Development of PSO Based Control Algorithms for Maximizing Wind Energy Penetration

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***Abstract*— In this paper, new methodologies have been proposed for attaining the maximum safe instantaneous wind energy penetration. Various types of control algorithms namely, load increase, generation displacement and the combined load increase and generation displacement have been developed to obtain the maximum penetration. Wind Turbine used is DFIG and dynamic model of the system by considering Turbine governor (TG), Automatic voltage regulator (AVR) have been considered. Grid stability at high penetration level is obtained by conducting eigenvalue analysis of the complete power system grid. All the control algorithms are powered by Particle Swarm Optimization Algorithm (PSO) which adjusts the grid parameters for achieving maximum wind penetration. The developed algorithms have been tested with 25-bus, 220kV practical system. The results have shown the maximum safe instantaneous wind energy penetration limit possible by various methodologies proposed.**

Keywords — Wind power generation, Wind Penetration, Particle Swarm Optimization

I. Nomenclature

E_j	Eigen Value of the state Jacobian Matrix
k, nk	Violated Constraint Index, No: of Violated Constraints
MVA_{line}	Line MVA rating
N_t, N_f	Total Number of Wind Turbines, Farms
N_b , M	Total No: of Buses , Generators
P, Q	Active Power , Reactive Power
Pf_k, U_k	Penalty Factor & Violation of constraint k.
P_{wt}^{wf}	Real Power Delivered by turbine *wt* of wind Farm wf
P_W	Total real Power Output of all the Wind Farms
R_{wj} / R_{Vj}	Wind speed /Voltage rank of Bus j
R_{TVj}	Voltage Tangent Vector rank of Bus j
R_{lj}	Interconnection cable length rank of Bus j
R_{wj} / R_{Vj}	Wind speed /Voltage rank of Bus j
S^{wf}	Wind farm placement distance from the Wind Bus
V_i	Voltage of the bus-i
V_{wb}	Voltage of the wind bus
wt, wf	Wind Turbine/Wind Farm Index
v_ω	Rotor Speed
I_{wpj}	Wind Farm Placement Index of Bus j
$i_{grid,j}$	Index of Grid connection of Bus j
ψ	Maximum Safe Instantaneous wind energy penetration limit.

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II. Introduction

FOR rapid decarbonization of the power sector and there by the society renewable power generation is inevitable. Among the various renewable energy sources, wind generation is said to hit large integrations in the future; but grid connected Wind Turbine Generators (WTGs) in large numbers introduces unwanted conditions such as: loss of synchronism, voltage collapse, load shedding, large deviations in voltage and/or frequency, introducing flicker and harmonics in high transmission and distribution losses, over loading and increased power oscillation [1]. Some of the solutions to the above stated problems are to use suitable type of wind turbines in the wind farms, connected to suitable buses and device strategic grid control mechanisms to assure grid stability. Among the various types of wind turbines available, DFIG is having lots of advantages [1] and hence DFIG has been used in this work. The strategic grid control mechanisms are suitable algorithm driven control measures to accept various levels of wind penetration.

The Wind power penetration, in a grid, is the ratio of total wind power output to the load at any instant of time and has been termed as instantaneous penetration [2].

So far, the work done in the area of maximum wind penetration were on stochastic analysis by taking into account the capacity credit and capacity factor [3] by taking into account the seasonal variations of the wind regime by assuming a fixed wind absorption rejection factor. In the deregulated electricity market, authorities always under rate the wind absorption rejection factor for the sake of maximum grid stability and have been treated as constant. The calculation of the above factor has been the trade secret of the electricity authority and lots of rejections are taking place due to the wrong choosing of the factor[4][5]. Moreover, the factor is quite time varying in nature and cannot be treated as constant.

The proposed algorithm is to fine tune the wind acceptance rejection factor for maximum penetration and consisted of two stages; one, identification of the suitable bus for wind farm placement [6] and secondly the calculation of the maximum instantaneous wind share possible in the grid by holding all the control and operational constraints within limits by means of various control algorithms.

The paper is organized as follows; section-3 deals with the underlined methodology and modeling aspects and maximum wind penetration problem formulation have been explained in detail in section-4. Section-5 deals with the proposed methodology and results and discussions are given in section-6.

III. Proposed Methodology & Modeling

The proposed methodology consisted of placing the wind farm in suitable location and a suitable algorithm to enable maximum grid penetration. Suitable control is selected depending on the nature of the grid. The development of suitable algorithm requires detailed problem formulation with dynamic modeling of wind farm and power system.

A. Control Algorithm Methodologies

Three control algorithms as given in figure 1 are proposed for maximizing the wind penetration and are explained below.

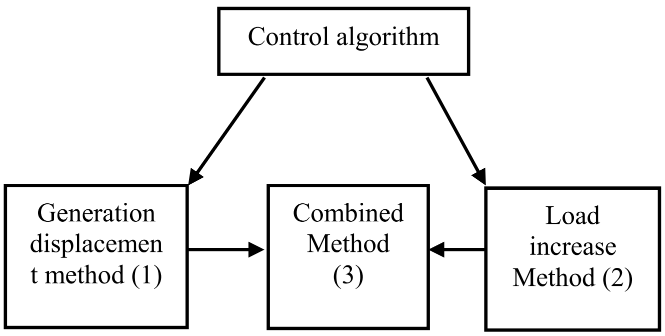

Fig.1.Control algorithms for maximum wind penetration

In generation displacement method, controller reduces the active power output of PV generators for maximizing the wind penetration with our varying the load. The wind generation substitutes or displaces the lack of active power in the system such that supply and demand is balanced. Load increase method lies in maximizing the wind penetration by increasing the load. Both the load increase and generation displacement are combined in method-3. The suitable algorithm need to be selected for maximizing the penetration based on the nature of the grid.

TABLE I
SALIENT FEATURES OF VARIOUS CONTROL ALGORITHMS

Load increase method (method-1)	Load is increased by the algorithm.
	No change in PV bus active power generation.
	Increase in load is shared by the slack generations.
Generation displacement method (method-2)	Load is held constant.
	All PV generations are reduced to a maximum of 50%
	Demand – supply gap is filled by the slack generations.
Combined generation reduction and load increase (method-3)	Combination of above two methods.
	Loads are increased by the algorithm.
	All PV generations are reduced to a maximum of 50%
	The generation demand gap is filled by the slack generations

B. Wind Farm Modeling

Wind has been modeled as a composite distribution by taking into account its composite nature by including average, ramp, gust and turbulence components [10]. The turbine generator used is DFIG whose stator is directly connected and the rotor is connected through slip rings and lossless power electronic converter.

C. Power System Modeling

The power system dynamic modeling was in compliance with IEEE 14 - bus dynamic model as given in Table 1.

TABLE II
COMPONENT MODEL SPECIFICATIONS

Power System Component	Model Details
Wind model	Composite distribution
Wind Turbine	Doubly fed induction generator
Generator	Synchronous ; Order V, Type 2
Turbine Governor/	IEEE Type -1
AVR	IEEE Type -2
Load	Constant PQ Model

IV. Maximum Instantaneous Wind Penetration PROBLEM FORMULATION

The quality of the operation has been assessed in terms of operational constraints and the normal operation presupposes that a number of constraint parameters are maintained with in 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 that can increase wind penetration, that which considered were capacity of the slack and wind generators and their mutual load sharing and the voltage settings of PV buses.

A. Problem Formulation

i. Objective Function:

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

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

ii. Power Balance Constraints:

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

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

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

iii. Generator & System Operating Constraints:

$$P_{Gi\ \min} \le P_{Gi} \le P_{Gi\ \max} \quad (4)$$

$$Q_{Gi\ \min} \le Q_{Gi} \le Q_{Gi\ \max} \quad (5)$$

$$|V_{i\ \min}| \le |V_i| \le |V_{i,\ \max}| \quad (6)$$

$$|MVA_{line}| \le |MVA_{line\ \max}| \quad (7)$$

iv. Wind power constraint:

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

$$0 \le P_D + P_L - \sum_{1}^{M} P_{Gi} \le P_W \quad (8)$$

v. Power System Stability Constraints:

The small signal stability model of the system with DFIG can be expressed as $\Delta \dot{x} = A \Delta x$, where A is the System State Matrix and x is the state vector. $A = F_x - F_y G_y^{-1} G_x$. Where F_x, F_y, G_y, G_x are power flow jacobian matrices. If the complex *eigenvalues* of the linearized state equation have negative real parts, then the power system can withstand small disturbances and is considered stable in the small-signal sense. The Eigen value based stability analysis [7] is incorporated to the constraint by the expression.

$$E_j(F_x, F_y, G_y, G_x) \le 0 \quad (9)$$

V. Optimization Algorithm

Particle swarm algorithm [8] has been used to identify the optimal loading pattern and thereby to determine the maximum safe instantaneous penetration. Fitness function for the above problem is formulated as

$$P_W = \sum_{wf=1}^{N_f} \sum_{wt=1}^{N_t} P_{wi}^{\ wf}(V_{wb}, S^{wf}) + \sum_{k=1}^{nk} (Pf_k * U_k) \quad (10)$$

A. *Wind Farm Placement*

The bus to which the wind farm to be placed is identified by the calculation of wind farm placement index [9]

$$I_{wpj} = R_{wj} + C_v R_{Vj} + \frac{1}{C_{TV}} R_{TVj} + \frac{1}{C_l} R_{lj} + i_{grid,j} \quad (11)$$

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

$R_{Vj} = 0$; for generator bus; rank high voltage to low

R_{TVj} = 1/abs (TV) ;R_{lj} = 1/R_{lj}

$i_{grid,j}$ = 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 have been suitably chosen depending on the grid by giving suitable weight. Tangent vector of the node voltage determines the weakest bus. Rank bus bars from higher value to lower for voltage and tangent vector. Another method to identify the best location for the placement of wind farm is by computer simulation.

A. *Methodology*

Step 1: Input line data and bus data, wind data, voltage and line limits, PSO settings.
Step 2: Identify the best location for wind farm placement and connect the wind farm to that particular bus.
Step 3: Calculate the base case power flow with the wind farm at the identified bus and identify the best suitable control algorithm.
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. Otherwise 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 include 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 and the fitness value gives the maximum safe instantaneous wind penetration limit (ψ) .

VI. Results & Discussions

The proposed methodology has been tested on Kerala (India) grid 220 kV 25-bus system given in fig.2. The details of the system are given in Appendix.

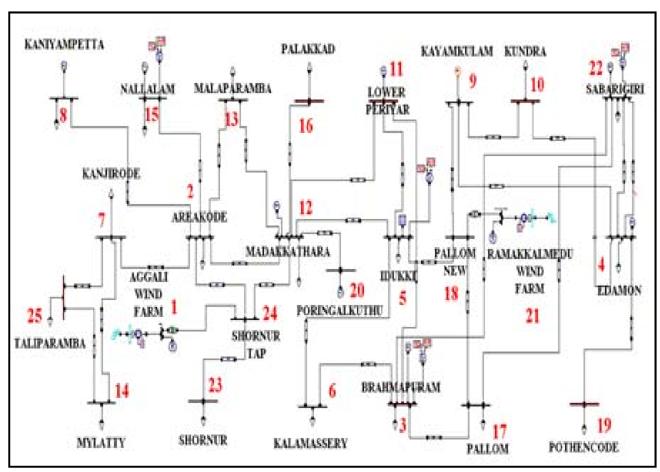

Fig. 2. Kerala grid 220kV 25-bus system

A. *Wind Farm Placement Index Calculation*

The Wind Farm Placement Index Calculation [9] identifies bus-1 and bus-21 as the most suitable bus and accordingly wind Farm is connected to bus-1 and bus-21. The equation constants were chosen based on the practical study conducted. Same has also been verified by conducting computer simulation

B. Maximum Penetration Calculation

Load increase method is the most common method for maximizing the wind penetration. In reality, the load increase in power system is subjected to lots of diversified practical constraints and is not always possible to increase the load beyond a certain maximum limit. Moreover, increase in load beyond the system capacity results in fall in voltage in various parts of the system and in cascaded tripping and black out in various parts of the grid. Since penetration depends on load increase and if load increase is limited, penetration is also limited. In short, the load increase method can be applied to only those systems in which there is adequate generation reserve. Load increase method often leads to less penetration.

Load increase method when applied shows that all active and reactive power generations are within limits and the maximum load possible is 18.865 pu by maintaining system stability. The base case load is approximately 17 pu. An addition of 1.865 pu load increase was possible by this method. All voltages are within limits. The wind farms are connected to bus-1 and bus-21 and the maximum penetration possible is 22.72%. The system slack is at bus-5 and slack generator is delivering 3.84 pu active power. The load increase method assumes that the system is having adequate energy storage.

In generation displacement method, since the wind power fills the gaps between the generation reductions and load by keeping the load constant, there is scope for more penetration. From the results, it is clear that load is same as the base case and all the buses and the active power generations have been reduced and the power balance was adjusted from the wind share. All active and reactive power generations and voltage levels are within specified limits.

A maximum penetration of 48.14 % could able to be obtained by the combined however; the disadvantage is that the load remains same. This method is mostly recommended in most of the cases.

Comparison of results

The bus generations in various methods are given in fig.-3. Wind bus is bus no 1 and 21, respectively. From the fig-3, it is clear that the wind farm-1 (Aggali) shares a considerable part of the load in method-3 and wind farm-2 (Ramakkalmedu) in method-2. This is due to the fact that in various methods generation and load direction varies. From figure-3, it is clear the slack bus (bus-5) is loaded to the same level in method-1 and method-3, respectively.

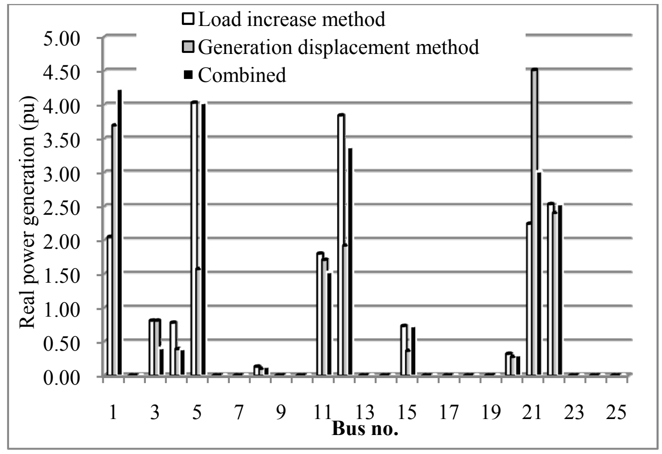

Fig. 3. Real power generation in various methods of wind penetration

Figure 4 shows the bus voltage profile by various methods. From the curve, voltage variations are more in method-3 and touching the extremes.

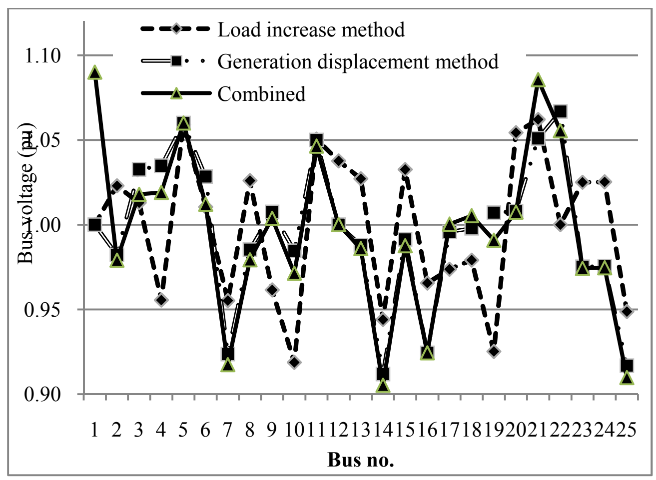

Fig. 4. Voltage profiles in various methods of wind penetration

Figure 5 shows the load changes at various buses. It is quite clear that, the load is more in method-3. Almost all the buses have load increase in method 3. From the figure, it is also quite visible that the loads are same as that of the base case load in method-2. In general, for maximizing the penetration, or at any time how much maximum penetration is possible, requires case to case subjective analysis. Capacity of the grid is the major factor limiting the same.

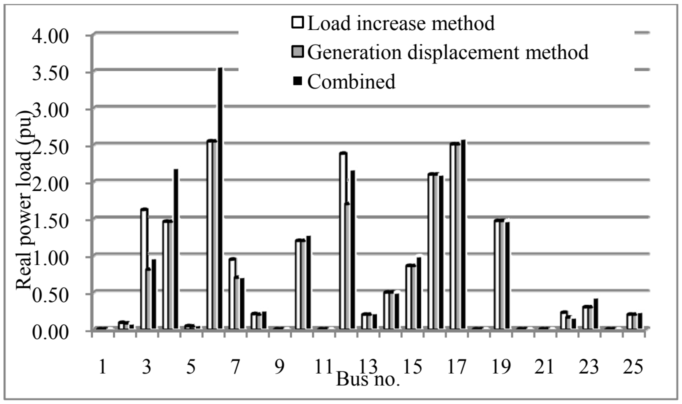

Fig. 5. Real power load in various methods of wind penetration

The active power flow changes by various methods are given in fig. 6. From the figure it can be identified that the most over loaded are the lines 33 and 34.

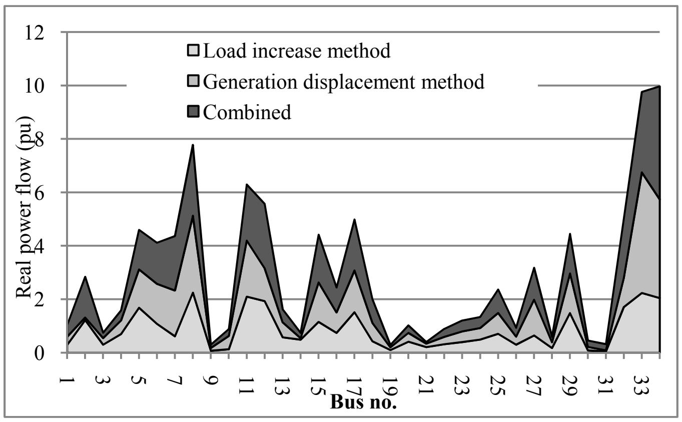

Fig. 6. Real power flow in various methods of wind penetration

The eigenvalues by various methods of penetration are given in fig.7, fig.8, fig.9 respectively. In all the cases, the system is stable in small signal sense. In all the figures, real eigenvalues from 0 to -5 have only been plotted and the higher order values are ignored due to clarity/space issue.

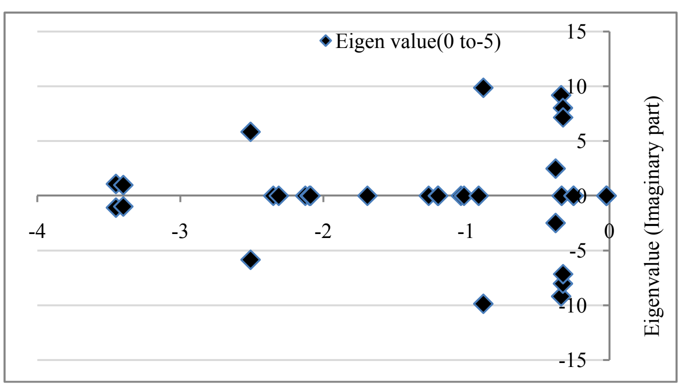

Fig. 7. Eigenvalues at maximum penetration by load increase method

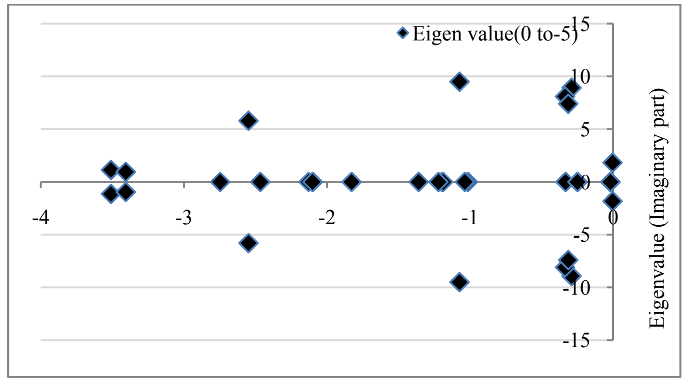

Fig. 8. Eigenvalues at maximum penetration by generation displacement method

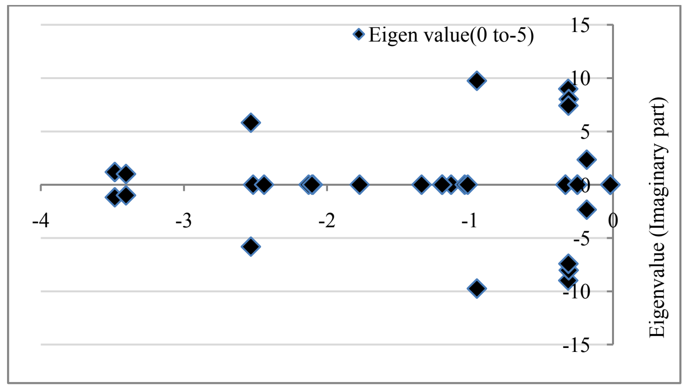

Fig. 9. Eigenvalues at maximum penetration by combined generation displacement and load increase method

From the eigen value analysis, it is clear that for the generation displacement method, the issue of stability is more prone with more real eigenvalues closer to zero when compared to the other two methods. The results are compared and consolidated for various methods of wind penetration as given in Table III. Maximum penetration is possible in method-2 with a penetration limit of 48.14%.

TABLE III
RESULT COMPARISON BETWEEN VARIOUS METHODS OF WIND PENETRATION

Penetration type	25-bus, 220kV Kerala grid system		
	Maximum wind share (pu)	Maximum active power generation (pu)	Maximum active power load (pu)
load increase method (method-1)	4.2873	19.2550	18.8648
	Maximum penetration (%)		22.7264
generation displacement method (method-2)	8.2044	17.7442	17.0400
	Maximum penetration (%)		48.14
combined generation displacement and load increase method (method-3)	7.2491	20.6597	19.9897
	Maximum penetration (%)		36.26

Each method is having its own advantages and disadvantages. Suitable method has to be chosen and adapted by analyzing the grid. In most of the cases combined method of load increase and generation displacement is recommended. Method-2 is the better method for maximizing the wind penetration and can be applied to most of the power grids. However, the grid small signal stability is a critical issue in method-2 when wind displaces a major portion of the system generations.

VII. Conclusion

In this paper, PSO based various control algorithm methodology have been formulated and tested with 25-bus, 220kV practical system. Three types of control algorithms, namely load increase, generation displacement and the combined generation displacement and load increase is having importance in different practical scenarios. Each method is having its own advantages and disadvantages. Suitable method has to be chosen and adapted by analyzing the grid. In most of the cases combined method of load increase and generation displacement is recommended.

VIII. Appendix

TABLE IV
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

TABLE V
DFIG PARAMETERS

[MVA,KV,Hz], kWs/kVA	[600 69 60], 3pu
[Rs,Xs] [Rr,Xr] Xm	[0.01 0.10] [0.01 0.08] 3.00pu
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	30Nos

TABLE VI
VARIOUS CONTROL ALGORITHM SETTINGS

Load increase method (method-1)		100
	Slack/line limit	10pu
	Voltage limit (%)	(+/-) 10
Generation displacement method (method-2)	Slack/line limit	10pu
	Voltage limit (%)	(+/-) 10
	Maximum generation reduction (%)	50
Combined generation reduction and load increase (method-3)	Maximum load increase (%)	50
	Slack/line limit	10pu
	Voltage limit (%)	(+/-) 10
	Maximum generation reduction (%)	50

IX. References

Authors would like to thank Dr Fedrico Milano for his excellent power system analysis software PSAT [10] and for the various useful discussions through the user group.

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