Wind Farms with HVDC Delivery in Inertia Response and Load Frequency Control

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***Abstract*—This paper develops a coordination control strategy for wind farms with line commutated converter (LCC) based HVDC delivery to participate in inertia response and load frequency control. The coordination philosophy is to let the HVDC rectifier sense the grid frequency. If the grid frequency is too high or too low, active power flow through the HVDC link will be ramped down or up by introducing a droop at the rectifier control loop. In turn, wind generation will increase or decrease the blade angles to reduce or increase the captured wind power. This will be done by wind generation pitch controllers. A case study demonstrates the effectiveness of the frequency droop in HVDC control. Simulation results in TSAT are given.**

***Index Terms*—Wind Generation, DFIG, HVDC, Load Frequency Control**

I. Introduction

HVDC delivery has been used in off-shore wind farms. The coordination of wind farm maximum power extracting and HVDC wind farm side converter has been addressed in [1]–[3]. All of the above mentioned papers only address the issue of wind farm and HVDC rectifier coordination.

However, the issue not addressed is: When the ac system has a change in load or generation, synchronous generators will act by first releasing the kinetic energy (inertia response) from their rotors and then changing the prime mover power (load frequency control). It is desirable for the wind power with high penetration to act the same way as the synchronous generators. With inertia response contribution from wind, the frequency deviation of the system will not be significant. With load frequency control, the wind farm can share the active power change along with the synchronous generators. How can a wind farm with HVDC delivery participate in inertia response and load frequency control (LFC)? This is the focus of this paper.

Research has been done on inertia response, active power sharing or LFC for DFIG-based wind farms directly interconnecting to the AC grids [4]–[10]. References [4]–[6] point out that DFIG-based wind farms have negligible contribution to inertia response without additional control. However, study has shown that wind turbine generators have enough kinetic energy to provide inertia support [8]. A supplementary control loop using the derivative of the system frequency as the input signal can be introduced to provide inertia contribution [4], [7]. Improvements on the inertia control loop are reported in [11], [12].

To provide primary frequency control, a feedback loop with the system frequency as the input signal is introduced in the wind generator electrical control system [7]. These approaches, using the derivative and deviation of system frequency as the input signals for inertia contribution and frequency control, have also been used for full converter permanent magnet synchronous generator (PMSG) based wind energy systems [13].

The usual operation of a wind farm is to get maximum wind power for a certain wind speed. Under the above circumstances, the wind farms will have no reserve to contribute more active power when the grid frequency is low. In order to be able to participate in LFC, the wind farms should operate with reserves. Wind farms have pitch controllers to reduce or increase the captured wind power. This feature can help wind farms to participate in power sharing when the system frequency is higher or lower [9], [14].

For wind farms with HVDC delivery to provide inertia contribution and frequency control, the HVDC needs supplementary controls and also the controls at the wind farm converters should be coordinated. Power transferred through an LCC-HVDC link is controlled by the firing angle of the rectifier converter. Hence it is reasonable to introduce a feedback loop with grid frequency and grid frequency deviation as input signals. The next question is: how much should the wind farm with HVDC delivery contribute to inertia response, and how much should the HVDC power transfer or the wind farm exporting be reduced? The inertia response contribution will be determined by the control loop gain [11], [12], which is determined by the kinetic energy the wind turbines possess [12]. In this research, investigation will be made on how to coordinate the controls of the wind farms and the controls of the HVDC converters and what should be the suitable control loop gains.

The inertial and frequency response will be determined by the gain of the inertia control and the droop gain of the frequency control loop. The concept is similar to the frequency droop loop in a synchronous generator. By doing so, the wind farms with HVDC delivery can successfully participate in LFC when the system has a load change. The prime mover-the wind turbine- will change its output through its pitch controller.

In the first three authors' previous letter [15], a simple system with a wind farm with HVDC delivery is participating in LFC via a supplementary frequency droop control. In this paper, detailed modeling and LFC control of LCC-HVDC will

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be presented. What is more, not only LFC but also inertia contribution from wind farms with HVDC delivery will be investigated.

The rest of the paper is organized as follows. Section II presents the inertial response enhancement via HVDC. Section III presents the frequency control loop introduced to the HVDC rectifier. Section IV presents the coordination in wind generators through pitch controllers. Section V presents simulation results by TSAT. Section VI concludes.

II. LCC-HVDC Average Model and Conventional Control

For a monopole, 12-pulse inverter of HVDC-link, the relation of AC/DC voltage and current are shown as below:

$$V_{dr} = \frac{3}{\pi}\sqrt{6}V_{ac}\cos\alpha \quad (1)$$

$$I_{dc} = I_{ac}/\sqrt{2}/0.816 \quad (2)$$

$$V_{dr} = I_{dc}R + V_{di} \quad (3)$$

$$P_{dc} = V_{dr}I_{dc} \quad (4)$$

where the leakage inductance of the converter transformer is neglected; V_{ac} is the rms value of the bus voltage, I_{ac} is the amplitude of the bus current, α is the firing angle of the rectifier, and R is the total resistance of the dc transmission line.

Hence the power through the DC link:

$$P_{dc} = 2.027V_{ac}\cos\alpha. \quad (5)$$

The HVDC delivering power is related with the firing angle of the rectifier. The larger the firing angle, the less the delivered power. Hence in order to improve the delivering power on a HVDC link, the firing angle should be reduced. Since the dc power is proportional to the dc current. A negative feedback control can be designated to adjust the firing angle based on the dc current measurement.

The widely used control scheme of the HVDC-link is constant power control as shown in Fig. 1 [16], where the current order is determined by the power order divided by the measured dc voltage. The measurement of the dc current is then compared with the current order and the error is passed through a proportional integral controller to generate the firing angle order.

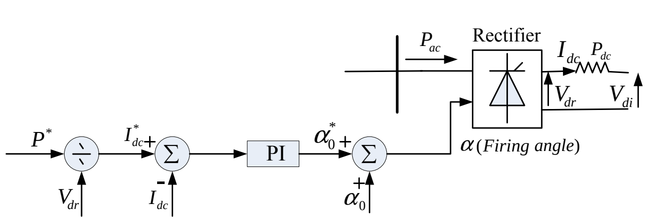

Fig. 1. Constant power control diagram.

III. Inertial response enhancement and frequency droop control via HVDC

A. Inertial response enhancement

To let the HVDC converter provide electrical inertia, the following scheme is designated as shown in Fig. 2. The differential of the system frequency is obtained and the power order is modified.

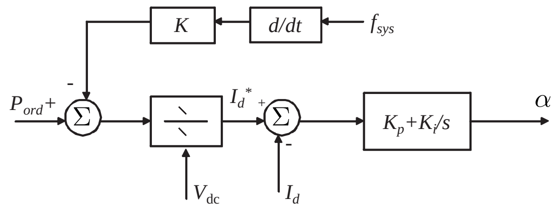

Fig. 2. Control loop for HVDC rectifier with enhanced inertia loop.

The benefit of the inertia enhancement loop can be explained by the following simple system where a wind farm with HVDC delivery is connected with a system with aggregated inertial H_{sys} shown in Fig. 3.

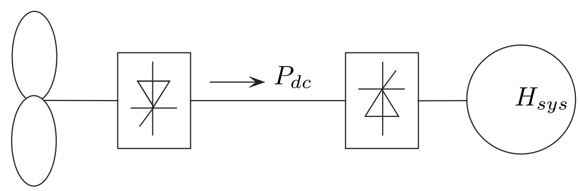

Fig. 3. A wind farm with HVDC delivery connected to a system with aggregated inertia H_{sys}.

The dynamics of the system frequency f_{sys} in pu can be written as:

$$2H_{sys}\frac{df_{sys}}{dt} = P_{m,sys} - P_{e,sys} + P_{dc} \quad (6)$$

where $P_{m,sys}$ is the equivalent prime mover power of the system, $P_{e,sys}$ is the equivalent generation output of the system. The HVDC will feed the system power. Assuming there is that there is no power loss in HVDC converters, we can assume the fed in power from the HVDC is P_{dc}. With the inertia enhancement control, P_{dc} can be said to have the following dynamics:

$$P_{dc} = P_{ord} - K\frac{df}{dt}. \quad (7)$$

(6) and (7) lead to the following dynamics of the system frequency:

$$2(H + \frac{K}{2})\frac{df_{sys}}{dt} = P_{m,sys} - P_{e,sys} + P_{ord}. \quad (8)$$

From (8), observation can be made that through the inertial enhancement control, the entire inertia of the system with wind generation will be improved. In another words, wind generation with HVDC delivery is now contributing to the system inertia. A larger inertia indicates a less significant transient frequency response during disturbances.

In our design, transfer function $\frac{s}{1+sT}$ is used to replace $\frac{d}{dt}$. The time constant T is chosen to be 0.01 s in order not to introduce any artificial delays and attenuation. The gain K reflects the inertia constant of the DFIG turbines.

B. Frequency droop control

In order to let wind farms participate active power sharing, a frequency droop is introduced to the HVDC rectifier control loop (Fig. 4). The idea is same as the frequency droop in the turbine-governor in a synchronous generator.

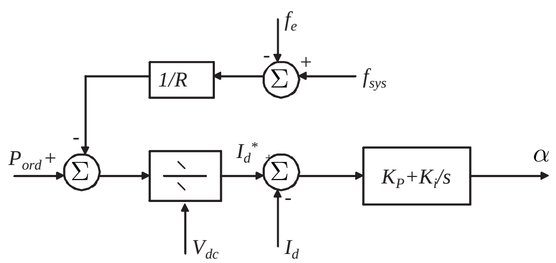

Fig. 4. Control loop for HVDC rectifier.

By introducing a frequency droop loop into the HVDC rectifier control loop, the total system frequency change will be reduced.

$$\Delta f = \frac{-\Delta P}{\frac{1}{R_1} + \frac{1}{R_2} + ... + \frac{1}{R_n} + \frac{1}{R_{HVdc}}} \tag{9}$$

where n is the number of the synchronous generators. If the system has a high penetration of wind power, it will be necessary to have frequency droop in the HVDC loop. Otherwise frequency change due to the load change will be too much.

IV. COORDINATION IN WIND GENERATION

Without HVDC interface, DFIG-based variable speed wind generators use supplementary control in torque or power control loop at rotor side converters for inertia and frequency regulation [4], [7]. With HVDC interface and the supplementary inertia and frequency regulation loops at HVDC rectifier side, no additional control loops will be applied at DFIGs. This is because that the purpose of these control loops is to adjust output power from the wind generators, whether the control loops are applied at HVDC converters or DFIG converters, the ultimate purposes are the same.

To coordinate with the inertia and frequency regulation loops in the HVDC interface, the mechanical power of a wind turbine should match the delivered power to HVDC. The following paragraphs will discuss the relationship of the mechanical power, the blade angle and the rotor speed. Insights of coordination in wind generation will be given.

The GE developed multi-megawatt commercial variable speed wind turbine (1.5 MW) is used in this study and the control block diagram of the wind turbine is shown in Fig. 5.

The extracted wind power can be expressed as (from [17])

$$P_w = \frac{\rho}{2} A_r V3_w C_p(\lambda, \theta) \tag{10}$$

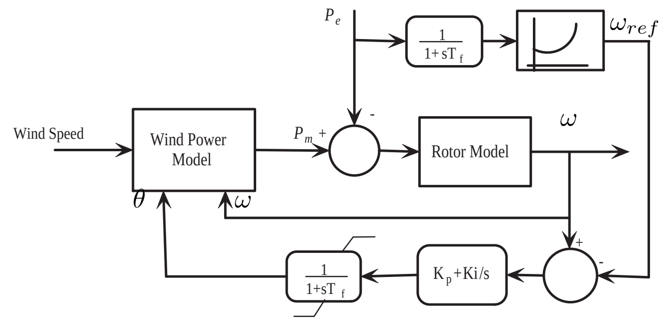

Fig. 5. Block diagram of a wind turbine.

where ρ is the air density in kg/m^3, A_r is the area swept by the rotor blades in m^2, v_w is the wind speed in m/sec, and C_p is the power coefficient (function of λ - tip ratio (v_{tip}/v_w), and θ - pitch angle in degrees).

The power setting of the HVDC line will be changed should the system has a load or generation change. HVDC control makes the power delivered from the wind farm decrease or increase. The mechanical power from the wind turbines will match the change. Pitch controllers in wind farms have the ability to adjust the blade angle θ and further the extracted wind power. Assuming that the wind farms are not operated at the maximum power point, then, when the power delivered through the HVDC increases, the pitch controller should reduce blade angles to extract more wind power.

Pitch controllers use the rotating speed of the wind turbines as input signals (Fig. 5) [17]. If there is unbalance between the mechanical power and the delivered power, the rotating speed will change. Pitch controllers sense the speed change and regulate the blade angle.

Meanwhile, a changing power output impacts the speed reference and hence the rotating speed of wind generators will change which will also affect the extracted wind power. The reference speed (ω_{ref}) is generated for maximum power tracking based on the measured electric power (P_e). When P_e is greater than 75% of the rated power, $\omega_{ref} = 1.2$ pu. When P_e is less than 75% of the rated power,

$$\omega_{ref} = -0.67P_e^2 + 1.43P_e + 0.51. \tag{11}$$

The graphic expression of the relationship between P_e and ω_{ref} is shown in Fig. 6:

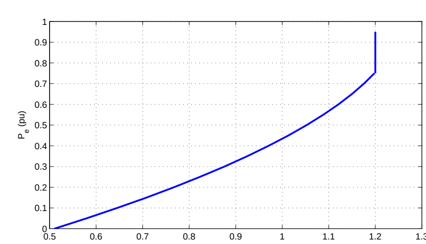

Fig. 6. Reference speed versus electric power output from a wind generator.

Following a drop of system frequency, the HVDC increases its delivered power. The increased electric power from the wind generator results in an increased speed reference. Hence the rotating speed will increase while the blade pitch angle will decrease and the extracted wind power will increase to match the electric power.

V. Simulation Results and Discussion

In the study system in Fig. 7, a wind farm (606 turbines and 1.5 MW capacity per turbine. Total rated capacity: 909 MW) is connected to a two-area four-synchronous generator system via a LCC HVDC link. The four synchronous generators were equipped with IEEE Type 2 speed governors [**?**]. No automatic generator control (AGC) is modeled in these generators. The GE developed current-source DFIG wind farm model [17] is used in this paper. The wind speed is assumed to be constant (14 m/s) and the initial HVDC power setting equals the wind farm output generation. The output of the wind farm is well below its capacity. Hence the wind farm can increase or decrease its output power. The load frequency control and frequency droop loops will be modeled and tested.

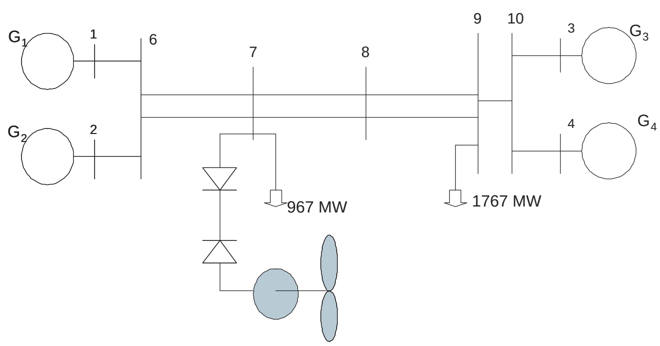

Fig. 7. The study system.

In the AC system, 600 MW generation is tripped. Without any inertia enhancement and frequency droop modeled in the HVDC rectifier, the system has a frequency drop 1.3 Hz. During the transient period, the frequency of Generator 1 can drop to 58.1 Hz. With the inertia enhancement control, and set the gain $K = 100\frac{MW}{Hz}$, the frequency of Generator 1 will drop to 58.4 Hz.

A. Discussion on inertial enhancement results

The gain of the inertia enhancement control will impact the transient response of the system frequency. With a larger gain, more inertia will be contributed to the system and the less the system frequency deviation during the transient period. However, it should not be set out of the limit of the wind turbine's own inertia. The inertia of the wind turbines in this study is $H = 4.94$ pu for each turbine. For the aggregated wind farm which is equivalence to a single DFIG with a capacity of 909 MW, the aggregated inertia is 4.94 pu as well. In the study case, the power base is chosen to be 100 MW. Hence the inertia of the wind farm is $4.94 * \frac{909}{100} = 44.9$ pu. The gain should be at most $2H$ (89.8 pu) . Since the nominal frequency is 60 Hz and the power base is 100 MW, the maximum gain in MW per Hz will be $K = 89.8pu\frac{100MW}{60Hz} = 150\frac{MW}{Hz}$. In this study, K is chosen to be $100\frac{MW}{Hz}$ and the simulation results are shown in Fig. 8.

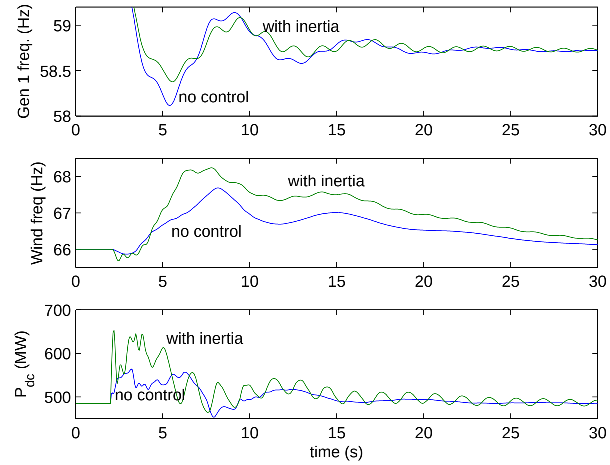

Fig. 8. Comparison of the dynamic responses of the system frequency, wind speed and P_{dc}.

Inertia enhancement control will reduce the frequency deviation during the transient period. Dynamic responses of the frequency of the synchronous generator 1, wind generator and the power delivered through the HVDC link P_{dc} are shown in Fig. 8. It is observed from Fig. 8 that about 100 MW more power supply can be supplied to the HVDC link during the transient period due to the inertia enhancement control. As a result, the frequency deviation during transient period is reduced by about 15%.

For the beginning 2-3 seconds, it is observed that the wind speed drops. During that period of time, the system frequency drops while the power from the wind turbines P_m can be assumed as constant. The electric power from the wind farm P_e increases since $P_e = P_{dc}$ and the dc power P_{dc} increases due to the inertial enhancement control. Thus the wind speed drops and the kinetic energy released from the wind blades supplies the temporary demand increase.

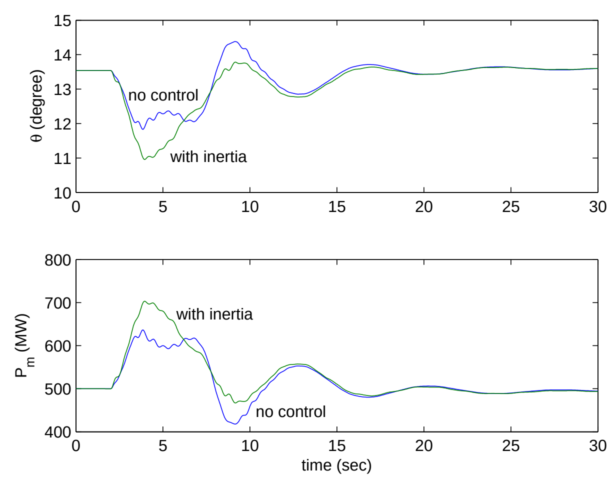

Fig. 9. Comparison of the dynamic responses of the pitch angle and wind power P_m.

After the initial period, the pitch controller will work and the pitch angle will be reduced. The mechanical power P_m from the wind turbines will be adjusted according to wind power, blade pitch angle and the rotating speed relationship. The higher the rotating speed, the more the wind power be extracted. The responses of the pitch angle and the wind power are shown in Fig. 9.

B. Frequency droop

With a frequency droop introduced in the HVDC rectifier control loop, the system frequency at steady state will be improved. Two droop values are tested in simulations. The system frequency drop, active power sharing through the HVDC based on computation (9) are shown in Table I. Simulation results are shown in Figs. 10 and 11. The computed results agree with the simulation results well.

TABLE I
SYSTEM DROP, ACTIVE POWER SHARING DUE TO VARIOUS DROOP VALUES

System	Frequency	Active Power Sharing
without HVDC droop	58.72 Hz	0 MW
with droop $1/R_{HVDC} = 250$	59.18 Hz	204 MW
with droop $1/R_{HVDC} = 125$	59.0 Hz	120 MW

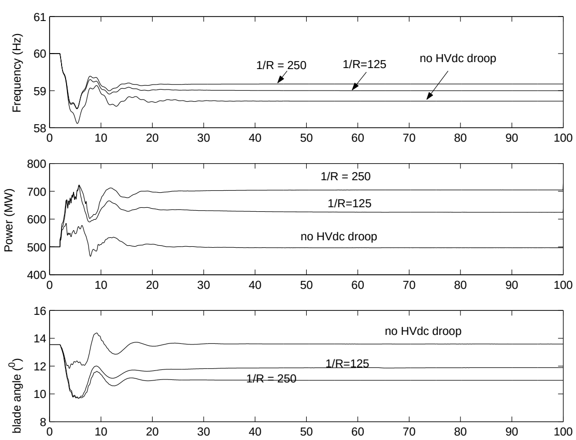

Fig. 10. Wind generator power output and system frequency.

C. With both inertia enhancement and frequency droop

Ultimately, both inertia enhancement and frequency droop will be applied to HVDC converters. The purpose is to have wind farms with HVDC delivery not only contribute to the system inertia but also contribute to load sharing. A comparison of the system without any of the control and with both control is shown in Figs. 12-13.

VI. CONCLUSION

This paper presents a method to help wind farms with HVDC delivery partqicipate in inertia response and load frequency control or active power sharing during system load or generation change. The paper has demonstrated the effectiveness of an inertia enhancement and a frequency droop

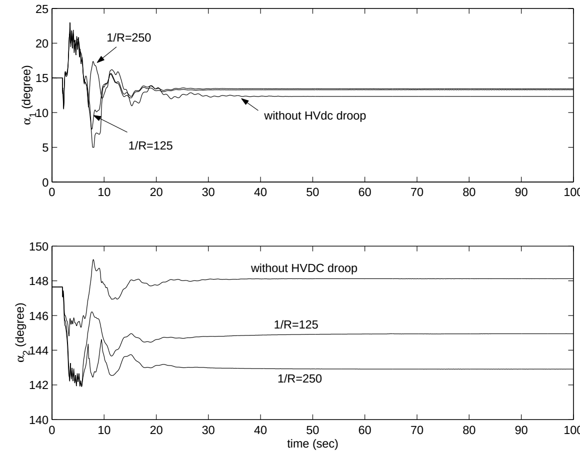

Fig. 11. HVDC converter firing angles.

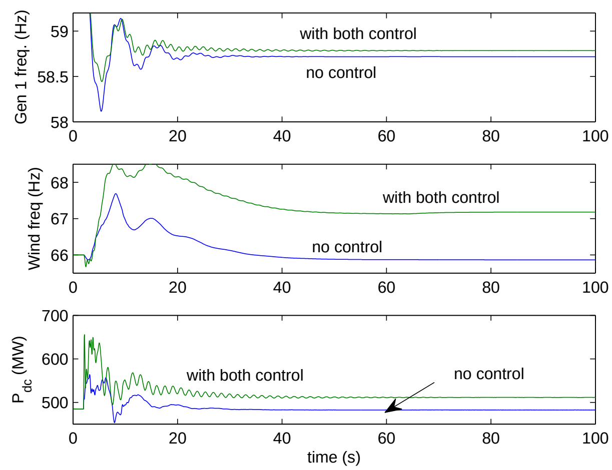

Fig. 12. Dynamic responses of the frequency of Gen 1, Wind Gen and P_{dc}. a) no control; b) with both inertia enhancement $K = 100$ MW/Hz and frequency droop $R = 50$ MW/Hz.

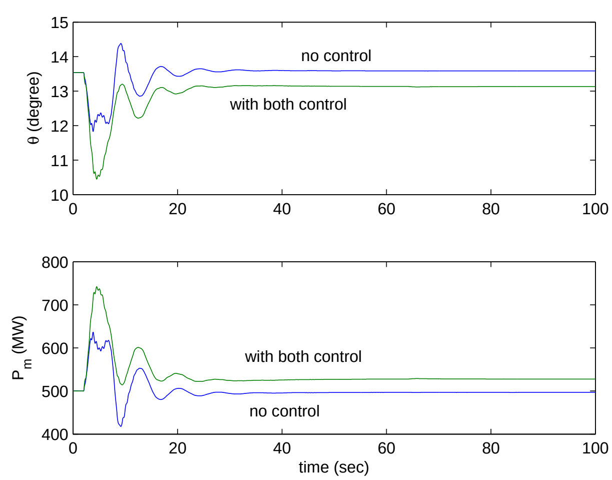

Fig. 13. Comparison of the dynamic responses of the pitch angle and wind power P_m.

in HVDC rectifier control loop. With both controls, wind farms can participate the inertia response, reduce the deviation of the system frequency at transient period and steady state, and share the active power change of the AC system.

APPENDIX

Parameters of the wind generator:

Parameters of the two-area system:

REFERENCES

[1] D. Xiang, L. Ran, J. R. Bumby, P. J. Tavner, and S. Yang, "Coordinated control of an HVDC link and Doubly Fed Induction Generators in a large offshore wind farm," *IEEE Trans. Power Del.*, vol. 21, no. 1, pp. 463–471, Jan 2006.

[2] R. Li, S. Bozhko, and G. Asher, "Frequency control design for offshore wind farm grid with LCC-HVDC link connection," *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1085–1092, May 2008.

[3] S. V. Bozhko, R. Blasco-Gimenez, R. Li, J. C. Clare, and G. M. Asher, "Control of offshore dfig-based windfarm grid with line-commutated hvdc connection," *IEEE Trans. Energy Convers.*, vol. 22, no. 1, pp. 71–78, Mar 2007.

[4] J. Ekanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," *IEEE Trans. Energy Convers.*, vol. 19, no. 4, pp. 800–802, Dec. 2004.

[5] G. Lalor, A. Mullane, and M. O'Malley, "Frequency control and wind turbine technologies," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1905–1913, Nov. 2005.

[6] A. Mullane and M. O'Malley, "The inertia response of induction machine based wind turbines," *IEEE Trans. Power Syst.*, vol. 20, no. 4, pp. 1496–1503, Nov. 2005.

[7] J. Morren, S. 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.

[8] P.-K. Keung, H. B. P. Li, and B. T. Ooi, "Kinetic energy of wind-turbine generators for system frequency support," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 279–287, Feb. 2009.

[9] R. G. D. Almeida and J. A. P. Lopes, "Participation of doubly fed induction wind generators in system frequency regulation," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 944–950, Aug. 2007.

[10] T. T. N.R. Ullah and D. Karlsson, "Temporary primary frequency control support by variable speed wind turbines - potential and applications," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 601–612, May 2008.

[11] J. Mauricio, A. Marano, A. Gomez-Exposito, and J. M. Ramos, "Frequency regulation contribution through variable-speed wind energy conversion systemsr," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 173–180, Feb. 2009.

[12] M. Kayikci and J. 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.

[13] J. Conroy and R. Watson, "Frequency response capability of full converter wind turbine generators in comparison to conventional generation," *IEEE Trans. Power Syst.*, vol. 23, no. 2, pp. 649–656, May 2008.

[14] M. Mokadem, V. Courtecuisse, C. Saudemont, B. Robyns, and J. Deuse, "Fuzzy logic supervisor-based primary frequency control experiments of a variable-speed wind generator," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 407–417, Feb. 2009.

[15] L. Fan, Z. Miao, and D. Osborn, "Wind farms with hvdc delivery in load frequency control," *IEEE Trans. Power Syst.*, to appear.

[16] P. Kundur, *Power System Stability and Control*. McGraw Hill, 1994.

[17] "Modeling of GE wind turbine-generators for gid studies," GE Energy, Schenectady, NY, Tech. Rep., Mar. 2005.

[18] "Transient stability analysis tool (tsat) manual," Power Tech Lab, Vancouver, Canada, Tech. Rep., 2007.

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