POWER SYSTEM STABILITY ENHANCEMENT BY USING VIRTUAL INERTIA CONTROL IN DFIG BASED WIND ENERGY SYSTEM

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Abstract- Distributed generation is characterized as a form of generation that is not directly connected to the bulk transmission grid. It is usually connected via power electronic devices if it is a renewable resource, in this case in the form of a voltage source converter (VSC) operating as an inverter (converting DC-to-AC). The grid impedance connected to the VSC has an influence on its stability and control performance. By looking at the output impedance of the VSC, the stability can be determined in relation to the impedance of the grid connection. A number of parameters influence the output impedance of a VSC, one of those being the control scheme used and the phase-locked loop (PLL) contained within it. Wind turbines with virtual inertia control are coupled to power system in dynamic characteristics, and the control input of virtual inertia control is directly affected by the tracking ability of phase-locked loop (PLL).

Thus, it is urgent to study the impact of DFIG wind turbines with virtual inertia control on power system small-signal stability considering the effects of PLL. And then, considering that both PLL and virtual inertia control will affect the oscillation modes of synchronous generators, analytical method is used to reveal system small-signal stability under the joint effects of the two factors quantitatively. The smaller the PI parameters of PLL are, the smaller the participation factor of virtual inertia control state variables in the inter area oscillation mode is, and the bigger the electromechanical oscillation mode damping ratio. MATLAB/SIMULINK Simulation results verify the reasonableness of the established model and the possibility that virtual inertia control may cause system small-signal stability to deteriorate in multi machine system.

Index Terms— DFIG wind turbines, virtual inertia, phase-locked loop, coupling characteristics, small-signal stability, damping characteristics.

I. INTRODUCTION

Power System Stability is defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. This definition shapes the aspects of power systems that each technique and methodology must address. This mentioned equilibrium to be maintained both before and after disturbances incorporates several aspects and is dependent upon specific system parameters. Synchronization of the machines within the system and voltage stability is of primary concern. The components that govern these characteristics are necessary to form the building blocks of stability analysis. One of the chief components of synchronization is machine rotor angle. Rotor angle is the angle between a rotor axis of the machine and its stator axis. In order for the system to remain stable, all of the synchronous machines within a power system must maintain a synchronized state of equilibrium between their rotor angles. Thus, rotor angle and system stability are one of the fundamental concerns of analysis. Another important factor of system stability that involves the rotors of the machines is the non-linear relationship between the machine electric power output and its rotor angle. It accounts for both the amount of power transferred and the system's ability to return to equilibrium i.e. stable after a certain disturbance. Finally, the third major component of power system stability is rotor speed. The change in rotor speed after a certain disturbance can significantly affect the damping characteristics of the system.

Small signal stability problems exist in power system for many decades. The system oscillates with undamped or growing phenomenon because of lacking of damping or synchronism. The unstable oscillations could appear as one generator or a small part against the rest of the power system or the whole interconnected power system. The problem in this situation is called local mode problem. On the other hand, the inter-area mode problem which refers to the interconnected power system's unstable oscillation, is well represented by the WSCC system (North American Western Interconnected System) incident happened in 1996, the circuits outages causes the low frequency oscillation as inter-area mode. It results in the outage of the whole power system.

Small signal stability refers to the ability to maintain synchronism when small disturbances happen. The disturbances are considered very small, so the equations to present the system state need to be linearized when study. Small disturbance angle stability and transient stability are both related to rotor angle changes. Small signal stability and transient stability belong to the rotor angle stability which follows the classification of the stability problem for power system shown in Figure.1. Power system stability problem has three categories: rotor angle stability, frequency stability and voltage stability.

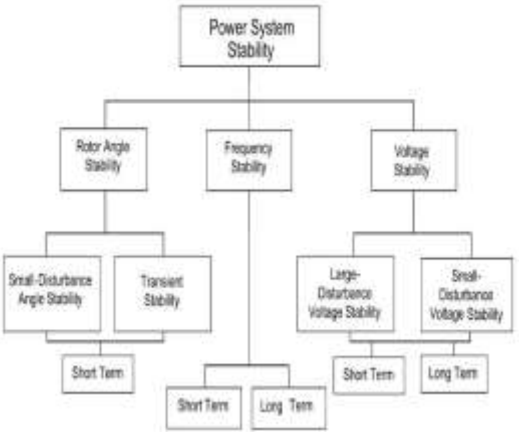

Fig:1. Classification of Power System Stability.

The basic PLL structure is comprised of three portions. These include a phase detector (PD), loop filter (LF), and voltage controlled oscillator (VCO). A diagram and their associated components are shown in Figure 2.

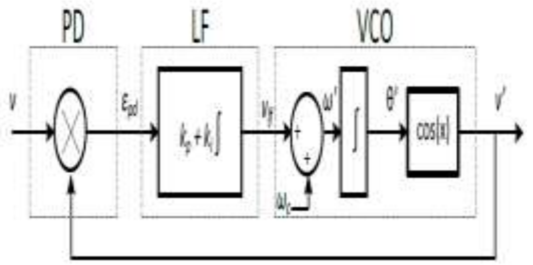

Fig:2. Basic PLL Building Blocks.

The phase detector compares the signal created by the VCO and the desired signal to determine their phase difference and outputs a value proportional to this difference. The output is then fed to a low-pass filter, which is usually represented by a proportional-integrator (PI) controller. Lastly, the value from the LF is used as an input to the VCO to create the desired signal (in this case, a 60Hz sine wave) to match that of the input signal to the PLL.

II. VIRTUAL INERTIA CONTROL

However, an emerging approach to the control of power electronic converters has been the emulation of essential properties of traditional power generation units, in order to gain the equivalent functionality. Virtual inertia is a combination of control algorithms, RESs, ESSs, and power electronics that emulates the inertia of a conventional power system. The concept of virtual inertia is summarized in Figure 3. The core of the system is the virtual inertia algorithm that presents the various energy sources interfaced to the grid through power electronics converters as SGs. Most modern wind turbines are operated as variable speed wind turbines and interfaced through back-to-back converters, completely decoupling the inertia from the grid. Similarly, PV systems and ESSs have a DC-DC converter and an inverter in the front-end, and do not contribute to the inertial response.

Virtual inertia systems based on current/voltage feedback from the inverter output generate appropriate gating signals to present these resources as SGs from the point-of-view of the grid. Although the basic underlying concepts are similar among the various topologies in the literature, the implementation is quite varied based on the application and desired level of model sophistication. Some topologies try to mimic the exact behavior of the SGs through a detailed mathematical model that represent their dynamics.

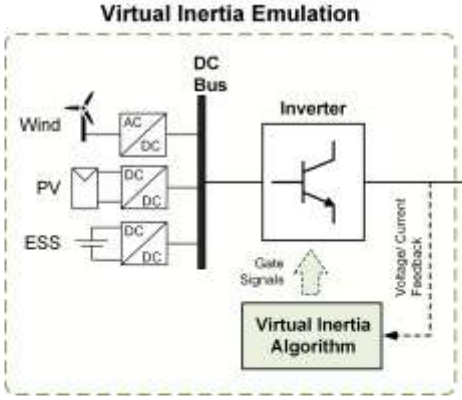

Fig:3. Concept of virtual inertia.

Other approaches try to simplify this by using just the swing equation to approximate the behavior of SGs, while others employ an approach which makes the DG units responsive to frequency changes in the power system. This section discusses the various topologies that have been proposed in literature.

III. SYSTEM MODELING

In this project, a small-signal model of interconnected system with DFIG integration considering the PLL and virtual inertial control is established first. Second, the attenuation time constants of DFIG state variables are calculated, and the coupling between them is revealed. And then, take the two-machine infinite-bus system for example; the small-signal stability of power system under the joint effects of PLL and virtual inertial control is analyzed using analytical method. According to the analysis results, for DFIG wind turbines with virtual inertial control, the impact of the PLL on system damping characteristics is contrary to that in wind turbines without virtual inertial control. For DFIG wind turbines with virtual inertial control, the PLL affects system damping mainly by affecting the participation of virtual inertia in the system. The smaller the PLL PI parameters are, the smaller the participation factor of virtual inertia control state variables in the inter-area oscillation mode is, and the bigger the electromechanical oscillation mode damping ratio is, which is beneficial for system stability. In stator flux directional control, *d*-axis of the synchronous rotating coordinate system is set to coincide with the stator flux vector. In steady-state operation, neglecting the stator resistance, the stator voltage vector is 90° forward the stator flux vector in phase. Due to the complexity of accurate flux observation algorithms, wind turbines commonly used in industry all apply the stator voltage directional control method, thus realizing indirect control of the stator flux. The overall picture of the virtual inertia control, PLL and DFIG rotor side converter is as shown in Fig.4. The typical virtual inertia control is shown in Fig.5. When system frequency drops, the active power reference value at the input of the rotor inverter will increase, thus by regulating the rotor current, the output active power will increase. The rotor then could release part of the kinetic energy as a dynamic support of system frequency variation.

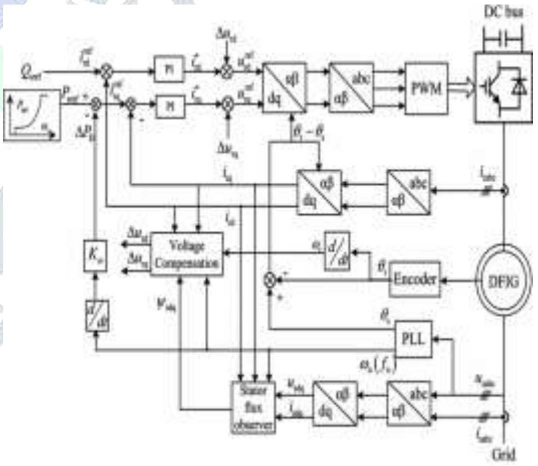

Fig:4. Diagram of DFIG stator voltage vector directional control strategy.

Suppose the type and operation state of all the wind turbines in the wind farm are the same, then the wind farm could be equalized to a large-capacity wind turbine, the parameters of which could be calculated according to parameters of single wind turbine. In this project, the equivalent wind farm model composed of multiple DFIG wind turbines is introduced to the multi generator power system for small-signal analysis. For a multi generator system with *n* generators, suppose that the first $n-1$ are synchronous generators which apply the four-order model, and the *n*th generator is an equivalent DFIG considering PLL and virtual inertia control. The system state equations can the other variables characterize the coupling relationships in different dynamic processes.

The matrix of coupling between synchronous generator and DFIG without virtual inertia control is zero matrix, thus the synchronous generator system is decoupled with the wind generator system, i.e. the state variables of wind generator do not participate in the electromechanical oscillation between synchronous generators.

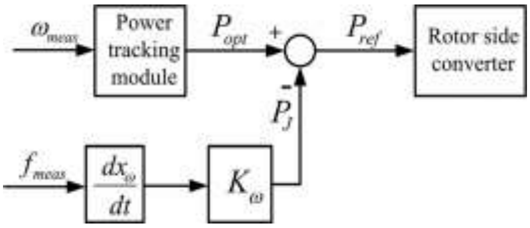

Fig:5. Typical block diagram of virtual inertia control.

This means that, in the study on small-signal stability, whether rotor speed ωr or pitch angle β changes, the disturbance will not pass on from the wind turbine to DFIG itself, neither will it affect the small-signal stability of synchronous generators in the system. Therefore, it can be taken that the mechanical part and electromagnetic part of DFIG are approximately decoupled with each other on small signal stability. As for the other state variables, i.e. the rotor voltage, rotor side converter, PLL and virtual inertia control, the coupling characteristics of them are analyzed below according to the time constant of oscillation mode of each variable.

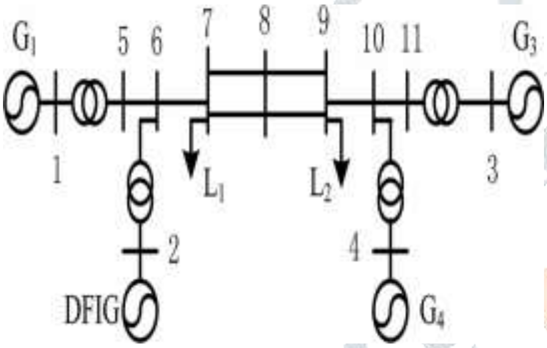

Fig:6. Diagram of four-generator two-area system.

Take the IEEE four-generator two-area system shown in Fig.6 for example, the inter-area oscillation modes of the system are analyzed. G1, G3 and G4 are synchronous generators with output power of 700MW. G3 is the balancing machine. A wind farm equalized by 500 DFIG wind turbines with stator-side capacity of 1.5 MW is integrated at Bus 2. Each wind turbine operates with 1.4MWpower output, thus the total power output of wind farm is 700 MW. The total system load is 2734 MW. This paper is mainly focused on analyzing the impact of DFIG integration on system small-signal stability considering PLL and virtual inertia control, i.e. how the integration of DFIG (as a dynamical system) to power grid affects the electromechanical oscillation between synchronous generators. Thus this paper is based on the hypothesis that the wind speed/wind farm output power is constant. Two groups of PI parameters are used in this paper, i.e. typical values *K*P PLL = 73.6 and *K*I PLL = 333.3, and weak damping values *K*P PLL = 0.5 and *K*I PLL = 17. The setting process and performance test of the typical values can be found in reference. According to DFIG wind turbines without virtual inertia control, when PLL applies typical values *K*P PLL = 73.6 and *K*I PLL = 333.3, the wind turbines do not participate in system electromechanical oscillation modes. When PLL applies weak damping values *K*P PLL = 0.5 and *K*I PLL = 17, the modes dominated by PLL are close to the frequencies of system electromechanical oscillation modes, and the PLL modes will be reflected in the wind power, which will further strongly affect the system electromechanical oscillation modes, causing system stability to deteriorate. While according to the above analysis, for DFIG wind turbines with virtual inertia control, PLL affects the system damping mainly by affecting the participation degree of virtual inertia in the system oscillation modes. In order to have a more intuitional comparison of the effects of PLL on system small-signal stability in DFIG wind turbines with/without virtual inertia control, and reveal the function mechanism of PLL in DFIG wind turbines with virtual inertia control, simulation verification is conducted below using the above two groups of values for PLL PI parameters.

IV. SIMULATION RESULTS

Case 1: Dynamic responses of system with different PI parameters (*K*P$_{PLL}$ = 73.6 and *K*I$_{PLL}$ = 333.3)

Due to the introduction of virtual inertia control, DFIG is similar to synchronous generator in inertia characteristics, and could support system active power within a short time after the frequency fluctuation. It can be seen that, the bigger the PI parameters of PLL are, the bigger the inertia support wind turbines provide for the system is, and the poorer the system power angle stability is. This conclusion is consistent with the above eigen value analysis.

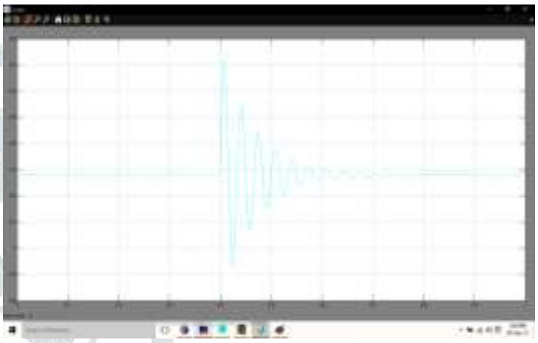

Fig:7(a)

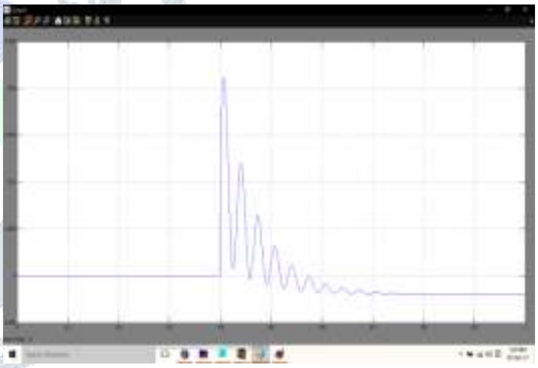

Fig:7(b)

Fig:7(a) & (b) Dynamic responses of system with different PI parameters (*K*P$_{PLL}$ = 73.6 and *K*I$_{PLL}$ = 333.3).

According to the variation of inter-area oscillation damping ratio and participation factors with the PI parameters of PLL, it can be see that the effects of PLL on system stability for traditional DFIG and DFIG with virtual inertia control are different. Traditional DFIG modifies PLL parameters to make the PLL modes manifest weak damping and be close to the system electromechanical oscillation modes in frequency, thus the PLL modes could affect system electromechanical oscillation modes significantly.

Case 2: Dynamic responses of system with different PI parameters (*K*P$_{PLL}$ = 0.5 and *K*I$_{PLL}$ = 17)

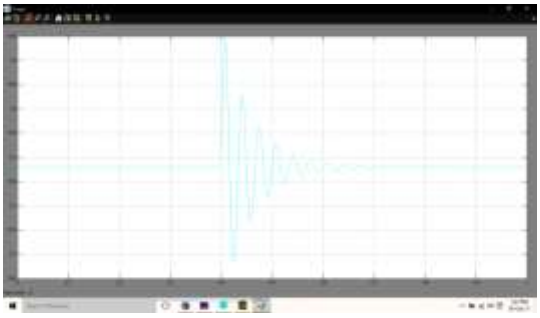

Fig:8(a)

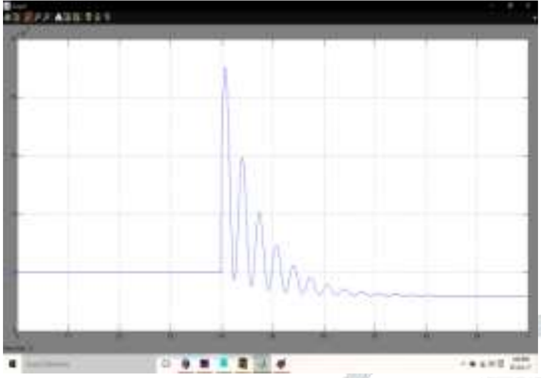

Fig:8(b)

Fig:8(a) & (b) Dynamic responses of system with different PI parameters (KP_{PLL} = 0.5 and KI_{PLL} = 17).

For DFIG with virtual inertia control, PLL affects the system damping mainly by affecting the participation degree of virtual inertia in system oscillation modes. The smaller the PI parameters of PLL are, the less accurately PLL could track the variation of system frequency, thus the weaker the participation of virtual inertia control state variable in system inter-area oscillation modes, and the stronger the system stability. It can be concluded that, as KP PLL and KI PLL increase, the participation factor of virtual inertia control state variable increases, while the damping ratio of inter-area oscillation mode decreases. Thus it is verified that PLL affects the system damping mainly by affecting the participation degree of virtual inertia in the system.

Case 3: Impact of PLL and Virtual Inertia Control on System Damping Characteristics

When the PI parameters of PLL apply the above two groups of values respectively, the variation of inter-area oscillation mode damping ratio with the virtual inertia is analyzed, and the system inter-area oscillation modes obtained with the simulation method shown in figures.

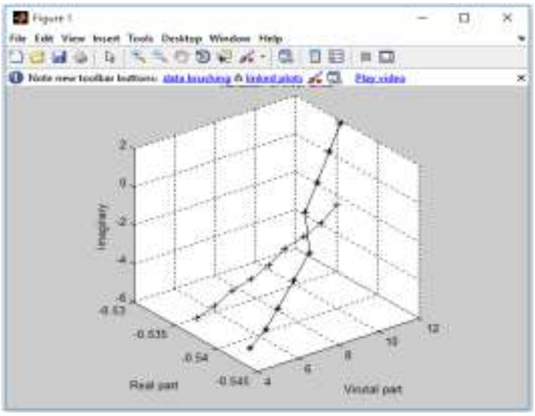

Fig:9. Variation of inter-area oscillation mode damping ratio with virtual inertia (KP_{PLL} = 73.6, KI_{PLL} = 333.3)

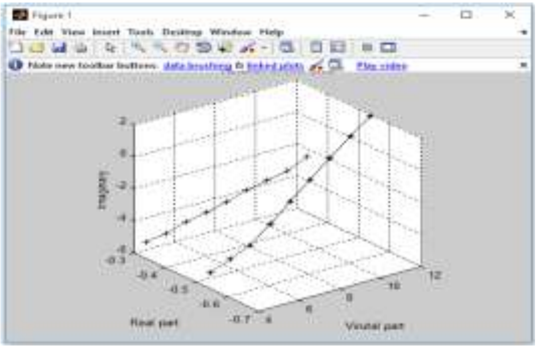

Fig:10. Variation of inter-area oscillation mode damping ratio with virtual inertia (KP_{PLL} = 0.5, KI_{PLL} = 17)

It can be seen that, the results obtained with the simulation method are close to each other. The variation of the damping ratio of inter-area oscillation mode with the virtual inertia is shown in Fig. 9 & 10, where the maximum damping ratio deviation within acceptable limits, which further verifies the correctness of the small-signal model, established in this project.

It can also be seen from Fig.9 & 10 that, the variation trend of damping ratio in two cases is the same, i.e. the damping ratio corresponding to the inter-area oscillation mode gradually decreases as virtual inertia control gain $K\omega$ increases. Meanwhile, when the PI parameters of PLL apply the weak damping values, the values of damping ratio are bigger than when the PI parameters apply the typical values. This is contrary to the case without virtual inertia control.

Case 4: Verification of the Impact of PLL on System Small-Signal Stability

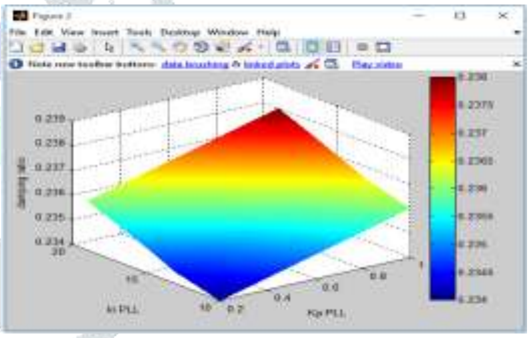

Fig:11(a)

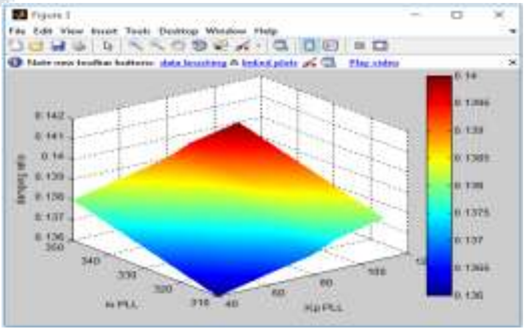

Fig:11(b)

Fig:11(a) & (b) Variation of damping ratio with PI parameters of PLL. (a) Typical values. (b) Weak damping values.

It can be concluded that, as KP PLL and KI PLL increase, the participation factor of virtual inertia control state variable increases, while the damping ratio of inter-area oscillation mode decreases. Thus it is verified that PLL affects the system damping mainly by affecting the participation degree of virtual inertia in the system.

V. CONCLUSION

A small-signal model of interconnected system with DFIG integration considering the PLL and virtual inertial control is established in this project, and the small-signal stability of power system under the joint influence of PLL and virtual inertial control is analyzed. The smaller the PI parameters of PLL are, the less accurately PLL could track system frequency variation, thus the participation of virtual inertia control state variables in the inter-area oscillation mode will be weaker, which will improve system power angle stability. Therefore, for wind turbines containing virtual inertia, the cooperation between PLL and virtual inertia should be taken into account when designing the parameters of PLL. Since how change of machine inertia affects power system electromechanical oscillation modes is truly complicated, the conclusions in this paper cannot be simply generalized to all large-scale inter-connected systems and operating conditions and the effect of mechanical inertia on system stability needs further research in depth. However, the research in this paper reveals that, the introduction of DFIG virtual inertia control may to some extent cause system small-signal stability to deteriorate, while PLL parameters could affect the small-signal stability by affecting the participation degree of virtual inertia, thus the joint effect of the two factors should be considered in the design of control strategy and parameters.

REFERENCES

[1] Y. Mishra, S. Mishra, F. Li, Z. Y. Dong, and R. C. Bansal, “Small signal stability analysis of a DFIG-based wind power system under different modes of operation,” *IEEE Trans. Power Convers.*, vol. 24, no. 4, pp. 972–982, Dec. 2009.

[2] S. Q. Bu, W. Du, and H. F. Wang, “Investigation on probabilistic small signal stability of power systems as affected by offshore wind generation,” *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2479–2486, Sep. 2015.

[3] F.Mei and B. Pal, “Modal analysis of grid-connected doubly fed induction generators,” *IEEE Trans. Energy Convers.*, vol. 22, no. 3, pp. 728–736, Sep. 2007.

[4] R. C´ardenas, R. Pe˜na, S. Alepuz, and G. Asher, “Overview of control systems for the operation of DFIGs in wind energy applications,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2776–2798, Jul. 2013.

[5] J. G. Slootweg and W. L. Kling, “The impact of large scale wind power generation on power system oscillations,” *Elect. Power Syst. Res.*, vol. 67, no. 1, pp. 9–20, Oct. 2003.

[6] S. Jiaying and S. Chen, “Impact of DFIG wind power on power system small signal stability,” in *Proc. IEEE PES Innovative Smart Grid Technol.*, Washington, DC, USA, 2013, pp. 1–6.

[7] Z. Wang, C. Shen, and F. Liu, “Impact of DFIG with phase lock loop dynamics on power systems small signal stability,” in *Proc. IEEE PES General Meeting Conf. Expo.*, Jul. 2014, pp. 1–5.

[8] J.Morren, S.W. H. de Haan,W. L.Kling, and J.A. Ferreira,“Wind turbines emulating inertia and supporting primary frequency control,” *IEEE Trans. Power Syst.*, vol. 21, no. 1, pp. 433–434, Feb. 2006.

[9] K. Ping-Kwan, L. Pei, H. Banakar, and B. T.Ooi, “Kinetic energy of windturbine generators for system frequency support,” *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 279–287, Feb. 2009.

[10] M. Kayikc¸i and J. V. Milanovic, “Dynamic contribution of DFIG based wind plants to system frequency disturbances,” *IEEE Trans. Power Syst.*, vol. 24, no. 2, pp. 859–867, May 2009.

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