Voltage Stability Analysis of Wind Integrated Grid

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***Abstract*—The importance of wind penetration is that it can reduce or replace the existing conventional generation. To increase the wind penetration, the wind farms have to be connected to the best suitable bus and should be controlled by suitable methods. Voltage and angle instability are the main limiting factors for maximizing the wind penetration. This paper attempts to identify the maximum safe instantaneous wind penetration without any voltage instability. Three control algorithms namely load increase, generation displacement, and combined generation displacement & load increase have been used for suiting various types of power grids. The IEEE 14 bus standard system is used for testing and validating the proposed methodologies using the Power System Analysis Toolbox (PSAT).The proposed techniques are tested on Kerala grid 24 bus practical system. The results shows the maximum instantaneous wind energy penetration limit without any voltage instability, the maximum safe bus loading and generation displacement point explicitly beyond which system drives into instability and the grid modifications to be done for maximum wind penetration.**

Keywords- wind power, wind penetration, power flow, FACT controller, voltage stability, small signal stability.

Introduction

Recently wind power generation has been experiencing a rapid development on a global scale. As the wind power penetration into the grid increases quickly, the influence of wind turbines on the power quality and voltage stability is becoming more and more important. It is well known that a huge penetration of wind energy in a power system may cause important problems due to the random nature of the wind and the characteristics of the wind generators. Normally synchronous machines are used as generators. Induction generators are simple in construction and comparatively cheap. But they could not supply reactive power if used as generators as they consume reactive power and supply real power. So, if induction generators are used in the wind turbines, separate sources are to be found or otherwise the voltage stability will be lost. The main factor, which causes these unacceptable voltage profiles, is the inability of the distribution system to meet the demand for reactive power. Whenever the voltage at of any one of the bus in the system decreases with an increase in Q for that same bus, the system is said to be unstable.

The aim of this work is to conduct a voltage stability analysis using an iterative Power System Simulation Package (PSAT) [1], to evaluate the impact of strategically placed wind generators on distribution systems with respect to the critical voltage variations and collapse margins. It also aims at developing suitable methodologies for maximum instantaneous wind penetration to the grid without any violation in stability, voltage, line and generator limit constraints.

I. MAXIMISATION OF WIND PENETRATION

To study about the voltage instability problem when wind energy is included in the grid along with conventional generators, we have to increase the amount of wind energy integrated in to the grid. So, a problem is formulated to maximize the wind generation with power balance [4], generator and system operating limits, wind power and system stability limits as constraints. One of the major problems associated with maximum wind penetration is the voltage instability. This issue is solved by placing wind farms by taking care of voltage stability for maximum penetration. Wind has been modelled as a composite model by including average, ramp, gust, and turbulence components. The turbine generator used is DFIG. Only fundamental frequency based analysis has been considered and the analysis assumed that there is suitable buffer energy storage to handle the unpredicted power level fluctuations in addition to the adequate spinning reserve. The objective is to maximise the wind share into the grid. Accordingly the objective function has been formulated for any time period (t) as,

Maximise

$P_w =$ EMBED Equation.3 EMBED Equation.3

Where, P_w is the total active power output of all the wind farms.
$P_{w_t}^{w_f}$ is the real power delivered by the wind turbine w_t of the wind farm w_f.
V_{wb} is the voltage of the wind bus.
S_{wf} is the wind farm placement distance from the point of coupling.
N_f is the total number of wind turbines.
N_t is the total number of wind turbines.
v_w is the wind speed at the wind farm.

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

$$P_i = P_{Gi} - P_{Di} - \sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\cos(\delta_i - \delta_j - \theta_{ij}) \qquad \text{eqn.2}$$

$$Q_i = Q_{Gi} - Q_{Di} - \sum_{j=1}^{N} |V_i||V_j||Y_{ij}|\sin(\delta_i - \delta_j - \theta_{ij}) \qquad \text{eqn.3}$$

Different methods are applied to maximize the wind penetration in power grid.

Method1: Increase the load and allow the excess power to be delivered by wind generators (Load Increase method).
Method2: Reduce the conventional generation without changing the load (Generation Displacement method).
Method3: Increase the load and reduce the conventional generation (Combined generation displacement and load increase method)The step by step procedure for finding out the maximum wind penetration to the grid and thereby the voltage instability of various buses is given below:
Step1: Input line data, bus data, wind data, voltage limits & line limits.
Step2: Connect the wind farm at the suitable bus.
Step3: Calculate the base case power flow with wind farm at normal load and normal generation.
Step4: Increase the load in the system to a maximum value such that there is no constraint violation and run the power flow to get the wind penetration.
Step5: Note the voltages of all the buses and connect SVCs in the buses where the voltage is minimum/close to the limit.
Step6: Again run the power flow and note the wind penetration.
Step7: Reduce the system load back to the normal value and reduce the conventional generation to a minimum such that there is no constraint violation and run the power flow to get the share of wind generation.
Step8: Now increase the load to a maximum keeping conventional generation as in step7 without constraint violation and run the power flow to obtain the wind penetration.
Step9: Compare the results to get the maximum wind penetration and the buses where the voltage profile is poor.

II. APPLICATION ON AN IEEE 14 BUS SYSTEM

A single line diagram of the IEEE 14-bus standard system is shown in Figure. It consists of five synchronous machines with IEEE type-1exciters, three of which are synchronous compensators used only for reactive power support. There are 11 loads in the system totaling 259 MW and 81.4 MVAR. Buses 2, 3, 6 & 8 are PV buses. Bus-1 is the slack bus. All other buses are PQ buses. A simple Automatic Voltage Regulator (AVR) model is used to represent the excitation control of generators. The loads are modeled as constant power (constant PQ) static load models, where the real and reactive powers have no relation to the voltage magnitude. It is also referred a constant MVA load model.

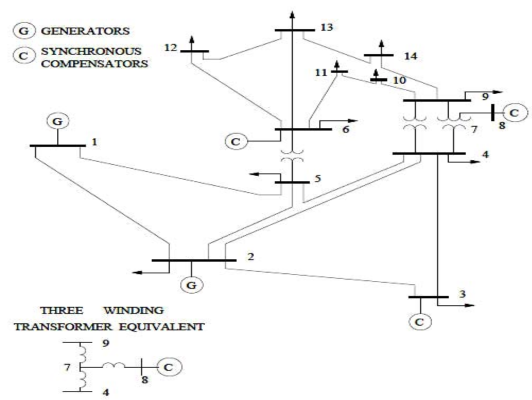

Fig.1.Single line diagram of IEEE 14-bus test system

III. ANALYSIS OF VOLTAGE STABILITY

i. Base Case

In the base case no wind farm or SVC are connected to the IEEE 14-bus system. As in method1, load in the system is increased to a maximum value and the power flow is run to get system variables such that no constraints are violated. A load increase up to 1.12 times the base case load is obtained. This is taken as the maximum load that can be applied to IEEE 14-bus system.

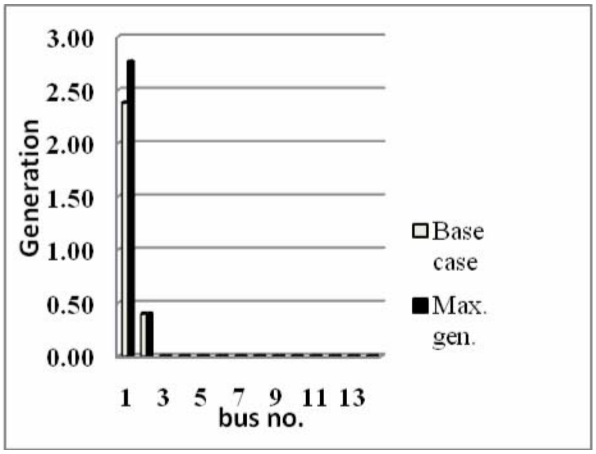

Fig.2Real power generation -Base case & Maximum generation.

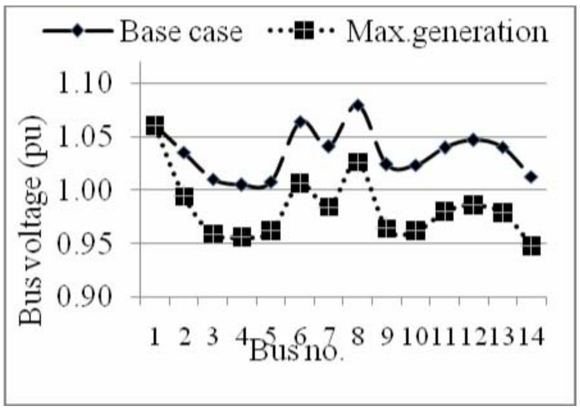

Fig.3 Voltage profile in various buses

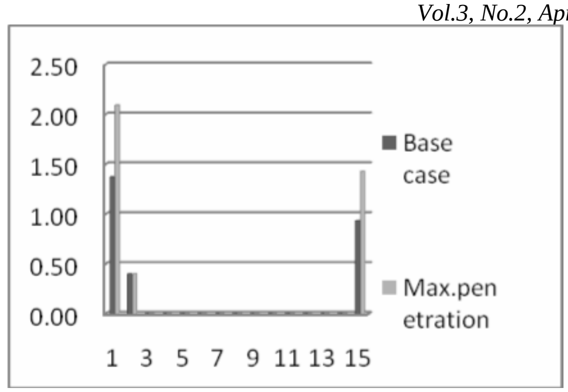

Fig.4 Real power generation

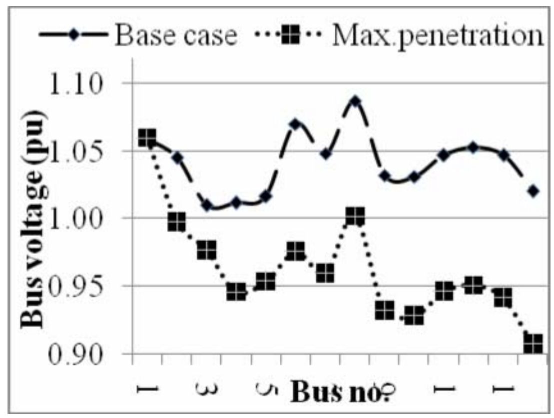

Fig.5 2Voltage profile in the buses

ii. Wind Farm Placement

Wind farm is placed based on wind farm placement [5] study conducted on IEEE 14 bus system by plotting PV curve. The study takes into account the impact of wind farm connection at various buses by changing the wind speed, interconnection cable length etc. Wind farm should be placed only on a strong bus for maximum system stability and increased penetration. Different buses have different power absorption capability and accordingly maximum penetration varies. Bus-3 is identified as the most suitable bus for wind farm placement and accordingly, wind farm of capacity 600 MVA/69 kV comprising of 300 wind turbines of equal rating has been connected to this test system by creating another bus (bus-15) through a transformer of tap ratio unity. The method followed in the above case is repeated to find out the maximum loading and penetration possible without violating the stability limits.

iii. SVC connected to the wind integrated system

One of the main factors that are limiting the wind penetration is the voltage instability. FACTS controllers, especially, shunt FACTS controllers can solve this problem. The FACTS controllers improve the power system performance by absorbing or injecting reactive power. They, due to its operational flexibility can be used to improve the penetration of wind power by relieving the overloaded lines and relaxing voltage limit violation. The simplest shunt FACTS controller i.e, Static Var Compensator, SVC is used for maximizing wind penetration.

The voltage on bus 14 is at the limiting value as seen from the above figure, and any further increase in load or penetration of wind will lower the voltage on that bus. So, a shunt compensating device is connected on that bus. The above described methods are followed to find out the maximum loading and maximum wind penetration into the system. An increase of 86% is obtained in the total generation and an increase of 105% is obtained in the wind penetration.

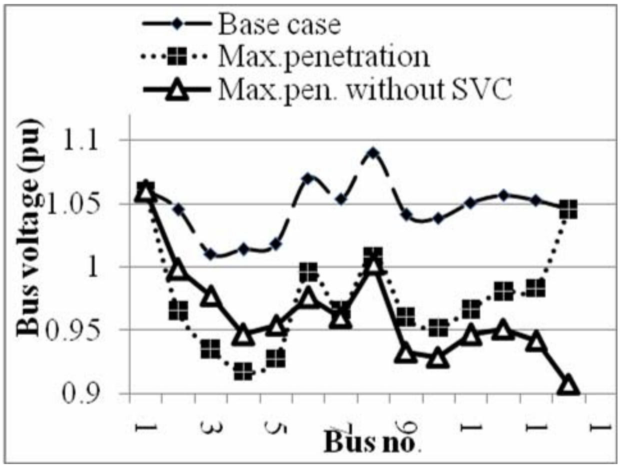

Fig.6 Voltage profiles of buses with SVC

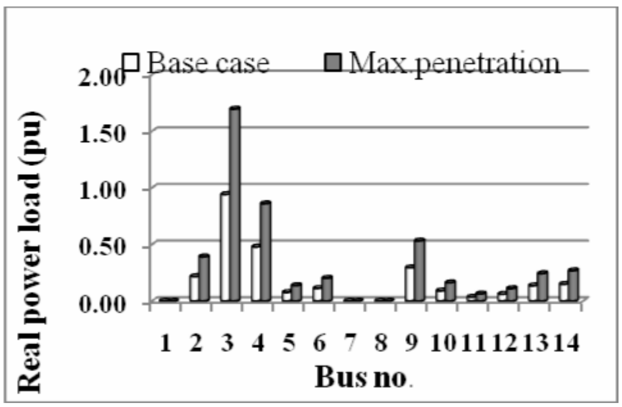

Fig.7 Real power loads in buses

The table below gives the results obtained on applying load increase method on IEEE 14 bus system before and after connecting wind farm & SVC. Since the IEEE 14 bus system includes only one generator other than slack and its contribution is limited to a small percentage, the other two methods of wind penetration discussed earlier will have no effect if applied on the system.

IV. RESULTS

Load Increase method for wind penetration maximization has been tested and the results are analyzed. While testing, the voltage and angle stability constraints were considered. Since the system is used only for testing the method devised, the line loading limits were not taken into account while testing

TABLE1 LOADING CONDITIONS

System status	Total real power generation p.u	Wind generation p.u
Base case	2.782	0
Maximum generation by Load Increase method	3.1663	0
Max.generation – wind farm connected	3.921	1.4286
Max.generation-wind & SVC connected	5.1768	1.9143

TABLE2

RESULTS OF TESTS ON IEEE 14-BUS SYSTEM

TEST RESULTS ON IEEE 14 BUS SYSTEM									
Base case									
Load multi.	Pg pu	Qg pu	Pload pu	Qload pu	Ploss pu	Qloss pu	Wind Gen.	System status	Remarks
1.12	3.166	1.8191	2.901	0.912	0.266	0.907	0	Stable	Max load for stability
Wind generator connected in bus15									
1.41	3.921	1.9962	3.652	1.148	0.269	0.849	1.4286	Stable	Max.load for Voltage stability
1.5	4.21	2.3211	3.885	1.221	0.325	1.1	1.5487	Stable	Voltage at bus14 dropped to 0.86
SVC is connected at bus 14									
1.8	5.177	3.2704	4.662	1.465	0.515	1.805	1.9143	Stable	Max.load for System stability
1.81	5.212	3.3162	4.688	1.473	0.524	1.843	1.9284	Un stable	2 positive eigens

V. VOLTAGE STABILITY ANALYSIS OF KERALA POWER SYSTEM

As mentioned above, three methods (Load increase method, Generation displacement method, combined method) are applied on the Kerala Grid for maximum penetration.

The results obtained from these methods are analyzed and the maximum amount of wind penetrated in the grid without violating the constraints is noted. From this analysis we can also find out the buses in which the voltage is not stable while loading. Next a FACTS controller is fixed on the buses where the voltage is unstable and again the same methods are applied on the grid. From the analysis of the results obtained, we can find out the maximum penetration level as well as the increment in penetration by using the FACTS controllers in the grid. We can also find out the grid modifications that have to be done to receive the penetration to the grid.

The graph compares the voltage profiles of the grid in the base case as well as that obtained by the load increase method, generation displacement method and combined method. From the graph it can be seen that there is not much variation of voltage in all the cases and hence the graphs are almost coinciding.

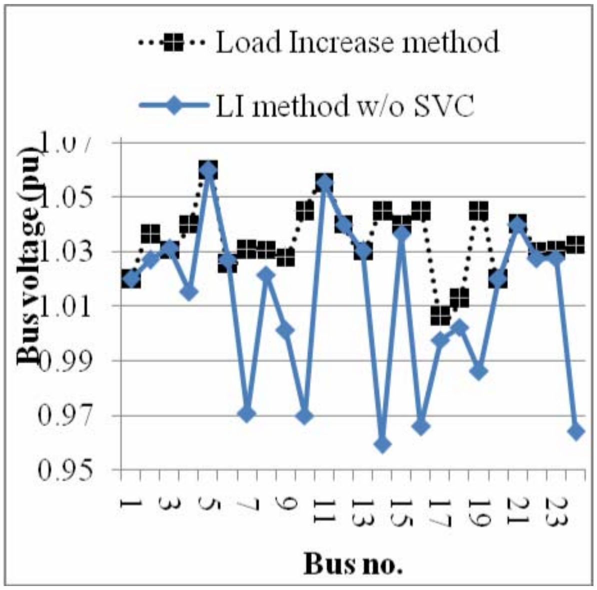

Fig.8 Voltage profiles of the buses

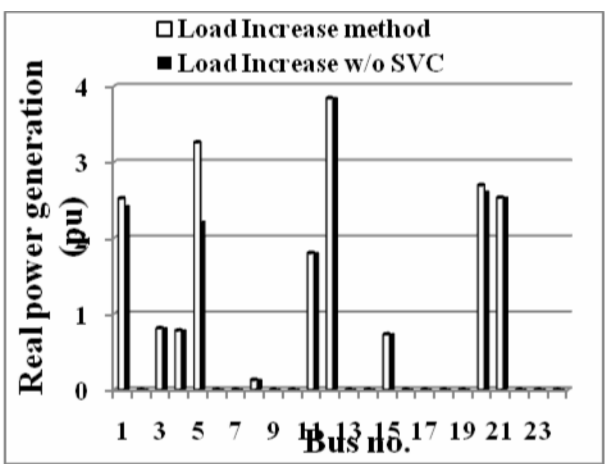

Fig.9 Real power generation of the buses

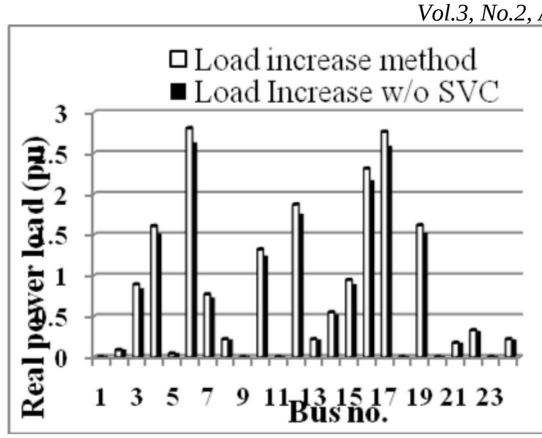

Fig.10 Real power loads in the buses

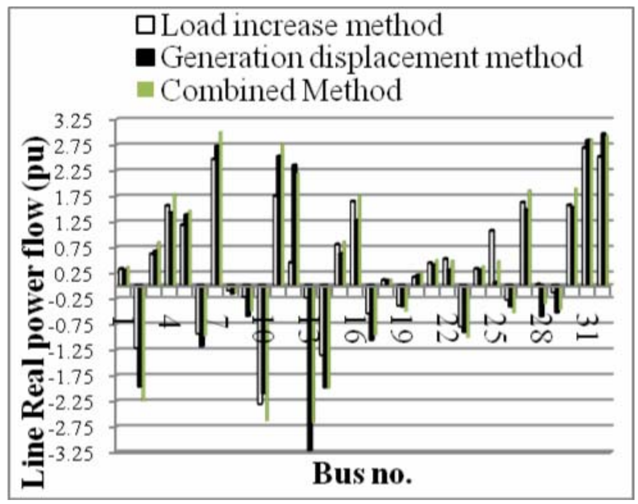

Fig.11 Line flows in various methods in the Kerala Grid with SVC

VI. CONCLUSION

For studying the voltage instability problem in the wind integrated grid, the wind penetration into the grid should be maximized. Three methods are discussed namely Load Increase method, Generation Displacement method, and Combined method. The methods discussed are tested on IEEE 14-bus standard test system modified by connecting wind farm at a suitable bus and then compensated by connecting SVC on the required bus. Since the IEEE 14 bus system consists of only one generator excluding slack and also its contribution is very small, only Load Increase method is tested on this system. The other methods if tested will not produce a reasonable result. The same three methods are tested on the 24 bus Kerala grid, a practical system, and found that maximum penetration is obtained in generation displacement method when compared to other two methods. However, the additional penetration is at the cost of reduced load. In all the cases the system is under stable condition.

The penetration is still increased by the introduction of SVC at the required buses. Here also the system stability is ascertained. This shows that by connecting SVC at suitable buses, the system stability can be improved.

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