PSO Based Tuningof FACTS Controllers for Maximizing theWind Energy Penetration in Power Systems

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Abstract—**In this paper, a new methodology has been proposed for attaining the maximum instantaneous wind penetration by the optimal placement and setting of Flexible AC Transmission System (FACTS) controllers. Multiple of single type of FACTS controller namely SVC have been used for achieving the maximum wind penetration. Particle Swarm Optimization (PSO) based algorithm has been developed to obtain the maximum instantaneous penetration by adjusting the grid parameters and FACTS controller settings. 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, optimal setting of FACTS controllers and also maximum safe bus loading point explicitly beyond which system drives into instability.**

***Keywords* — Wind power generation, Wind Penetration, Particle Swarm Optimization, Power system modeling, FACTS controllers.**

I. INTRODUCTION

Micro grids consisting of renewable energy sources are one of the new and typical characteristics of modern power system. Among the various renewable energy sources, wind power generation is said to be the most promising source for the future. [1]. Nowadays, the increased penetration of wind power introduces unwanted conditions such asloss 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 [2]. 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.

There are various types of wind turbines available in the market and each type of wind turbine has got its own advantages and disadvantages. Studies have proved that Double Fed Induction Generator (DFIG) based wind turbines are having better performance characteristics. It does not create any oscillatory instability problems and can also provide reactive power compensation [2]. The wind farm should be attached to the best suitable bus for maximizing the wind penetration by taking into account the wind resource availability, closeness to the 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 [4][5].

Wind energy "penetration" refers to the fraction of energy produced by wind compared with the total available generation capacity. The wind power penetration, into a grid, is the ratio of total wind power output to the total load at any instant of time and has been termed as instantaneous penetration[6].

For the above problem of maximizing the wind energy penetration, a number of methodologies and techniques are available depending on the wind resource availability, grid limitation etc and varies from country to country and region to region[3]. 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 a suitable grid control mechanisms to enable maximum penetration. One of the alternate methods to increase the wind penetration is to use suitable FACTS controllers' at best suitable location with suitable settings [5].

Most of the works done in the area of maximum wind penetration is based on stochastic analysis which depends on the annualized energy yield calculated through the capacity credit and capacity factor [7] [8]. A novel computational algorithm for maximum wind penetration calculation in the autonomous island of Greece was proposed by Kaldellis*et al,*where the entire algorithm is based on a factor termed as the instantaneous upper wind energy penetration limit, fixed by the network manager of Greek Public Power Corporation[9][10]. The algorithm seems to be not available and so states that there is lot of wind energy rejection taking place due to under limiting of the factor for maximum grid stability. Moreover, the algorithm is based on stochastic analysis accumulated for yearly average. Another method of obtaining maximum wind penetration was explained by Papathanassiou [11], where the maximum wind turbine output is limited by a constant C_D, dynamic penetration limit factor; a grid constant and the value is assumed between 15 to 45% but stating normally 30%. The selection algorithm for C_D also seems to be not available in the literature. Kaldellisalso proposed a methodology for optimizing the wind energy in Power System, where the optimization is through a local energy storage power electronics buffer via Uninterrupted Power Supply (UPS) in WTG side and not by optimizing the grid parameters and none of the articles explains the methodology for maximizing the instantaneous wind penetration and is treated as a constant throughout the analysis [12].

From the above literatures, it is well evident that the

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researchers have made immense contributions for enhancing the wind penetration. However, no significant research focuses on the development of a good transparent methodology for increasing the instantaneous wind penetration in the grid by optimizing the grid control parameters especially, based on advanced techniques such as Particle Swarm Optimization (PSO) by incorporating FACTS Controllers.

For increasing the penetration, in wind penetration study, the load has to be adjusted in a tricky fashion to reach the maximum penetration strategy without affecting the grid stability as mentioned by Kazantzakis [13]. Accordingly, suitable optimization algorithm has to be used. Moreover, the problem requires detailed dynamic modeling of the wind and wind turbine generators. Among the various meta heuristic optimization methods, PSO 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 [14]and hence has been incorporated in this paper .

In this paper, a new algorithm has been proposed for achieving maximum safe wind energy penetration using FACTS controllers. Dynamic nature of the grid by incorporating devices such as Automatic Voltage Regulator (AVR), turbine governor (TG)etc has been incorporated. In addition, eigenvalue based small signal stability constraint; Fast Voltage Stability Index (FVSI) and Line Stability Factor (LQP) have also been incorporated to assure grid stability.DFIG based wind turbine and one type of FACTS controller namely SVC have been used for maximizing the wind penetration by connecting the wind farm.

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 discussion based on the test systems used. Finally, conclusions and major contributions of the paper have been summarized in section 5.

II. PROPOSED METHODOLOGY & MODELING

The proposed methodology consisted of connecting the DFIG based wind farm at the best suitable bus [15] 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 3).

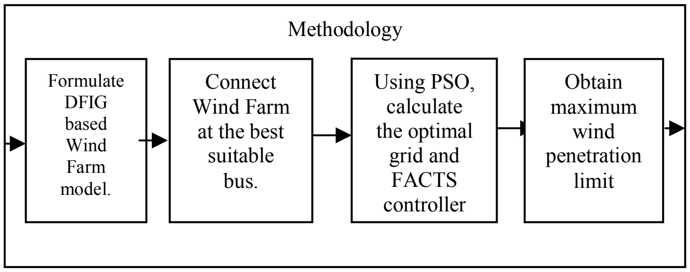


Figure1. Proposed methodology

.2.1 Modeling of power system components

Wind has been modeled as a composite distribution by taking into account its composite nature by including average, ramp, gust and turbulence components. DFIG based wind turbine and SVC have been used in this paper for analysis. In course of increasing the penetration, the power system conditions such as voltage, line flows and generations are maintained within the safe limits. Also the system is stable in small signal sense. The problem formulation requires detailed dynamic modeling of wind, TGs, AVRs and FACTS controllers. Standard models have been used for all the power system components as given below and the FACTS model have been explained in detail in the next section.

Table 1. Component model description for maximum wind penetration

Component	Model Description
Synchronous generator	IEEE Type 5.2
Turbine Governor	IEEE Type 1
Automatic voltage regulator	IEEE Type 2
Wind Turbine Generator	Double Fed Induction
Wind Model	Composite distribution

2.2 Modeling of SVC

The SVC is defined as a shunt compensatorand its output is adjusted to exchangecapacitive or inductive reactance in order to maintain or control specific parameters of an electrical power system, typically a bus voltage. In this paper, the SVC is modeled by the algebraic equation expressing the reactive power injected at the SVC node [16]:

$$\left.\begin{aligned} Q &= b_{SVC} V^2 \\ b_{SVC}^{\min} &\le b_{SVC} \le b_{SVC}^{\max} \end{aligned}\right\} \qquad (1)$$

III. PROBLEM FORMULATION

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 are 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, parameter settings of FACTS controllers 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 (t) as
Maximize,

$$P_W = \sum_{wf=1}^{N_f} \sum_{wt=1}^{N_t} P_{wt}{}^{wf}(V_{wb}, S^{wf}, v_{\omega}) \quad (2)$$

Equality Constraints:

These constraints represent the typical load flow equations as follows:

$$\left.\begin{aligned} P_{G_i} &= P_{L_i} + V_i \sum_{i=1}^{N_b} V_j \left(G_{ij}\cos\theta_{ij} - B_{ij}\sin\theta_{ij} \right); \qquad i = 1,2,3 \ldots N_b \\ Q_{G_i} &= Q_{L_i} + V_i \sum_{i=1}^{N_b} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij} \right); \qquad i = 1,2,3 \ldots N_b \end{aligned}\right\} \quad (3)$$

where, N_b is the number of buses in the system.

Inequality Constraints:

The inequality constraints are limits of control variables and state variables. Generator active power P_G, reactive power Q_G, voltage V_i, and phase angle δ_i are restricted by their limits as follows:

$$\left.\begin{aligned} & P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max} && i = 1, \ldots\ldots, N_G \\ & Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max} && i = 1, \ldots\ldots, N_G \\ & V_i^{\min} \le V_i \le V_i^{\max} && i = 1, \ldots\ldots., N_b \\ & -0.9 \le \delta_i \le 0.9 && i = 1, \ldots\ldots., N_b \end{aligned}\right\} \quad (4)$$

The parameter settings of svc are restricted by their limits as follows:

$$b_{SVC}^{\min} \le b_{SVC} \le b_{SVC}^{\max} \quad (5)$$

The constraint of transmission loading P_{ij} is represented as:

$$\left| P_{ij} \right| \le P_{ij}^{\max}; \quad ij = 1, \ldots\ldots., N_l \quad (6)$$

The load factor λ_f is constrained by its limits as:

$$1 \le \lambda_f \le \lambda_f^{\max} \quad (7)$$

Power system stability constraints:

Every generator has anarrangement of nonlinear differential equations relating to the synchronous machine, exciter, and any other control mechanisms. Every generator also has a series of algebraic equations, which link the generator state variables and the generator's steady state operating point power injection into the system. Last, are the power system network equations;namely, Kirchhoff's law circuit equations, that the steady-state operating point must satisfy. The small signal stability model of the system with DFIG can be expressed as $\Delta \dot{x} = A_s \Delta x$ where A is the System State Matrix [17]

$$A_s = F_x - F_y G_y{}^{-1} G_x \quad (8)$$

where, F_x, F_y, G_y, G_x are power flow Jacobian Matrices

If the complex eigenvaluesof the linearized system have negative real parts, then the power system would be able to withstand small disturbances and is thus, considered stable in the small-signal sense. The eigenvalue stability analysis is incorporated in the constraint by the equation

$$\mathrm{Re}\,al\left[E_i(A_s) \right] < 0 \quad (9)$$

The eigenvalue based stability assures grid stability under various levels of system loadability.

a) *Fast Voltage Stability Index*

Fast Voltage Stability Index (*FVSI*) proposed by Musirin[18] is utilized in this paper to assure the safe bus loading.

$$FVSI_{sr} = \frac{4Z^2 Q_r}{V_s{}^2 X} \quad (10)$$

The line that exhibits *FVSI* close to 1.00 implies that it is approaching its instability point. If *FVSI* goes beyond 1.00, one of the buses connected to the line will experience a sudden voltage drop leading to the collapse of the system. *FVSI* index incorporation in the controller assures that no bus will collapse due to overloading.

$$\sum_{s=1}^{N_l} \sum_{r=1}^{N_l} FVSI_{sr} < 1 \quad (11)$$

b) *Line Stability Index*

Line Stability Index (L_{mn}) proposed by M Moghavvemi[18] has been utilized in this paper to identify the maximum bus loading point.

$$LQP = 4\left(\frac{X}{V_s{}^2} \right)\left(\frac{X}{V_s{}^2} P_s{}^2 + Q_r \right) \quad (12)$$

$$\sum_{s=1}^{N_l} \sum_{r=1}^{N_l} LQP_{sr} < 1 \quad (13)$$

The value of L_{mn} should be less than 1 to maintain a stable system

3.1.4 Optimization Algorithm

Fitness function for the above problem have been formulated as

$$P_W = P_W = \sum_{wf=1}^{N_f} \sum_{wt=1}^{N_t} P_{wt}{}^{wf}(V_{wb}, S^{wf}, v_{\omega}) + \sum_{k=1}^{Nk} (Pf_k * U_k) \quad (14)$$

As mentioned before the algorithm consisted of two stages; identify the bus to which the wind farm to be placed by using WFPI calculation and second the formulation of maximum penetration model by using the particle swarm optimization. The wind farms have been connected to the best suitable bus which is identified through the calculation of Wind Farm Placement Index or by simulating the wind farm placement [19].

3.2 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

$$V_i^{k+1} = \omega^k V_i^k + a_1 rand_1 * \left(P_{besti}^k - X_i^k\right) + a_2 rand_2 * \left(G_{best}^k - X_i^k\right) \tag{15}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1}. \tag{16}$$

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_{besti}^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 (16).

For the Inertia Weigh Approach (IWA) PSO, particles are updated according to (15) and (16). The linearly decreasing inertia weight from the maximum value $\omega_{\max}$ to the minimum value $\omega_{\min}$ is used to update the inertia weight as

$$\omega^k = \omega_{\max} - \frac{\omega_{\max} - \omega_{\min}}{k_{\max}} * k \tag{17}$$

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

3.3 Methodology

Step 1: Input line data, bus data, wind data, voltage, line limits and PSO settings.

Step 2: Connect the wind farm to the best suitable bus.

Step 3: Calculate the base case power flow with the wind farm connected.

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}.

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, 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

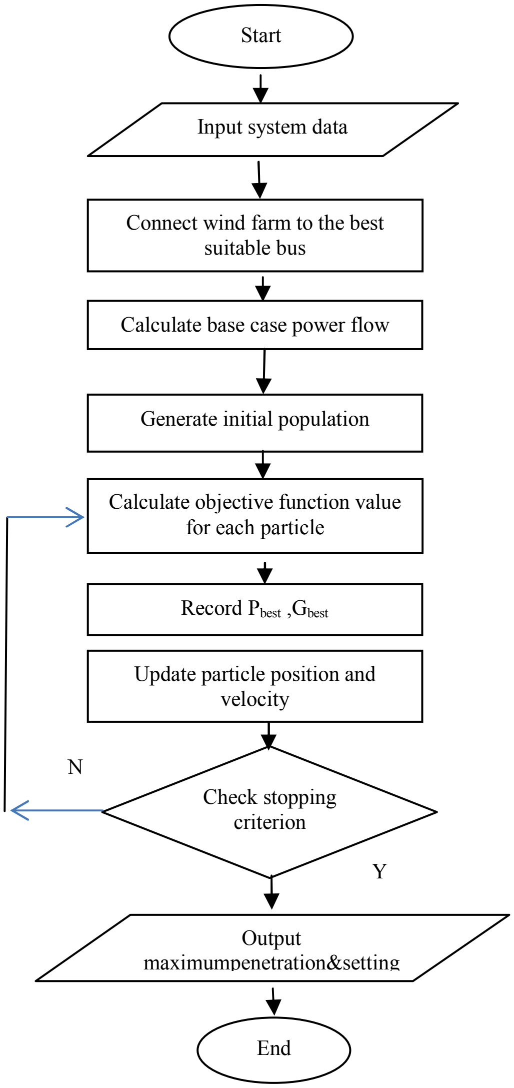
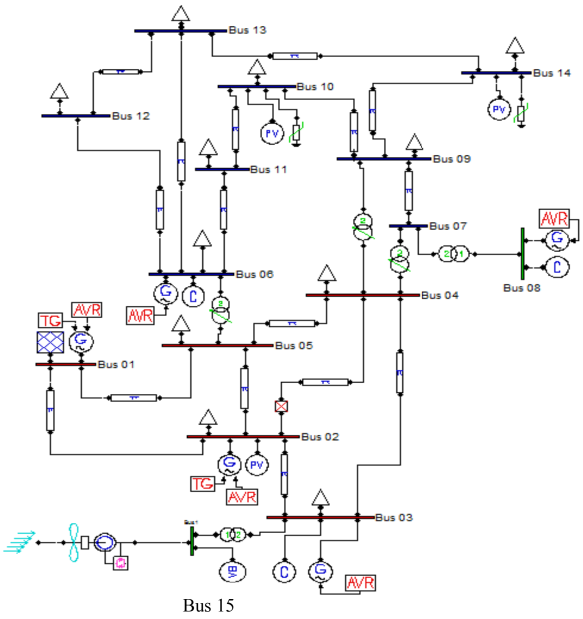


Figure 2. Flow chart of proposed methodology

IV. RESULTS AND DISCUSSIONS.

The results consist of two steps. The first step is to conduct the voltage stability analysis of the grid to access the best location for SVC and the second is the calculation of maximum penetration. The best location for the placement of SVC is the weakest bus of the system. The bus that is near to collapse and is having shortage of reactive power is generally termed as the weakest bus. In this work, the weakest bus is identified by tangent vector analysis.



(TG- Turbine Governor; AVR-Automatic Voltage regulator; C-Synchronous Compensator)

Figure 3.IEEE 14-bus modified test system with SVC

The tangent vectors of IEEE 14-bus system are given in Table 2. Bus-14 is the weakest bus with the tangent vector value of 0.015802. The wind farms have been connected to the bus-3.

Table 2. Tangent vector of first four weak buses

Bus number	Normalized tangent vector near collapse point
14	0.015802
10	0.01404
13	0.013938
9	0.013764

A. Maximum penetration calculation

Two SVC controllers have been connected at first two weakest buses say bus-14 and bus-10 as shown in Figure 3. In this work, voltage and angle settings of the slack bus and voltage settings of the PV buses and SVC have been considered for maximizing the penetration.

Active power loading levels of various buses are given in Figure 4. The thick black bar indicates the loading level corresponding to the maximum penetration and the white bar denotes the base case without wind generation. It is to be noted that controller could able to meet the additional demand requirement of almost all the buses by holding the grid stability within limits.

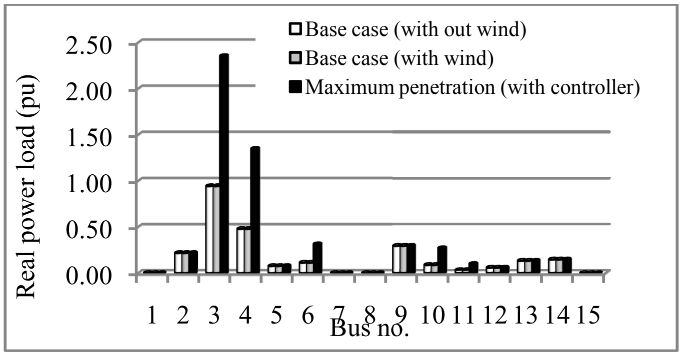


Figure 4.Typical real power loads with and without SVC

Similarly, the bus voltage level at maximum penetration has been compared against the base case voltage level in Figure 5. The figure shows that the controller adjusted the voltages of the PV buses, SVC buses and slack bus slightly for maximizing the penetration. The thick black line indicates the voltage corresponding to the maximum penetration by using the controller with SVC. Without controller, it is so assumed that the slack buses shares load equally. The base case voltages with and without wind is approximately the same and the curves overlapped each other. From the Figure 7, it is also well clear that all the bus voltages within the set limits at maximum penetration.

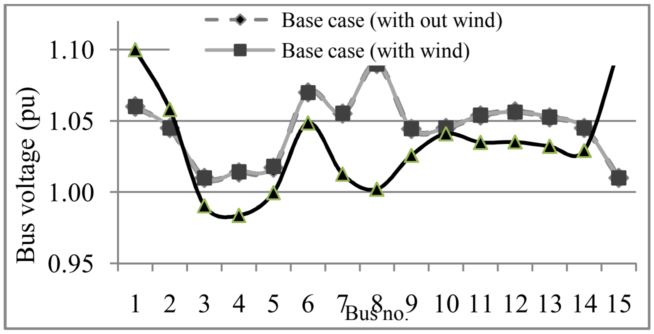


Figure 5.Typical voltage levels with and without SVC

Figure 6 shows the bus generations at maximum penetration using the SVC robust controller. The thick dark black bar represents the real power generation at maximum penetration, and the white bar, the base case without wind. Slack bus generation has been reduced by the controller and the supply demand was balanced by increasing the wind penetration.

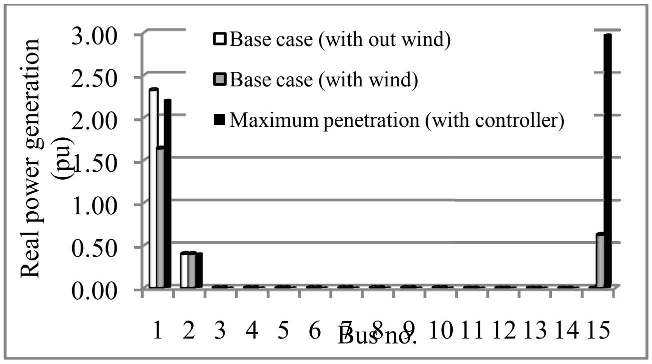


Figure 6.Typical generation levels with and without SVC

The active power flow in various lines are given in Figure 7. The thick black bar corresponds to the maximum penetration by using the controller and the white bar indicates the base case without wind.

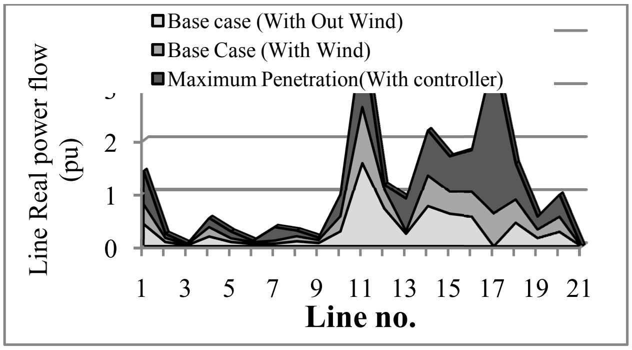


Figure 7. Typical line flows with and without SVC

The eigenvalues at maximum penetration with controller were given in Figures 8, and 9, respectively. It is quite evident that controller assures grid stability with all the eigenvalues in the left hand side of the S-plane during maximum penetration with SVC. The graphs were plotted such that far end stable eigenvalues (real eigenvalue less than -100) are not included.

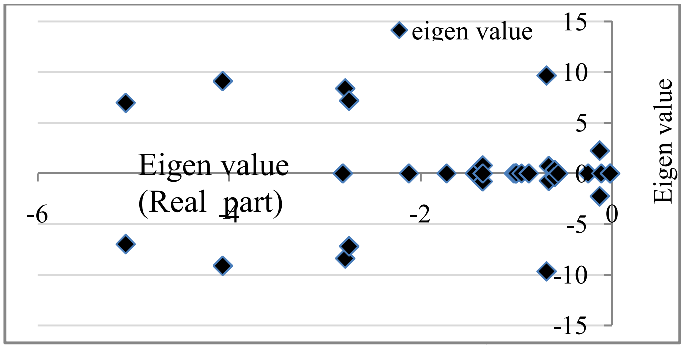


Figure 8. Lower order eigenvalues at maximum penetration with SVC

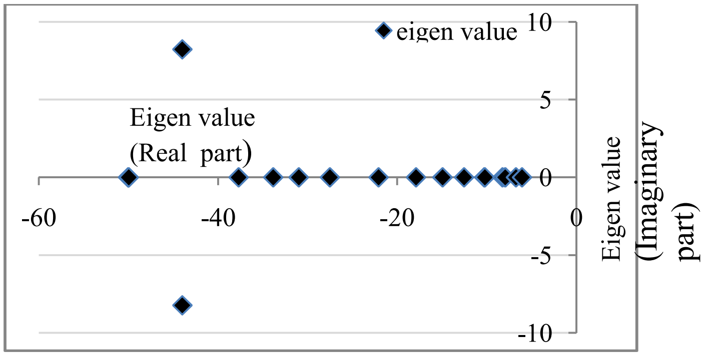


Figure 9. Higher order eigenvalues at maximum penetration with SVC

For maximizing the penetration, different control strategies for voltages of PV buses, SVC controllers and angles of slack buses can be formulated and the best control strategy based on the grid conditions can be chosen and adapted depending on the flexibility of the grid in terms of AVR/ALFC settings, response characteristics, losses, load level etc.

V. CONCLUSION.

In this paper, a new methodology for maximizing the wind penetration by using the FACTS controllers has been presented. A particle swarm optimization based algorithm has been used to obtain the maximum instantaneous wind penetration by optimal setting of FACTS controllers. The result seemed to be quite promising when tested on IEEE 14-bus system.

Nomenclature

k, Nk	Violated constraint Index, number of violated constraints
MVA_{line}	MVA rating of the line
N_t, N_f	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. $_{wf}$
P_{wt}^{wf}	Real power delivered by wind turbine *wt* of wind Farm
P_{Di}, Q_{Di}	Active and reactive power demand & load of bus i
P_{Gi}, Q_{Gi}	Active & reactive power produced by generator i.
P_D, P_L	Total demand and load
P_W	Total power output of all the wind Farms at time t
S^{wf}	Wind farm placement distance from the wind bus
v_ω	Wind speed of the wind farm
V_{wb}	Voltage of the wind bus
V_i, δ_i	Voltage &voltage angle of bus *i*
N_b	Number of buses in the system
Y_{ij}, θ_{ij}	Admittance & angle of line $_{ij}$
wt, wf	Index of wind turbine , wind farm

Appendix

Wind was modeled as a Weibull distribution 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 3 Wind model parameters.

Nominal wind speed/ air density	15m/s /1.225Kg/m^3
Filter time constant/sample time	4s,0.1s
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 [16]

Table 4 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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