag{4}$$

3.1.3. Wind power constraints:

The wind power used for dispatch should not exceed the available wind power from the wind park:

$$0 \le P_D + P_L - \sum_{i=1}^{M} P_{Gi} \le P_W \tag{5}$$

3.1.4 Optimization algorithm:

Fitness function for the above problem have been formulated as

$$P_W = \sum_{wf=1}^{NF} \sum_{wi=1}^{NT} P_{wi}^{\ wf}(V_{wb}, S^{wf}, v_{\omega}) + \sum_{k=1}^{Nk} (Pf_k * U_k) \tag{6}$$

As mentioned before, the algorithm consisted of two stages; identify the bus to which the wind farm is to be placed by using WFPI calculation and second, formulation of maximum penetration model by using the particle swarm optimization.

3.2. Wind farm placement:

The bus at which the wind farm to be placed was identified by the calculation of wind farm placement index based on assessing the impacts and benefits as mentioned by Teng *et al.* (2005). The wind farm placement index has been calculated from the equation given as follow.

$$I_{wpj} = R_{wj} + C_v R_{Vj} + \frac{1}{C_{VSI}} R_{VSIj} + \frac{1}{C_l} R_{lj} + i_{grid,j} \tag{7}$$

R_{wj} = 1; if $6 \le W_j \le 9$; R_{wj} = 2; if $W_j \le 6$; R_{wj} = 3; if $W_j \ge 9$

$R_{Vj} = 0$; For generator bus; rank from high voltage to low voltage.

$R_{VSIj} = 1/abs(VSI)$; Rank bus bars from higher value to lower.

$R_{lj} = 1/R_{lj}$; Rank bus bars from higher value to lower.

$i_{grid,j}$ = 0; for major power system grid else $i_{grid,j}$ = Number of buses in the small mesh of load buses getting connected to the single node of the major grid. The constants are suitably chosen depending on the grid by giving suitable weight.

3.3 Voltage sensitivity index:

Voltage sensitivity index based on the tangent vector at the collapse point was explained by Benabid *et al.* (2007). It is given by the expression

$$VSI_k = \frac{dV_k}{\sum_{i=2}^{n} dV_i} \tag{8}$$

The highest sensitivity index results in the weakest bus and vice versa. The tangent vector of the node voltage determines the relative weakness of the bus with respect to the reactive power.

3.4 Particle swarm optimization:

The particle swarm optimization (PSO) is a population based optimization method inspired by the social behavior of bird flocking or fish schooling. 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 multi dimensional search space. During flight, each particle adjusts its position according to its own experience (The value is called P_{best}) and according to the experience of neighboring particle (This value is called G_{best}), makes use of the best position encountered by itself and its neighbour. The modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation. The velocity (position change) of the ith particle is denoted as

$$V_i^{k+1} = \omega^k V_i^k + a_1 rand_1 * \left(P_{best\,i}^k - X_i^k\right) + a_2 rand_2 * \left(G_{best}^k - X_i^k\right) \tag{9}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1}. \tag{10}$$

In the updating, a new velocity for each particle based on its previous velocity V_i^k is determined. The particle's location at which the best fitness ($P_{best\,i}^k$) and the best particle among the neighbours (G_{best}^k) have been achieved. The inertia weight ω^k controls the exploration properties of the algorithm. The learning factors, a_1 and a_2, are the acceleration constants which change the velocity of a particle towards P_{best} and G_{best}. The random numbers, $rand_1$ and $rand_2$, are uniformly distributed numbers in range [0, 1]. Finally, each particle's position X_i^k is updated by (10).

For the Inertia Weigh Approach (IWA) PSO, particles are updated according to (9) and (10). The linearly decreasing inertia weight from the maximum value ω_{max} to the minimum value ω_{min} is used to update the inertia weight as

$$\omega^k = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{k_{max}} * k \tag{11}$$

where, k_{max} is number of maximum iteration.

In this paper, neutral network trained inertia weight approach based particle swarm optimization algorithm has been employed to focus to global optima under dynamic variations of load.

3.5 Proposed methodology:

Step 1: Input line data, bus data, wind data, voltage limits, line limits and PSO settings.
Step 2: Identify the best location for wind farm placement by the calculation of wind farm placement index and connect the wind farm to that particular bus.
Step 3: Calculate the base case power flow with the wind farm connected at the identified bus.
Step 4: Randomly generate an initial population (array) of particles with random positions and velocities on dimensions in the solution space. Set the iteration counter k = 0
Step 5: For each particle, calculate and compare its objective function value with the individual best. If the objective value is higher than P_{best}, set this value as the current P_{best} and record the corresponding particle position.
Step 6: Choose the particle associated with the minimum individual best P_{best} of all particles, and set the value of P_{best} as the current overall G_{best}.

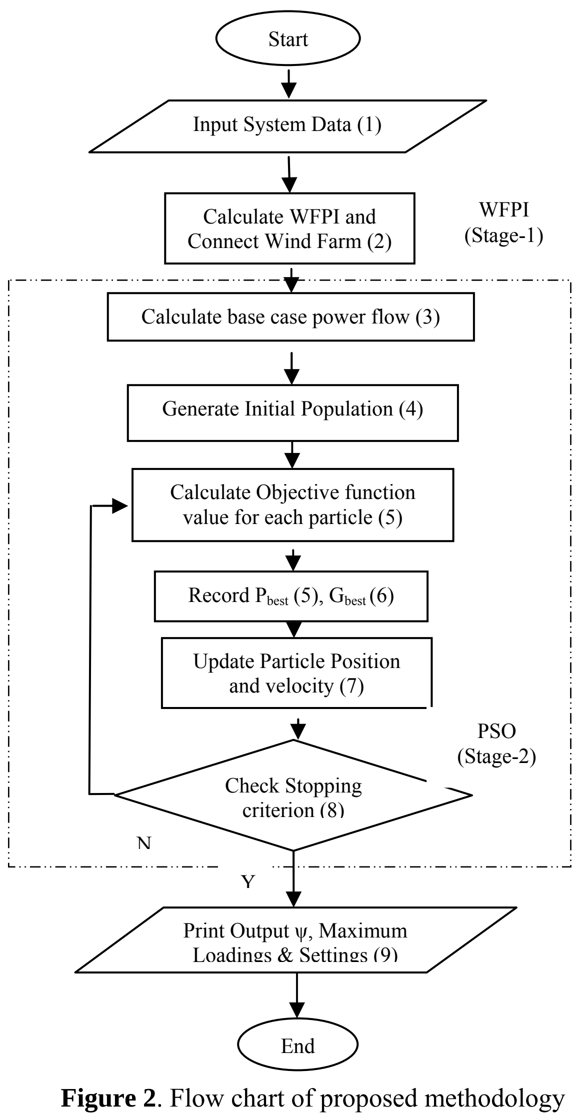

Figure 2. Flow chart of proposed methodology

Step 7: Update the velocity and position of particle using the velocity and position update equations.
Step 8: If the iteration number reaches the maximum limit, go to step 9. Else set iteration index k = k+1 and go back to step 5.
Step 9: Print out the optimal solution to the target problem. The best position includes the maximum load in each load bus , the initial MVA , power angle settings of slack generators and the initial voltage settings of all the PV buses .The fitness value gives the maximum instantaneous wind penetration limit (ψ) .

4. Results and Discussions

The proposed methodology has been tested on IEEE 14-bus modified test system as shown in Figure 3. The wind farms have been connected to wind bus and the loads have been scaled down to 50% from 100% initially to form the base case. Bus-2 is PV bus and 3, 6 and 8 are synchronous compensator buses. Loads were modeled as constant power loads (PQ load) and were solved by using Newton Raphson power flow routine. The load sharing between the wind generators and the system generators is through the initial power angle setting. The program was coded in PSAT/MATLAB integrated environment as suggested by Milano F (2005) and was run for 75 iterations. As discussed, the algorithm was implemented in two stages.

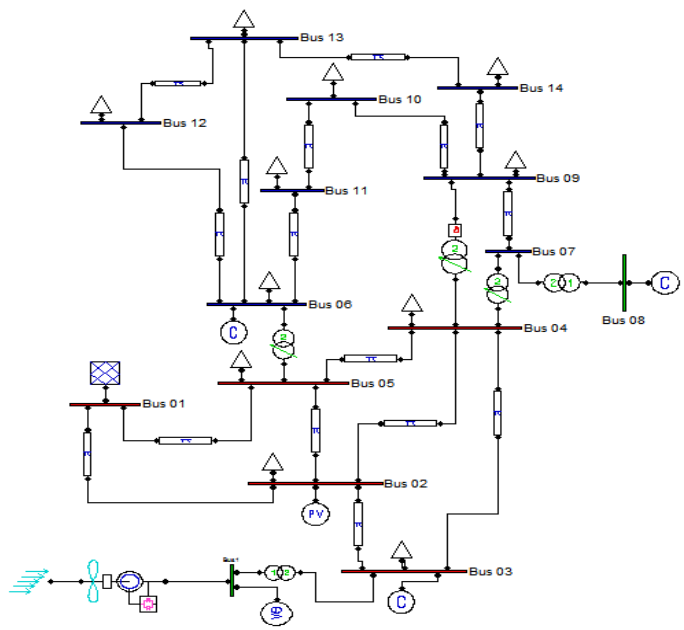

Figure 3. IEEE 14 bus modified test system

4.1. Wind farm placement

The Wind Farm Placement Index (WFPI) calculation identified bus-3 as the most suitable bus and accordingly wind farm of 600 MVA / 69kV capacity comprising of 300 wind turbines has been connected to this bus by creating another bus (bus no: 1) through a transformer of tap ratio unity.

Table 1. WFPI and maximum penetration in various buses

WFPI rank	Wind bus	Max wind share (pu)	Max penetration (%)
1	BUS-3	0.9894	44.88
2	BUS-2	0.9678	43.89
3	BUS-6	0.9098	42.14

Table 1 showed the wind farm placement calculation and the associated penetration. Wind bus is the bus to which the wind farm is attached. Different buses have different power absorption capability and accordingly maximum penetration varies. Bus-3 has been found as the best bus for maximum penetration, followed by bus-2 and bus-6.

It is also interesting to note that maximum penetration can be attained by connecting the wind farm at bus-3 as obtained from

WFPI rank. The wind farm placement index calculation assumed that wind farm was located at an equidistant point from all the buses while the constants were chosen by trial and error based on practical study conducted by Nilakshi *et al.* (2006) . The first bus being the slack bus was ignored from computations.

4.2 Maximum wind penetration calculation

For maximizing the penetration, the load variation has been taken up to 3.0 times of the base case. In this work, voltage and angle settings of the slack bus and voltage settings of the PV buses have been considered.

The optimization result recorded the maximum instantaneous wind share as 0.98 pu and accordingly, the maximum penetration possible is 45% approximately, when wind farm was placed at bus- 3 as given in Table 1.

Table 2 Typical generation and load at maximum penetration

Penetration level	P_G (pu)	Q_G (pu)	P_L (pu)	Q_L (pu)
Base penetration	1.84	0.52	1.81	0.57
At max penetration	2.30	1.02	2.22	0.76
Difference (max pen - base pen)	0.46	0.50	0.41	0.19

The total generation and load at maximum penetration is given in Table 2. The base penetration is given in first row where the base case real and reactive power loads were 1.81 pu and 0.57 pu, respectively. When the penetration was increased, more demand was met. In other words, 0.41 pu additional real power load was able to be handled.

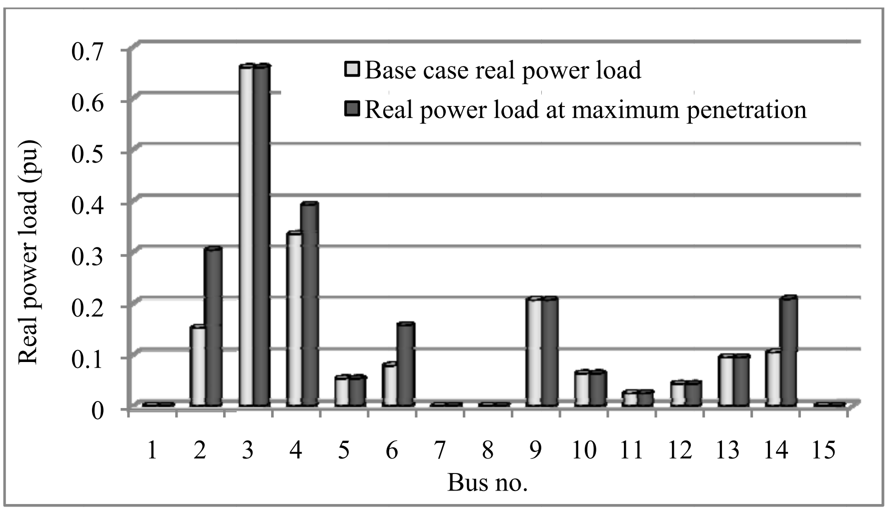

Figure 4. Typical load level during maximum penetration

Typical bus active power load level during maximum penetration was given in Figure 4. The thick black bar indicated the load at maximum penetration. Due to the randomness involved in PSO, different solution sets in terms of the load levels and bus voltages are possible; but maximum penetration is approximately the same. Suitable solution set can be chosen based on the operating requirements. In Figure 4, load at buses-2, 4, 6 and 14 are increased; however, the load at other load buses remained constant.

Similarly, the bus voltage level at maximum penetration has been compared against the base case voltage level and given in Figure 5. The figure shows that the voltages of the PV buses have been increased to slightly higher value for increasing the penetration. The thick black line represents the maximum penetration. Typical voltage levels corresponding to various samples have been given in Table 3.

Figure 6 shows the bus generations at various levels of penetration. The thick dark black bar represents the real power generation at maximum penetration. During the maximum penetration the wind share rose to around 1.0 pu, from the base case value of 0.64 pu . Slack bus also shared a small percentage of load increase; whereas the generation at bus-2 was maintained constant. The reference phase angle of wind bus was set at 0.1 radian approximately.

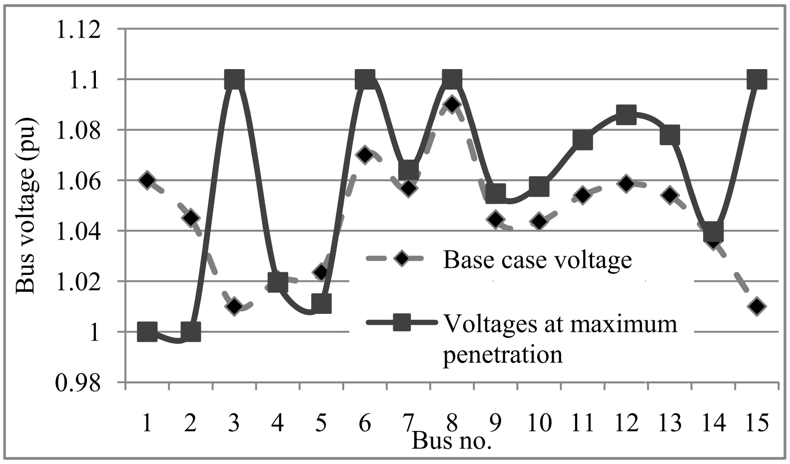

Figure 5. Typical voltage level during maximum penetration

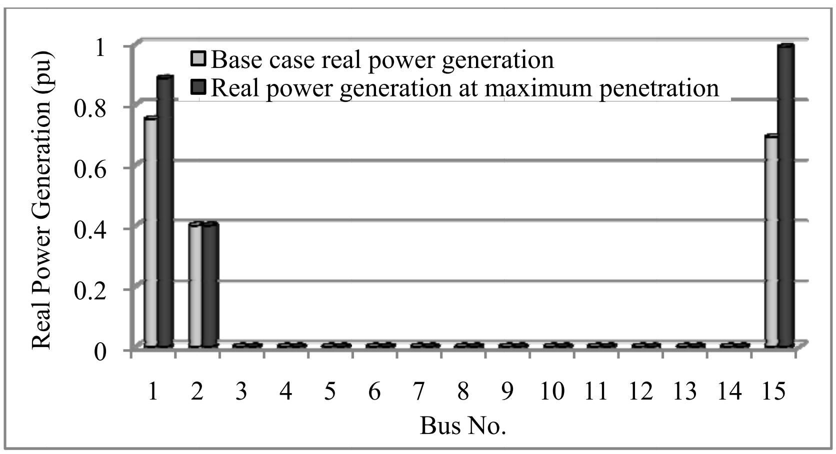

Figure 6. Typical generation levels during maximum penetration

The increase in line flow due to the increased penetration has been given in Figure 7. The increment in wind penetration even though made the line flow to increase, but was held within the permissible limits. The solid thick black wall indicated the line flow at maximum penetration. From this Figure 7, it was very clear that, the line flow in some lines, say line-17, certainly limited the penetration since the line limit was set as 1.0 pu as per the IEEE 14-bus system data.

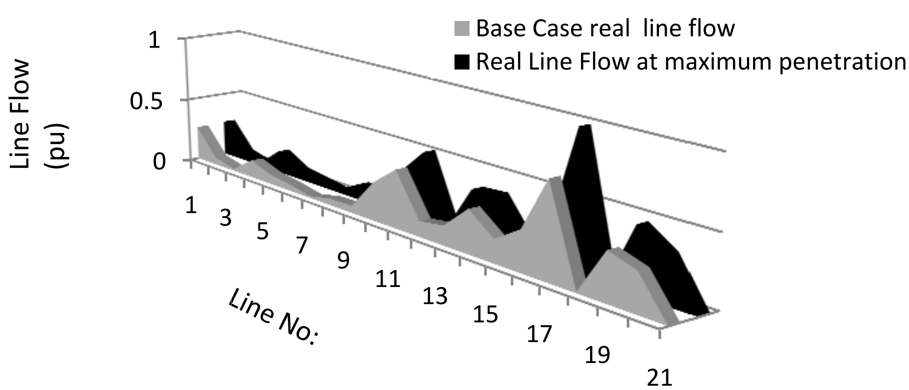

Figure 7. Typical line flow before and after penetration

In Figures 4 to 7, it was assured and proved that all voltages, generations, load variations, line flows were held within permissible limits of the IEEE 14-bus system.

Table 3. Maximum penetration in various control dimensions.

PSO Parameters	Remarks		Control strategy 1	2	3
V_1 (V)	Slack bus	PSO VARIABILES	1.0	1.0	1.0
V_{15}(V)			1.1	1.1	1.07
θ_{15}(Rad)			0.1	0.1	0.1
V_2(V)	PV		1.1	1.0	1.0
V_6(V)	SC bus*		1.0	1.07	1.1
V_3(V)	SC bus*		1.08	1.05	1.1
V_8(V)	SC bus*		1.0	1.04	1.08
P_w (pu)	Max wind share		0.985	0.99	0.9926
Ψ (%)	**Max penetration**		**45.14**	**44.9**	**44.6**

*SC- Synchronous compensator bus

For maximizing the penetration, different control strategies have been formulated for comparison as given in Table 3 and the best can be chosen and adapted depending on the flexibility of the grid in terms of AVR ratings, response characteristics, losses, load level etc. In the IEEE 14-bus test system, bus-2 is PV and 6, 3 & 8 are synchronous compensator buses. The PSO variables are voltage and angle of slack bus, voltages of PV buses and the voltages of the synchronous compensator buses. The maximum penetration depends on the optimal setting of these variables. OLTC transformer tap setting was not taken into account in this work.

5. Conclusion

In this paper, a new concept of wind farm placement index has been proposed to identify the best suitable location for the placement of wind farm by taking into account the voltage sensitivity index. Also, a new concept of maximum instantaneous wind energy penetration limit (ψ) has been introduced and methodology has been proposed. A particle swarm optimization based algorithm has been used to obtain the maximum instantaneous wind penetration. The developed algorithm also gives explicitly the maximum permissible loadings at each bus. The result seemed to be quite promising, when tested on IEEE 14-bus system.

Nomenclature

C_l	Interconnection cable length constant
C_{VSI}	Voltage sensitivity index constant
C_v	Voltage constant
dV_k	Voltage tangent vector of bus-k
I_{wpj}	Wind farm placement index of bus-j
$i_{grid,j}$	Index of grid connection of bus-j
k, nk	Violated constraint Index, Total number of violated constraints
M	Total number of existing generators in the grid other than wind
MVA_{line}	MVA rating of the line
NT , NF	Total number of wind turbines, farms
P_i , Q_i	Active & reactive power injection of bus-i
Pf_k, U_k	Penalty factor & violation of constraint-k.
P_{wi}^{wf}	Real power delivered by wind turbine *wt* of wind Farm wf
P_{Di} , Q_{Di}	Active and reactive power demand at bus-i
P_{Gi} , Q_{Gi}	Active and reactive power generation at bus-i.
P_D , P_L	Total real power demand and losses
P_W	Total real power output of all the wind Farms
R_{wj}	Wind speed rank of bus-j
R_{Vj}	Voltage rank of bus-j

R_{VSIj}	Voltage sensitivity index rank of bus-j
R_{lj}	Interconnection cable length rank of bus-j
S^{wf}	Wind farm placement distance from the wind bus
v_{ω}	Wind speed at the wind farm
VSI	Voltage sensitivity index
V_{wb}	Voltage of the wind bus
V_i, δ_i	Voltage & voltage angle of bus-*i*
N_b	Total number of buses in the system
Y_{ij}, θ_{ij}	Admittance and angle of line $_{ij}$
wi, wf	Index of wind turbine , wind farm
ψ	Maximum Instantaneous wind energy penetration limit.

Appendix

Wind was modeled as Weibull distribution as proposed by Milano F (2005) by taking into account the composite nature of wind which included average, ramp, gust, turbulence and low pass filters were used to smooth the wind speed variations..

Table 4. Wind model parameters.

Nominal wind speed/ air density	15m/s /1.225Kg/m^3
Filter time constant/sample time	4s,0.1s
Weibull constant C & K	20,2
Ramp constants [t_{sr}, t_{er}, A_{wr}]	5s,15s,1m/s
Gust constants [t_{sg}, t_{eg}, A_{wg}]	5s,15s,0m/s
Turbulence constants [h, Z_0, df, n]	50m,0.01,0.2Hz,50

DFIG Model:

Assuming lossless converter and the active power of the converter coincides with the rotor active power; the active and reactive power injected to the grid by the DFIG turbine was expressed as a function of stator and rotor currents as proposed by Milano F (2005).

Table 5. DFIG parameters.

[MVA,KV,Hz], kWs/kVA	[600 69 60], 3pu
[Rs,Xs] [Rr,Xr] Xm	[0.01 0.10] [0.01 0.08] 3.00 pu
K_p, T_p, K_v, T_e	[10pu 3s], 10pu, 0.01s
Pole, Gear Ratio,	[4 1/89]
Blade length and number	[75.00m 3]
P_{max}, P_{min}; Q_{max}, Q_{min}	[1.00 0.00]pu; [0.7 -0.7] pu
No of generators	300Nos

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Biographical notes

Sasidharan Sreedharan was born in Kerala, India in 1974. He received his B.Tech and M.Tech degree in Electrical Engineering from Govt. Engineering College, Thrissur, Kerala, India in 1995 and 1997 respectively. He is currently pursuing his doctoral degree from Asian Institute of Technology, Bangkok. His Research interests are in grid integration of Renewable, AI applications to power systems and grid stability.

Dr Weerakorn Ongsakul received the M.S. and Ph.D. degrees in electrical engineering from Texas A&M University, College Station, USA in 1991 and 1994, respectively He is currently Associate Professor and Dean of School of Environment, Resources and Development, Asian Institute of Technology, Thailand. His current interests are in parallel processing applications, AI applications to power systems, and power system restructuring and deregulation.

Dr Jai Govind Singh received his M. Tech. and PhD degrees in Electrical Engineering from I.I.T. Rookree, and IIT Kanpur, India, in 2003 and 2008, respectively. He is currently Assistant Professor in the energy field of study, Asian Institute of Technology, Thailand. His research interests include power system operation and control, FACTS, power sector deregulation and power system planning, grid integration of renewable energy sources, power distribution systems.

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