STUDY OF SMALL SIGNAL STABILITY USING PSAT INCLUDING DFIG BASED WIND PENETRATION

Ram Prasad Pandey*[1]

ABSTRACT

In early days of power engineering, the power system consisting of synchronous generators faced different low frequency oscillation problems and they were solved by different researchers by using suitably AVR and PSS. Later, the electricity industry is turning increasingly to renewable sources of energy to generate electricity. Wind is the fastest growing and the most widely utilized emerging renewable energy technology for power generation at present. With the increasing penetration of wind power in the power system, the impact in power system performance should be fully investigated, particularly for doubly fed induction generation (DFIG) wind turbine since this type of renewable source is gaining prominence in the power system industry. Main purpose of this study is to examine the impacts of wind power integration in the low grid from low frequency oscillation perspective. The benchmarked Two Area System is considered for this analysis using Power System Analysis Toolbox(PSAT). The critical modes of oscillation are selected from eigenvalue analysis and their participation factors are studied to identify their sensitivity. Also the time domain analysis is run in every cases to study the transient stability. From TAS, concept of local and global mode oscillation can be understood clearly. Replacing synchronous generators in TAS by DFIG WTG one by one of same rating gave conclusion that low frequency stability depends on the location of DFIG penetration and operating scenario. The results show that there is both beneficial and detrimental effects due to DFIG WTGs. The installation of PSS in the critical generators greatly enhances the system damping.

Keywords: *Small signal stability, AVR, PSS, DFIG, Transient Stability*

1. INTRODUCTION

The small oscillation in synchronous generators which was referred to as hunting was the problem for power system engineers in early days of 19th century. It was noted when an under loaded synchronous generator was connected through a long transmission line. On the other hand, the generator lost synchronism when it was overloaded. This was referred to as steady state stability [4]. The introduction of damper winding for hunting and the use of synchronous condensers and automatic voltage regulators enhanced the steady state stability limit. Steady state stability became less important and transient stability occupied the power system engineer.In 1960s, the problem of low frequency oscillation resurfaced which was termed as dynamic stability or low frequency oscillation in power system. The major causes of the dynamic stability were the introduction of high gain, low time constant automatic voltage regulator (AVR) and the power evacuation over a long distance. The

[1] *Department of Electrical Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal*

* *Corresponding author*

E-mail : ramprajwol@pcampus.edu.np

development of PSS for excitation control and using other means such as governor, SVC or HVDC helped to damp these oscillation. However, in the modern time due to large scale penetration of renewable energy and weak grids have resurfaced the problem.

Critical challenge for Nepal and the hydro industry is the continuing reduction of water resources due to climate change. The unpredictable but steadily declining hydrology has demonstrated a severe vulnerability in the ability of the hydro sector to meet the claims of electrifying the nation and this challenge is becoming increasingly insurmountable. To make an appreciable reduction in the dependency on Hydro power by the use of PV systems and wind energy, a large number of PV generators and wind turbines have to be embedded in the network. However, large scale installation of renewable sources will give rise to potential power system problems. This includes voltage stability problem, protective device coordination problems, unintentional islanding, and angle stability problem. However, a control and monitoring system across the network would have to be highly reliable. Power system stability is one of the major aspects that need to be identified especially small signal stability since the oscillations caused by this type of stability have resulted many incidents.

2. SMALL SIGNAL STABILITY

Small signal stability is the ability of the power system to maintain synchronism under small disturbances [4]. Such disturbances occur continually on the system because of small variations in loads and generations. There may be two cases of instability: Steady increase in rotor angle due to lack of synchronizing torque or rotor oscillates of increasing amplitude due to lack of sufficient damping torque. The nature of system response to small disturbances depends on a number of factors including the initial operating, the transmission system strength and the type of generation excitation controls used.

In modern power system, insufficient damping of oscillations creates the problem of small-signal stability. The stability of the following types of oscillations is of concern:

1. Local modes or machine modes are associated with the swinging of units at a generating station with respect to the rest of the power system. The oscillations are localized at one station or a small part of the power system in local mode. The frequency ranges of these modes is from 0.8 Hz to 2.5 Hz.
2. If many machines in one part of the system are swinging against machines in other part, then that is inter area mode. These are caused by two or more groups of closely coupled machines being interconnected by weak ties. The frequency of these modes ranges from 0.1 Hz to 0.8 Hz.
3. Control modes are associated with the generating units and other controls. Poorly tuned exciter, speed governors, HVDC converters and static VAR compensators are the usual cause of instability of these modes.
4. Modes associated with the turbine-generator shaft system rotational components is Torsional modes. Interactions of the shaft oscillations with excitation controls, speed governors, HVDC controls and series-capacitor-compensated lines result in the instability of torsional modes.

The automatic voltage regulator action enhances a positive synchronizing torque for a high value of external system reactance and high generator output, but may produce a negative damping torque component. Such effect is more pronounced as the exciter response increases. Although a high response exciter is beneficial in increasing synchronizing torque but in doing so, it introduces a negative damping. Thus there is conflicting requirement with regard to exciter response. So a compromise is to be made and this can be achieved by setting the exciter response so that it results in sufficient synchronizing and damping torque component for the desired range of system operating conditions. This may not be always possible. Sometimes high synchronizing torque may be required for the transient stability performance which can be achieved by high response exciter. With a very high external system reactance even with low exciter response, the net damping torque coefficient may be negative.

3. TRANSIENT STABILITY

It is commonly referred to as the ability of power system to maintain synchronism when subjected to a severe disturbance such as a short circuit on a transmission line, loss of large generating unit etc. It is also called large-disturbance rotor angle stability. The resulting response involves large excursions of generator rotor angles and is influenced by the non-linear power angle relationship. Initial operating state of the system and the severity of the disturbance both affects the transient stability. Instability normally appears in the form of aperiodic angular separation due to insufficient synchronizing torque, manifesting as first swing instability. However, in large power system, transient instability may not always occur as first swing instability associated with a single mode; it could be result of superposition of a slow inter area swing mode and local plant swing mode causing a large excursion of rotor angle beyond the first swing. The time frame of interest in transient stability studies is usually 3 to 5 seconds following the disturbances. It may extend to 10 to 20 seconds for very large systems with dominant inter area swing.

4. DOUBLY FED INDUCTION GENERATOR (DFIG) WIND TURBINE GENERATOR

Among the various types of Wind Turbine Generator, Doubly Fed Induction Generator (DFIG) is greatly used in modern power system [2]. A typical configuration of doubly fed induction generator (DFIG) wind turbine is shown in Fig. 1. Basically, several major components contribute to the dynamic performance of a DFIG wind turbine.

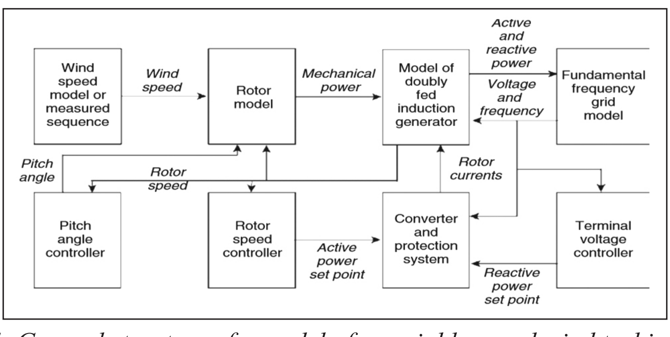
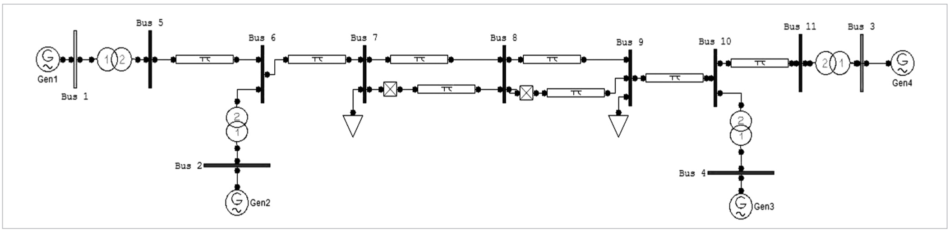


Fig. 1. General structure of a model of a variable speed wind turbine with doubly fed induction generator (type C)

5. TWO AREA SYSTEM: A BENCHMARK TEST MODEL



There are four generators G1,G2,G3,G4 where G1 and G2 lies in area 1 and G3 and G4 lies in area 2. These two areas are connected by a double circuit line. Fig. 2 shows the test system. The parameters used for this case can be found in Ref. 3. The study of this benchmark model is done assuming different scenarios,

- A two area system - base case
- A two area system with AVR and PSS
- A two area system with DFIG penetration

Once the conventional synchronous generator is replaced by DFIG of same power one by one. Again the analysis is done with adding DFIG wind power penetration at different buses at different penetration level.

6. RESULTS AND DISCUSSION

Case 1- Two area system – Base case (Without AVR & PSS)

This case tries to understand the problem of small signal stability in a two area system. The critical eigenvalues for the base case system is shown in Table 1. The modal analysis report suggest that there are mainly three modes for this system. The first local mode Generators 1 and 2 of area 1 and the second local mode between Generators 3 and 4 of area 2. The final mode is the interarea mode and is the most critical mode as it has a very low damping 4.75%.

The information about local mode and interarea mode can be inferred from studying the participation factor shown in Table 2. The first pair of eigenvalues clearly has the most dominant contribution from states of Generators 1 and 2. This concludes it is a local mode of area 1. The second pair of eigen values has the largest participation from G3 and G4 which makes it local mode for area 2. The last pair of eigen values is contributed by almost all the generators equally suggesting it as an interarea mode. The time domain simulation is then run for the test system where one of the line is disconnected at 10s. Fig. 3 depicts the generator rotor angles of four generators and corridor bus voltages. It can be clearly seen that the angles and voltages suffer the problem of low frequency oscillation after 10s. Furthermore, the coherency between generators 1 and 2 and generators 3 and 4 can also be verified.

Table 1: Critical Eigenvalues in Interarea case

Real part	Imaginary part	Frequency(Hz)	Damping Factor	Most Associated states	Mode Type
-0.627	±7.047	1.126	8.86	Δδ4, Δω4	Local
-0.61	±6.932	1.1085	8.75	Δδ2, Δω2	Local
-0.2	±4.2	0.68	4.75	Δδ1, Δω3	Inter-area

Table 2: Participation factor in Interarea base case

Critical Eigen Values	Δδ1, Δω1	Δδ2, Δω2	Δδ3, Δω3	Δδ4, Δω4	Mode
-0.627 ± 7.047	15.80%	5.34%	2.63%	21.75%	Local
-0.61 ± 6.932	4.09%	19.18%	18.48%	3.80%	Local
-0.2 ± 4.2	15%	10.25%	13.40%	8.90%	Inter-area

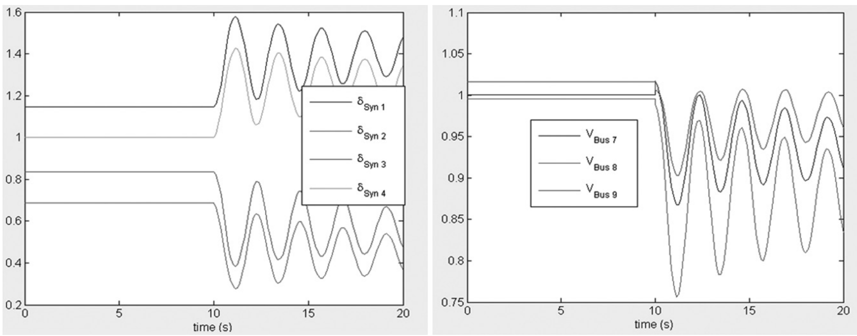


Fig. 3. Generator Rotor Angle and Bus Voltage of TAS- Base case

Case II – Two area system with AVR incorporated at each generators

In the previous network, Automatic Voltage Regulators with gain 50 are connected to each generators. AVRs are used in order to solve the problem of non-oscillatory (aperiodic) instability. Such instability is related to lack of synchronizing torque. Although high gain of AVR is very much desired as it enhances the transient stability margin, this may lead to oscillatory instability. It is seen from table 3 that the previous damping factor of critical eigen 4.75% is now reduced to 0.89% with the introduction of high gain AVR.

Table 3 : Critical Eigen Values in Interarea case with AVR

Real part	Imaginary part	Frequency (Hz)	Damping Factor	Most Associated states	Mode Type
-0.77	±7.41	1.18	10.33%	Δδ4, Δω4	Local
-0.76	±7.34	1.175	10.3%	Δδ2, Δω2	Local
-0.041	±4.57	0.9	0.89%	Δδ1, Δω3	Inter-area

Table 4 : Participation factor in Interarea case with AVR

Critical Eigen Values	Δδ1, Δω1	Δδ2, Δω2	Δδ3, Δω3	Δδ4, Δω4	Mode
-0.77 ± 7.41	14.56%	5.3%	3%	18.8%	Local
-0.76± 7.34	4.5%	17.4%	15.8%	3.7%	Local
-0.041± 4.57	13.7%	9.3%	13.4%	9.2%	Inter-area

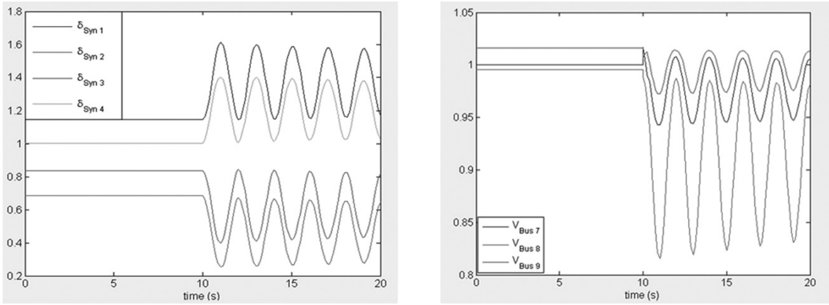


Fig. 4. Generator rotor angle and Bus voltage of TAS with AVR

Case III – Two area system with AVR and PSS

The aforementioned problem of decreased damping can be enhanced by the introduction of PSS. The PSS modulates the input of AVR and increases the system damping. Table 5 shows that the addition of PSS increases the interarea damping of previous 0.89% to 14.2 %. The time domain simulation of Fig. 5 shows that both the generator angles and corridor bus voltages are stable following a disconnection of line at 10s.

Table 5 : Critical Eigen Values of TAS with AVR and PSS

Real part	Imaginary part	Frequency (Hz)	Damping Factor	Most Associated states	Mode Type
-1.39	±7.73	1.25	17.7%	Δδ2, Δω2	Local
-1.38	±7.6	1.23	17.8%	Δδ3, Δω3	Local
-0.62	±4.32	0.69	14.2%	Δδ1, Δω3	Inter-area

Table 6 : Participation in TAS with AVR and PSS

Critical Eigen Values	Δδ1, Δω1	Δδ2, Δω2	Δδ3, Δω3	Δδ4, Δω4	Mode
-0.627 ± 7.047	15.80%	5.34%	2.63%	21.75%	Local
-0.61 ± 6.932	4.09%	19.18%	18.48%	3.80%	Local
-0.2 ± 4.2	15%	10.25%	13.40%	8.90%	Inter-area

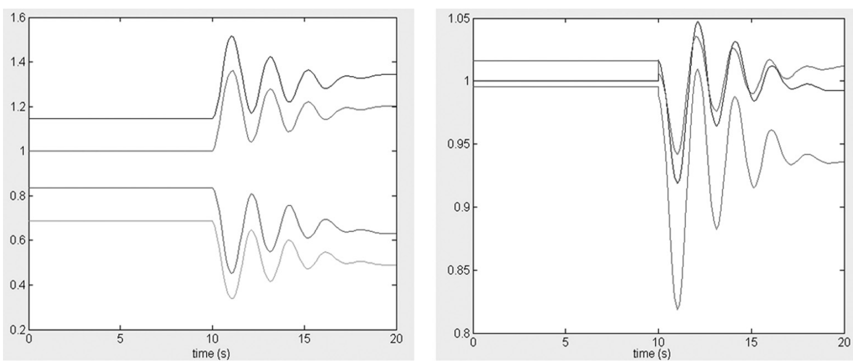


Fig. 5. Generator rotor angle and Bus Voltage with AVR and PSS

Case IV - TAS -Synchronous Generator is replaced with DFIG of same capacity

This sections analyse associated small signal problems if each generators of aforementioned two area system are replaced with DFIG power penetration of same capacity one by one. Both the small signal and time domain simulations are run. Among the four generators used, G_3 is used as a slack bus for power flow analysis. All the remaining generators G1, G2 and G4 comprises equal power generation of 700 MW each. A large wind farm of 700 MW using 45 numbers of wind generators is modelled to replace that huge size of generator.

The most critical eigenvalues, damping factors and most associated states are shown in Table 7 below when SG(s) at bus1, bus2 and bus3 are replaced with DFIG based wind power.

Table 7 : Critical Eigenvalues when SG is replaced with DFIG

DFIG at	Real part	Imaginary part	Frequency (Hz)	Damping Factor	Most Associated states	Mode Type
Bus 1(G1 is replaced)	-0.255	±5.365	0.855	4.6%	$\Delta\delta 2$, $\Delta\omega 2$	Local
Bus 2(G2 is replaced)	-0.0225	±4.898	0.779	0.45%	$\Delta\delta 1$, $\Delta\omega 1$	Local
Bus 4(G4 is replaced)	-0.198	±4.82	0.767	4.1%	$\Delta\delta 3$, $\Delta\omega 3$	Local

When the first generator (G1) is replaced with DFIG, the damping factor of critical eigenvalue is 4.6%. In case, generator at bus 2 is replaced with DFIG of same capacity, new damping factor becomes 0.45% i.e. the system is in the verse of instability.Lastly, synchronous generator at bus 4 is replaced with DFIG keeping all other generators as it is. In this case, the damping factor is improved to 4.1% and the system is stable. The most associated states for the critical values are the perturbation in speed and generator rotor angle of the next generator at the same area in all cases.

Similarly, time domain analysis is performed with a tie line interruption at 10s.The generator rotor angle and corridor bus voltages comes to steady state in a few seconds except in case G2 is replaced with DFIG. Fig. 6 below shows generator rotor angle and corridor bus voltages with DFIG at bus 4.

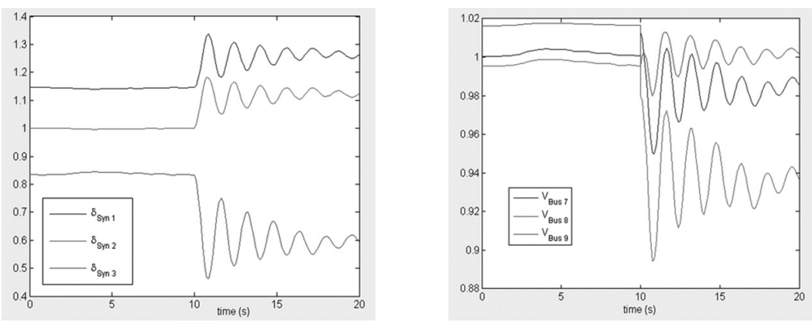


Fig. 6. Generator rotor angle and Bus Voltage with DFIG at BUS 4

This study shows that replacing synchronous generators of same capacity with DFIG power at different locations have different impacts on low frequency oscillations. The rotor angle and speed of synchronous generator at the same local area i.e. nearer to DFIG wind turbine generator has the highest contribution to critical eigenvalue.

Case 5 - Different level of DFIG power is penetrated in bus 5, 6, 10 and 11

During this analysis, all synchronous generators are kept as it is and additional wind power is penetrated via different buses rather than generator and load bus i.e. at the bus 5, 6, 10 and 11 in the two area network. The wind power penetration level is maintained at different penetration level on the basis of total load demand of the network.

Table 8 shows the most critical eigen values with different level of penetration and their respective damping factor. The system is becoming more stable from small signal stability point of view as the wind penetration level is increased at different points.

Table 8: Most Critical Eigenvalues with different wind penetration level

Penetration Level	Real part	Imaginary part	Frequency (Hz)	Damping Factor	Most Associated states	Mode Type
10 %	-0.19346	±5.103	0.81	3.7%	Δδ1, Δω1, Δδ3, Δω3	Inter-area
20%	-0.2508	±5.08	08	4.9%	Δδ1, Δω1, Δδ3, Δω3	Inter-area
30%	-0.32206	±5.038	0.803	6.3%	Δδ1, Δω1, Δδ3, Δω3	Inter-area

Fig. 7 below shows the waveform of time domain simulation after a line interruption at 10s when 30% of load is penetrated via DFIG. It shows the oscillation is damped out in few seconds.

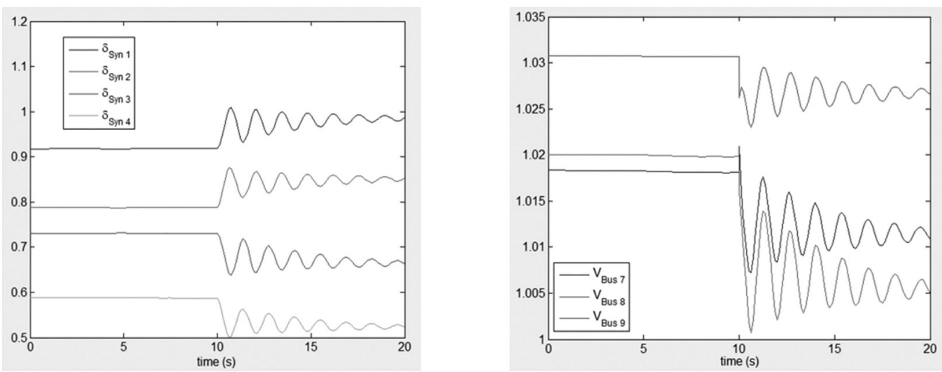


*Fig. 7.*Generator rotor angle and Bus Voltage with DFIG level 30%

Conclusion

The benchmarked Two Area Network analysis was then analysed. From TAS, concept of local and global mode oscillation can be understood clearly. These all research work has made easy to understand rotor angle stability problems in stepwise manner. The major findings from this case study are:

1. Replacing synchronous generators in TAS by DFIG WTG one by one of same rating gave conclusion that low frequency stability depends on the location of DFIG penetration and operating scenario.
2. Direct replacement of Synchronous Generator can either improve the system damping or has potential of instability.

   DFIG penetration enhances system damping from small signal perspective.[2]

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