Puerto Iguazú
Argentina

XIII ERIAC
DÉCIMO TERCER ENCUENTRO
REGIONAL IBEROAMERICANO DE CIGRÉ
24 al 28 de mayo de 2009

XIII/PI-C1 -22

Comité de Estudio C1 - Desarrollo de Sistemas y Economía

SMALL SIGNAL STABILITY OF POWER SYSTEMS WITH LARGE SCALE WIND POWER INTEGRATION

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Abstract *– This paper surveys the impact of large scale wind power integration on the small signal stability performance of the power systems. For this purpose, different factors concerning wind power generation such as wind power integration levels and wind power plant location are considered in the small signal stability assessment of a weak power system via modal analysis. The changes in the modal characteristics of the system are evaluated by observing the movement of the oscillatory modes in the complex plane. Besides, time domain simulations were carried out in order to verify the conclusions inferred from modal analysis and to further determine in which way do large scale wind power integration levels affect the transient stability of a power system. It was found out that large wind power integration can have a positive or negative impact on both types of angle stability depending on the location of the wind power plant, the amount of the conventional generation replaced by wind power and the stress level of the power system.*

Key words: Doubly-fed induction machine – Wind generator control - Modal analysis – Small signal stability – Transient stability – Wind power

1 INTRODUCTION

The use of renewable energy technologies exhibits a significant growth in nowadays power systems mainly due to critical factors such as limited available primary energy resources used in conventional power plants, the fast increase in fuel prices, and environmental concerns. Wind power constitutes the renewable generation technology which has experienced the fastest growing among all types of renewable generation technologies currently investigated [1]. Extrapolating the current trend into the future, it is easy to foresee installed wind capacities exceeding 50 % of the overall capacity in some countries in the not too distant future [2]. Nearly all modern larger turbines use doubly-fed induction generators (DFIGs). These machines are collectively referred to as variable speed machines and they possess important advantages such as reactive power control capabilities, smaller and cheaper converter compared with a full size one[3]. Further, there are some important contributions regarding to modeling of DFIGs and the corresponding converters for stability studies [4].

Large integration of wind power into power networks will affect considerably the dynamic behavior of the power system since wind based generation systems and conventional synchronous generators exhibit fundamentally different transient responses. This stems first and foremost from their inherently different dynamic characteristics [5]. Additionally, wind generation systems result in the reduction of the overall system inertia pegged to the network in relation to the installed capacity. Furthermore, modern power networks are operated close to their security limits due to economical and technical considerations.

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Additionally, wind power is habitually dispatched on a priority basis irrespective of its merit order. This shifts the load flow configuration and in countries with widespread and expansive wind installations this can adversely impact the stability performance of the entire system.

Problems related to small signal stability have also been reported [6]. The small signal stability (SSS) problem of a power system occurs usually due to insufficient damping of electromechanical oscillations [7]. The transient stability problem in the sense that one or a group of generators may be forced out of synchronism following a grid fault does not as such apply to wind power generation systems. In critical situations, the converters can be stopped for duration of a few milliseconds and then resynchronized. The role of the inertial response, which is so central to the behavior of conventional synchronous generators following a disturbance, is largely supplanted by the response of the controllers in wind generation systems.

With increasing wind power generation, interest to fully understand and quantify the impact of this development on the performance of the interconnected system has also grown. Thus, different publications concerning wind power on stability studies has been reported in the recent past [5], [8].

However, further research is required for better understanding of the main factors influencing the impact of large scale wind power integration on SSS. This paper provides an attempt to assess how large scale wind power integration influences the SSS and transient stability, since these stability constraints are essential for power system security, as evidenced in recent blackouts throughout the world [9]. The SSS and the transient stability of a benchmark weak interconnected power system comprising conventional thermal power plants and a DFIG based wind power plant were evaluated through modal analysis and time domain simulations respectively.

2 MODELING AND SIMULATION

2.1 Small signal stability analysis

The dynamic behavior of a power system can be described by a set of ordinary differential equations denominated state equations, together with a set of algebraic equations, developed on the basis of the system model, to be solved simultaneously [10]:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}\left(\boldsymbol{x},\boldsymbol{u}\right),\ \ \boldsymbol{y} = \boldsymbol{g}\left(\boldsymbol{x},\boldsymbol{u}\right) \tag{1}$$

Where $\mathbf{x}=[x_1, x_2,\ldots x_n]^T$ is the vector of state variables, $\mathbf{y}=[y_1, y_2,\ldots y_m]^T$ is the vector of system outputs variables, $\mathbf{u}=[u_1, u_2,\ldots u_r]^T$ is the vector of system input variables, and $\mathbf{f}=[f_1, f_2,\ldots f_n]^T$ and $\mathbf{g}=[g_1, g_2,\ldots g_m]^T$ are the vectors of nonlinear functions defining the states and the outputs respectively. The SSS analysis may be done via modal analysis. The modal analysis uses a linear representation of (1) around a system operating point, which is suitable to analyze small disturbances in the power system [10]:

$$\Delta\dot{\boldsymbol{x}} = \boldsymbol{A}\Delta\boldsymbol{x} + \boldsymbol{B}\Delta\boldsymbol{u},\ \ \Delta\boldsymbol{y} = \boldsymbol{C}\Delta\boldsymbol{x} + \boldsymbol{D}\Delta\boldsymbol{u} \tag{2}$$

Where, the prefix Δ denotes a small deviation. $\Delta\mathbf{x}$ is the state vector, $\Delta\mathbf{y}$ is the output vector, **A** is the state matrix, **B** is the input matrix, **C** is the output coefficient matrix, and **D** is a matrix describing the connection between the input and output variables. The eigenvalues of the state matrix **A** determine the time domain response of the system to small perturbations and therefore provides valuable information regarding the stability characteristics of the system. If all eigenvalues have a negative real part all oscillatory modes (OM) decay with time and the system is said to be stable [11]. The critical eigenvalues are characterized for being complex and for being located near the imaginary axis of the complex plane [12]. In order to determine which of these eigenvalues have greater influence in SSS the use of the damping ratio constitutes a suitable measure [11]. For a particular eigenvalue $\lambda_i = \alpha_i + j\omega_i$, the damping ratio ζ_i is defined as:

$$\zeta_i = \frac{-\alpha_i}{\sqrt{\alpha_i^2 + \omega_i^2}} \tag{3}$$

The mode shape associated to each critical eigenvalue helps to distinguish the various types of oscillation. The phase angle of speed elements in the right eigenvector belonging to a critical mode indicates the phase contribution of each state variable to that mode. Moreover, a speed participation factor indicates the relative contribution of each state variable to a certain mode. Thus, high speed participation factors and phase angle differences in the order of 180º indicate oscillation between groups of generators. Besides, the location of the generators in the power system determines the oscillation type [10], [11].

2.2 Transient stability analysis

Transient stability issues, also referred to as the first swing stability, are defined as the ability of the power system to maintain synchronism when subjected to severe disturbances such as short circuits. Transient stability depends on the initial operating conditions of the system as well as the type, severity and location of the disturbance [7]. The widely used methods for transient stability assessment are based on the time domain simulations and the analysis of the transient energy function, which corresponds with the extended equal area criterion under some assumptions [13]. For our study, time domain simulations are employed to assess the impact of wind power integration level on the transient stability of the power system. Here, the power angle between two synchronous generators can be chosen as an indicator to evaluate the transient stability.

2.3 Wind turbine modeling

By far the larger number of wind generation plants at this point in time are still equipped with the doubly-fed induction generator (DFIG). As a result, this paper focuses on this type of machine only. As is well known, the rotor terminals of a DFIG are fed with a symmetrical three-phase voltage of variable frequency and amplitude fed through a voltage source converter usually equipped with IGBT based power electronic circuitry [3], [4]. The basic topology including its control system is shown in Fig. 1. As a general approach, the space-phasor coordinates with orthogonal direct (d) and quadrature (q) axis is used. The choice of the stator voltage as the reference frame enables the decoupled control of P (d control channel) and Q (q control channel). The two complex (i.e. complex in terms of space-phasor representation) voltage differential equations, one each for the stator and rotor circuits, together with the equation of motion represent the full set of mathematical relationships that describe the dynamic behavior of the machine [10], [14]. Then, by setting the derivative of the stator flux linkage with respect to time to zero, the quasi stationary model of the machine is obtained [15].

A complete model of the DFIG also includes models of the real and reactive power control together with speed and pitch angle control. These models, however, are not relevant for the purposes of this study, which is synchronism of generators in conventional plants following a fault. The structures of both the rotor side controller (RSC) and line side controller (LSC) are given in Fig. 2 and Fig. 3, respectively. The two figures summarize the models of the core functionalities of the systems, which are of relevance for stability studies. Manufactures often augment these core structures variously. The structures as presented here reproduce neither any eventual blocking of the converters nor crowbar activation during grid faults. Additionally, due to the assumption that the DC voltage can be maintained approximately constant during the simulation time span models of the DC link and the crowbar are not needed. The air gap torque of the machine is also assumed to remain constant. The voltage controller in Fig. 2 maintains a deadband of ±5 % to preclude controller action until the voltage exits this limit [15].

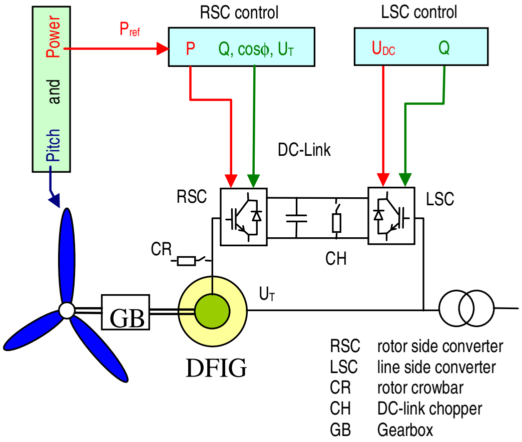


Fig. 1: Layout of DFIG based wind turbines.

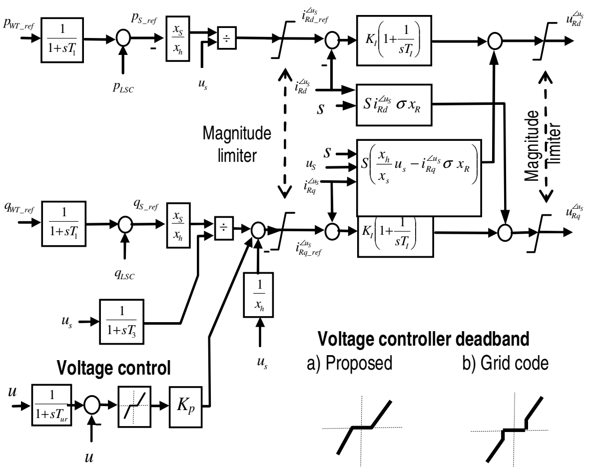


Fig. 2: Rotor side converter model.

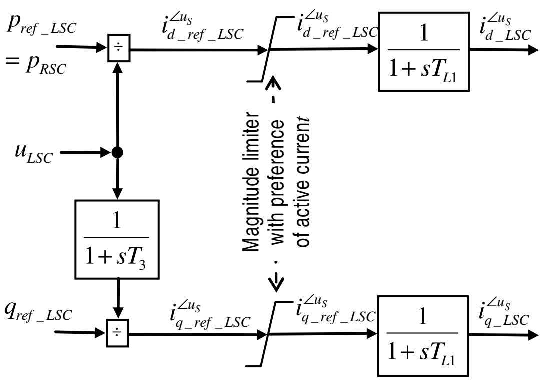


Fig. 3: Line side converter model.

2.4 Test power system

The two area-four machine power system presented in Fig.4 is used in this research to assess the impact of DFIGs on small signal stability. This system was derived from the original test system introduced in [10]. Synchronous generators G1 to G4 do not represent a single machine, but a group of strongly coupled generators. It was assumed the existence of 4 machines of 247 MVA each. Parameters of generators, transformers and transmission lines were obtained from the PST16 system data base [16].The nominal output power of each wind power plant is 750 MW. This corresponds to the output of 150 DFIG-based wind generators, each with a nominal capacity of about 5 MW. A single equivalent model was used to represent all individual units within the wind power plant in order to avoid increasing computation time. The single equivalent is represented using the model proposed in [4], and it is connected to the system using a typical layout of an offshore wind power plant as shown in Fig. 5. Synchronous generators are modeled using a five order model, with magnetic saturation neglected, where the governors and excitation systems are included and modeled with the models described in [10].

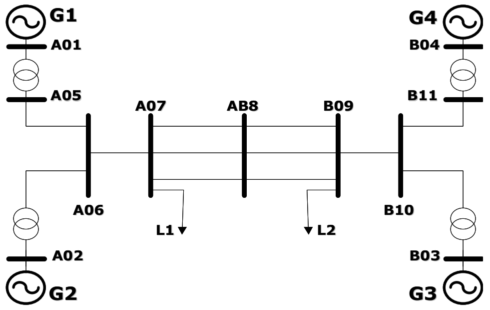


Fig. 4: Single line diagram of the studied power system.

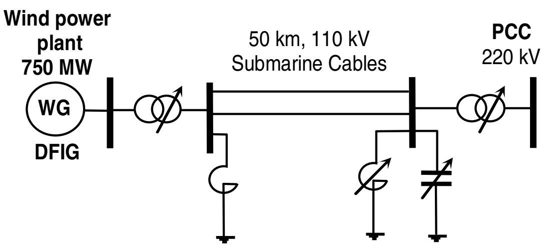


Fig. 5: Connection of an offshore wind power plant to the grid.

3 STABILITY ANALYSIS

The test system was studied for different scenarios generated from a highly loaded condition and corresponding to different power generation dispatches of conventional synchronous machines and wind power plants in order to create different wind power levels. Here, each power output from the wind farm will correspond to the power available for a given wind speed. The total load demand is about 2734 MW, with 967 MW and 1767 MW corresponding to L1 and L2 respectively. Additionally, different wind power plant locations are considered in order to investigate the effect of a wind power plant located within the same highly loaded area (west area) or with a wind power plant located far from that area.

The modeling and simulation of the test system, and the scenarios are accomplished using the "Power System Dynamics" simulation package [14]. Each scenario will define an operating state which is determined through load flow calculation. Next, modal analysis will be performed in each scenario. This will help in explaining the sensitivities of the oscillatory modes (OM) to large wind power integrations. OM as well as eigenvectors and participation factors were computed for different wind power integration levels in order to investigate the effects of wind power in the shape of power system oscillations.

Besides, since power system oscillations are caused by the working principle of synchronous generators and dynamic behavior of power systems is highly nonlinear, time domain simulations will also allow studying the way the OM are excited and observable in system response [17]. A 150 ms self-clearing tree phase fault is applied at bus A07, for the initial condition and the final condition for some different scenarios. Subsequently, the power angle between two synchronous generators will allow assessing the impact of wind power on transient stability.

3.1 Small signal stability

The initial scenario comprises to a total load of 2734 MW, 2652.5 MW of conventional generation power and 215.7 MW of wind power. From this scenario, two separate wind power plant locations are considered:

- Wind power plant connected to bus B10: Wind generation increase gradually whereas conventional generation in i) in G3, or ii) in G2 and G3 reduce.
- Wind power plant connected to bus A06: Wind generation increase gradually whereas conventional generation in G3 and G4 reduce.

3.1.1 Wind power plant connected to bus B10

In the first case, G3 power generation was replaced gradually by wind generation. Fig. 6 shows the root loci for the three OMs: i) Inter-area mode (the blue one), ii) West local mode 1 (the red one), and iii) East local mode 2 (the green one). The circles represent the initial scenario and the squares the final scenario (85 % of G3 power generation replaced by wind generation). The upward-pointing triangle represents the case when G3 was fully replaced by wind generation. The figure shows that inter-area and west local modes exhibit a small increase of damping whereas the east local mode is not significantly affected. This probably means that wind power does not affect local oscillations in distant areas.

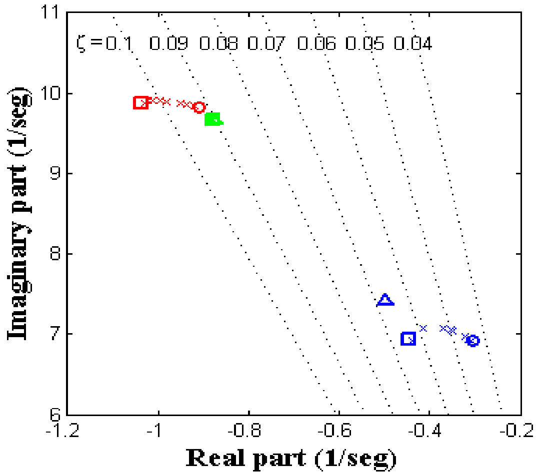
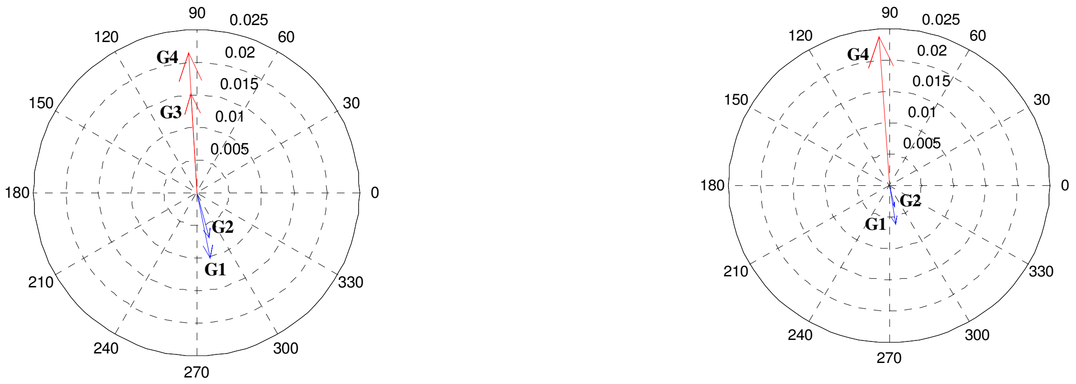


Fig. 6: Root loci: movement of OM when G3 output power was replaced by wind power.

Furthermore, the west local mode does not exist and the inter-area mode path changes when G3 was fully replaced by wind generation. The changes in west local and inter-area modes arise from the fact that synchronous generator G3 (which is involved in both types of oscillatory modes) is replaced by wind power generation. Besides, these changes in modal characteristics can be due to the fact that DFIG does not interface with the network through an internal angle as a synchronous machine does. This causes the absence of mechanical states associated to G3 (speed and angle) from the right eigenvector associated to each corresponding eigenvalue. This situation is depicted in Fig. 7 and Fig 8, when comparing the mode shapes and participation factors corresponding to inter-area mode respectively.

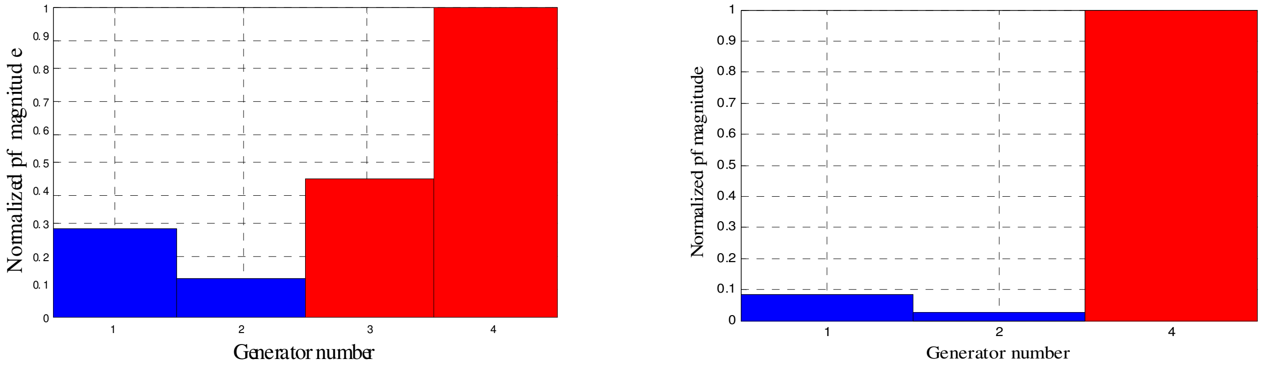
In the second case, G2 and G3 power generation were replaced gradually by wind generation. The movement of the OMs in the complex plane is shown in Fig. 9. The circles represent the initial scenario and the squares the final scenario (50 % of G2 and G3 power generation replaced by wind generation).



a)

b)

Fig. 7: Speed mode shape: for inter-area mode:
a) Initial scenario, and b) Final scenario (G3 output power was fully replaced by wind power)



a)

b)

Fig. 8: Normalized speed participation factors: for inter-area mode:
a) Initial scenario, and b) scenario (G3 output power was fully replaced by wind power)

It can be observed that inter-area, east local and west local modes exhibit a small increase of damping. Further, the changes in the three modes arise from the fact that synchronous generators G2 and G3 (which are involved in the three types of oscillatory modes) are partially replaced by wind power generation, and because of power transfers from east area to west area have decreased (G2 output power level diminished and replaced by wind power). In this case, the power system is less stressed (conventional generators operating far from their limits and less power transfers). Thus, DFIGs appear to contribute to damping enhancement when increasing wind power generation helps in reducing the power system stress level.

3.1.2 Wind power plant connected to bus A07

In the third case, G3 and G4 power generation were replaced gradually by wind generation. Fig. 10 shows the root loci for the three OMs. The circles represent the initial scenario and the squares the final scenario (50 % of G3 and G4 power generation replaced by wind generation). Here, it is possible to note that the east local and west local modes are not significantly affected. The inter-area mode exhibits a small decrease of damping. This decrease is more noticeable in the final scenario, which corresponds to a more stressed condition (because higher power amount is transferred from east area to west area, since conventional generating power from units G3 and G4 near loads are replaced by wind power located far from loads). Thus, DFIGs appear to contribute to damping decrease when increasing wind power generation contributes in increasing the power system stress level.

3.2 Transient stability

Time domain simulations were carried out according to the Section 2.2. Fig. 11 shows the change on power angle deviation between G1 and G4 for the second and the third cases respectively. The initial scenario corresponds to the curves with solid lines and the final scenario corresponds to those curves with dotted lines in each case. By observing the first swing, it is clearly evident that the DFIG based wind power plant reduces the magnitude of the maximum power angle deviation for the second case. Thus, the transient stability of the power system has been improved probably due to the contribution of the wind power plant to reduce the stress level. Moreover, the inter-area mode is clearly visible as the simulation progress. Comparing both the initial and final scenarios it is interesting to note a small damping increase on inter-area oscillation in the simulation period. These results correlate well with those of the modal analysis. On the other hand, the magnitude of the maximum power angle deviation increases for the third case due to increment of power system stress level. Hence, the transient stability of the power system has worsened. Furthermore, the figure also shows a small damping decrease for the inter-area oscillation, thus confirming the results obtained via modal analysis.

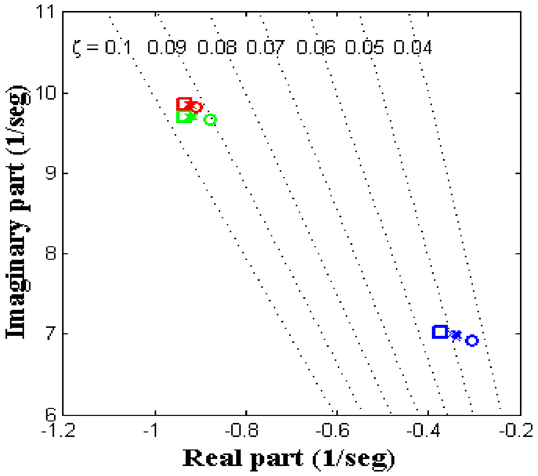


Fig. 9: Root loci: movement of OM when G2 and G3 output power were replaced by wind power.

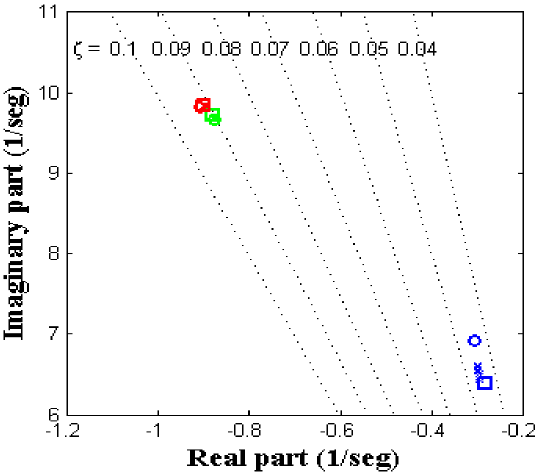
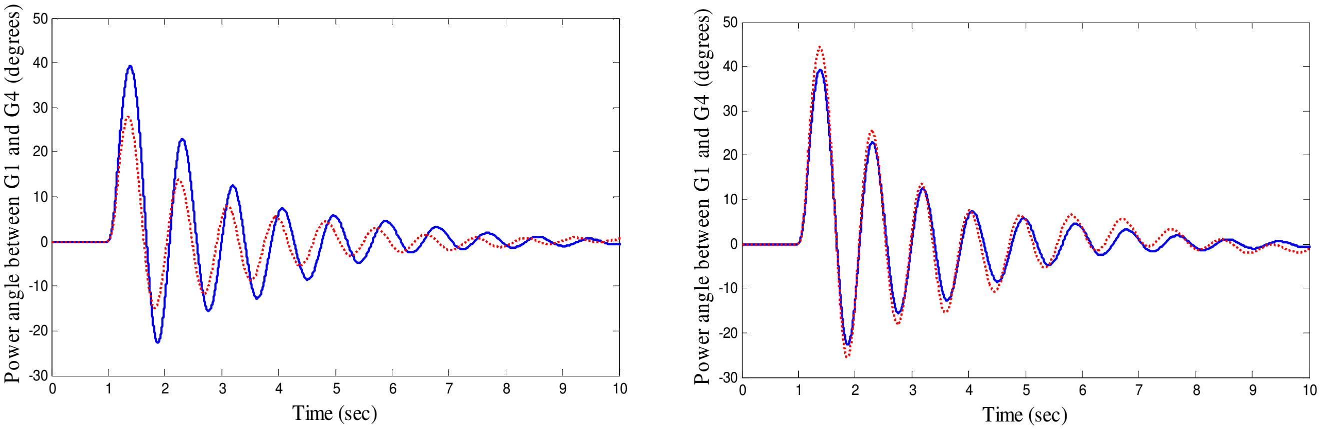


Fig. 10: Root loci: movement of OM when G3 and G4 output power were replaced by wind power.



a) b)

Fig. 11: Power angle deviation of synchronous generators G1 and G4 due to a tree phase fault: a) Second case, and b) Third case.

4 CONCLUSIONS

The results presented in this research show that large wind power integration can have a positive or negative impact on small signal stability of power systems. These impacts depend on the location of the wind farm, the amount of the conventional generation replaced by wind power and the stress level of the power system. An inter-area oscillation was determined via modal analysis and by observing time domain simulations. It also would appear that inter-area oscillations are the most sensitive to large wind power integration since wind power replaced the power generated by synchronous generators involved in inter-area oscillations, and the contribution of synchronous generators to the overall demand for power became less. Changes in shape of oscillations can occur when conventional generation is switched off. The changes in local and inter-area modes arise when synchronous generators involved in any oscillatory mode are replaced by wind power generation. It was founded that DFIGs appear to contribute to damping and transient stability decrease when increasing wind power generation contributes to increase the power system stress level, especially when it contributes to congest weak interconnection lines as in the case study provided here. Additionally, wind power does not affect local oscillations in distant areas. Conversely, it was also observed that DFIGs contribute to damping and transient stability enhancement when increasing wind power generation helps in reducing the power system stress level. Some counter measures should be applied to mitigate adverse impacts, e.g. power system stabilizers (PSS). It is worthwhile to mention that these impacts should be accounted in PSS tuning since the structure of power system oscillations can suffer modifications.

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