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# Frequency Regulation with Wind Power Plants

Badrul H. Chowdhury, *Senior Member, IEEE*, Hong T. Ma, *Student Member, IEEE*

**Abstract**— A new frequency regulation scheme is developed for the wind turbine/generator/converter trio that will provide the capability to participate in restoring frequency in a way similar to the droop response of conventional generators. Output active power adjustment can be realized by both converter and pitch angle control in addition to inertial response of the wind turbine. This helps in maintaining instantaneous power balance as well as in longer term frequency regulation.

**Index Terms**—windfarm, pitch angle control, inertial control, converter control, double-fed induction generator.

## I. INTRODUCTION

WITH the steadily increasing penetration of wind turbine into the grid, grid inertia that is derived from conventional generators is reduced. Thus, primary frequency control contribution from wind turbines and windfarms is required for maintaining the same level of system stability. In the most common model of a wind turbine equipped with a double-fed induction generator (DFIG), the output power and system frequency are decoupled. The rotor side converter is used to control the generator output power and voltage (or reactive power) measured at the grid terminals. The grid side converter is used to generate or absorb active power from grid to keep DC link voltage constant. New methods are currently being discussed in the literature that will provide some form of frequency regulation capability from these wind turbines: energy release from wind rotor blades [1-3] and de-loading of optimal active power extraction from wind [4-8].

Compared to the steam valve of a synchronous generator, the energy source of wind is not controllable and thus primary frequency control is difficult to realize. In the de-loading process, the induction generator is forced to have some active power reserves for grid frequency contribution during a system power imbalance. This sub-optimal operating point, based on wind and rotor speeds determines how much the generator is de-loaded.

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On the other hand, the wind turbine rotor blades have a significant amount of stored rotor kinetic energy which can be used to support system frequency for short amounts of time. For a 2 MW machine, the moment of rotor inertia is approximately six times that of the conventional electrical generator.

## II. INERTIAL RESPONSE

The inertial response control loop is added to the DFIG active power control loop, as shown in Fig. 1. The intent is that when system frequency changes, not only do the synchronous generators respond to this change, the wind plant also quickly changes its output active power to share in the frequency restoration process during such short term frequency fluctuations. The output active power reference is predefined for different wind speeds. With the given DFIG rotor speed, optimal power signal  $P_{\text{optimal}}$  is obtained and compared with measured output electrical power. The error signal is regulated by the rotor side converter controller to obtain the required rotor current  $I_{qr}$ . The inertial control loop is responsible for sending additional power regulation signal  $\Delta P_{\text{ref}}$  to the rotor side converter controller. When the system load increases leading to a frequency drop, the inertial control loop sends additional active power  $\Delta P_{\text{ref}}$  to the DFIG active power reference  $P_{\text{ref}}$ .

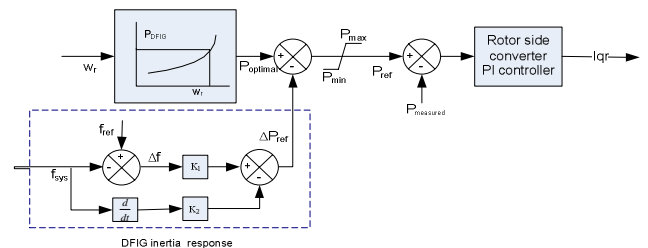


Fig. 1. Inertial controller schematic for the DFIG

## III. PITCH ANGLE CONTROL FOR LONG-TERM FREQUENCY REGULATION

Pitch angle control of the wind turbine is designed much like governor control of synchronous machine in this part to make the wind power plant have a long term frequency regulation capability. The DFIG, in this case, should operate near but not on the optimal maximum active power operation point as before so that the turbine can extract more mechanical power from wind flow as system frequency drops

(considering pitch change rate  $[-2 \sim 2]$  degree/s). This non-optimal operation of the wind turbine is called de-loaded operation.

As described in Fig. 2, the pitch angle is regulated as  $\beta_{ref} = \beta_0 + \Delta\beta$ , where  $\Delta\beta = K_1 (f_{sys} - f_{ref})$  and  $f_{ref}$  is the steady state system frequency, and  $f_{sys}$  is the measured system frequency. The DFIG droop characteristic is considered the same as that of a synchronous machine and shown in Fig. 3, so that while system load increased, the DFIG can share some load increase as synchronous machine. To restore system frequency to 60Hz, the load reference should also be changed. With reference electrical power curve  $P_{ref}$  and mechanical power curve with different pitch angles, one can get the pitch angle  $\beta_0$  with specific active powers from Fig. 4. The output electrical power reference curve can be predefined in several ways. Here, we use the optimal output reference line for different wind speed as before. Determining the best reference curve for frequency control will be investigated in the future.

The initial pitch angle  $\beta_0$  can decide how much wind power can be de-loaded. A trial and error method may be tried. Here, output active power with 0.3 MW is reserved by setting pitch angle  $\beta_0 = 3^\circ$ . While the load is increased at bus 2, the load reference simply drives the pitch angle  $\beta_0$  to  $0^\circ$  to test the maximum dynamic response to system frequency change.

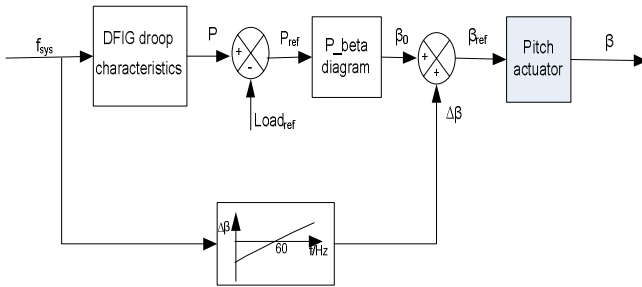


Fig. 2. Pitch angle control schematic.

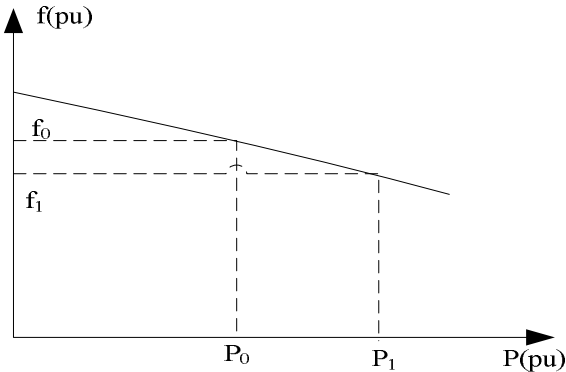


Fig. 3. The DFIG droop characteristic.

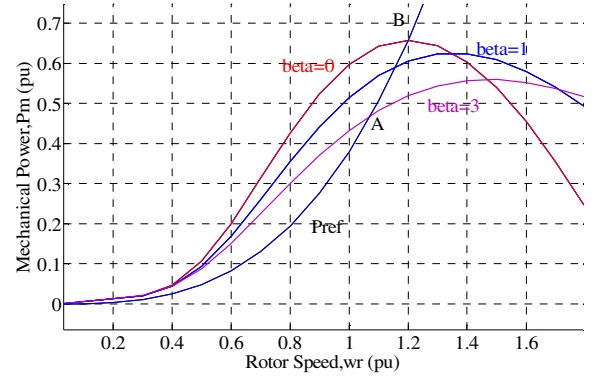


Fig. 4. Mechanical power of the wind turbine generator for different pitch angle and electrical power reference.

#### IV. TEST SYSTEM

The simulation results are based on a four bus test system with system parameters presented in the appendix. The test system is shown in Fig. 5. The synchronous generator present on bus 1 is equipped with a governor and an exciter. Bus 2 is the load bus; load change on this bus lead to system frequency change. The wind turbine with the associated DFIG and converter is located at bus 4. A constant wind speed is assumed for the simulations.

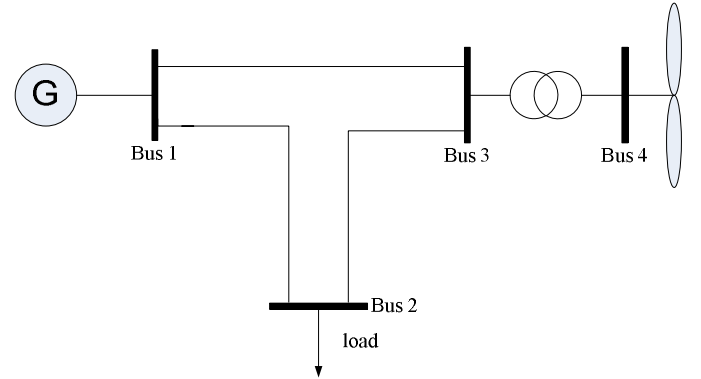


Fig. 5. A 4-bus test system.

#### V. RESULTS

##### A. Case I: No Frequency Control

In this part, the load on bus 2 is increased from 2.78 MW to 3.08 MW at  $t = 2s$  as shown in Fig. 6(a). The wind speed is assumed constant at 12m/s and the pitch angle is preset at 3 deg. As expected, the system frequency dips as shown in Fig. 6(b). Without frequency control on the wind plant, the output active power of the DFIG remains constant at 0.76 MW and the rotor speed also remains constant. The increased load is picked up only by the synchronous machine by means of governor control as seen in Figs. 6(c) and 6(d). As obvious, system frequency is regulated only by the synchronous machine at bus 1. However, because of the slow nature of governor response, system frequency dropped from 60 Hz to 58.5 Hz at 4.7s.

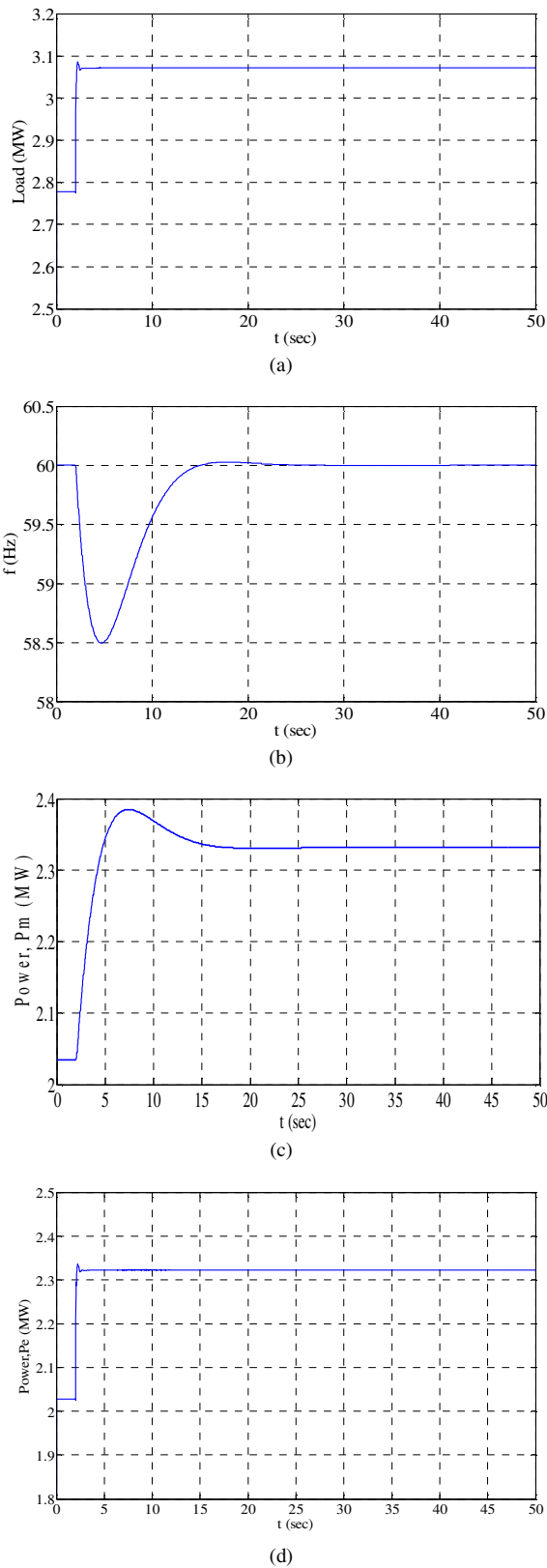


Fig. 6 No frequency control.  
 (a) System load change (b) System frequency response (c) Mechanical power of generator at bus 1 (d) Output active power of generator at bus 1.

### B. Case II: Inertial Response of the Wind Turbine

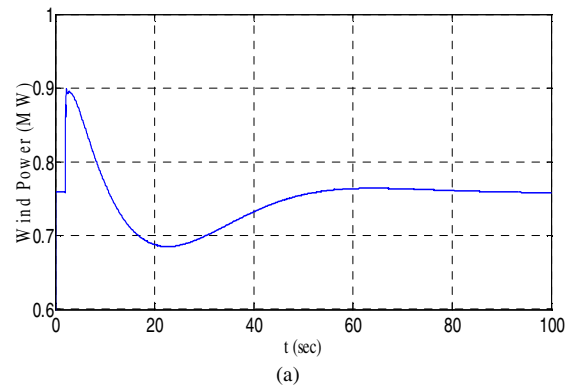
Similar to Case I, the load on bus 2 is increased from 2.78 MW to 3.08 MW at 2s as shown in Fig. 6(a). With inertial response control loop, the DFIG increases its output active power from 0.76 MW to 0.90 MW as shown in Fig. 7(a). With the help of the DFIG, the synchronous generator active power output only changes from 2.03 MW to 2.18 MW shown in Fig. 7(b) compared with Case I results where the change is from 2.03 MW to 2.32 MW. With the help of the rapidly increased electrical output active power from the DFIG, the maximum frequency drop of the synchronous machine is changed from 58.5 to 59.1 Hz as shown in Fig. 7(c). The figure shows inertia control on DFIG obviously helps alleviate short term frequency stability and security concerns.

For constant wind speed and no pitch angle control, the optimal mechanical power extracted from air flow is commonly expressed by the following equation:

$$P_w = \frac{\rho}{2} A_r V_w^3 C_p(\lambda, \beta) \quad (1)$$

where  $P_w$  is the mechanical power wind turbine extract from the airflow,  $\rho$  is the air density,  $C_p$  is the performance coefficient or power coefficient,  $\lambda$  is the tip ratio  $v_t/v_w$ , the ratio between blade tip speed  $v_t$  and the wind speed upstream the rotor  $v_w$ ,  $\beta$  is the blade pitch angle.

While the output electrical active power is suddenly increased, the DFIG mechanical power is smaller than the electrical power and the rotor speed will drop as shown in Fig. 7(d). Because of the drop of rotor speed, both mechanical power and electrical power becomes smaller as shown in Fig. 7(e) and Fig. 7(a). At 20s, the DFIG outputs the smallest active power and the synchronous machine has to output the maximum power of 2.4 MW, which is larger than the total of load increase (0.3 MW) and initial power (2.03 MW) ( $2.4 \text{ MW} > 2.03 \text{ MW} + 0.3 \text{ MW}$ ). The frequency response with inertial control (60s) shown as Fig. 7(c) is much longer than constant active power output (15s) shown in Fig. 6(b).



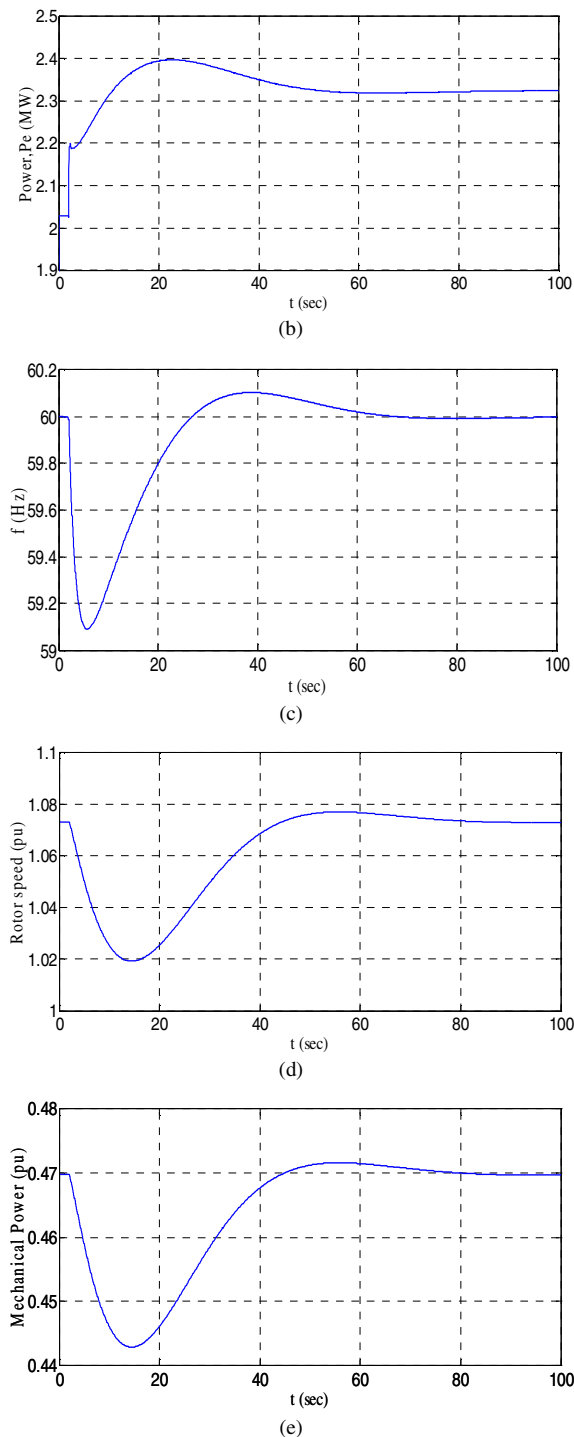


Fig. 7. Inertial control of the wind turbine.

(a) DFIG output active power (b) Output active power of synchronous generator (c) System frequency (d) Rotor speed of DFIG (e) DFIG mechanical power.

Based on the analysis, one can draw the conclusion that the wind plant's inertial response control can help improve the frequency (from 58.5 to 59.1 Hz), but the trade-off is that the DFIG takes a long time to reach the steady operation point. The main reason is that with a larger electrical power, the rotor speed will decrease, which results in less mechanical power extracted from the air flow. There is some time as

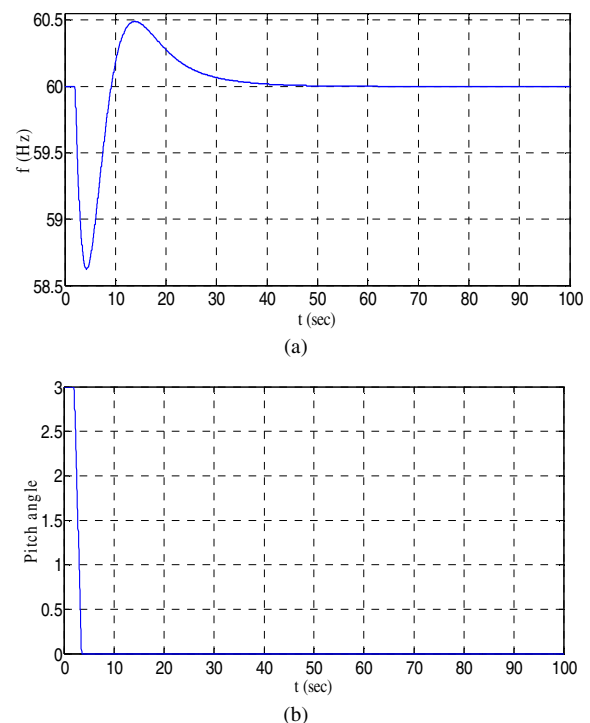
shown in Fig. 7(a) around 20s DFIG can only output less power than initial active power to restore steady operation.

### C. Case III. Pitch Angle Control of DFIG

While the load on bus 2 is increased by 0.3 MW as shown in Fig. 6(a), the dropping system frequency as shown in Fig. 8(a) will trigger the pitch angle control of the wind plant. Because of the limitation on pitch angle change rate, pitch angle is changed from  $3^\circ$  to  $0^\circ$  in 1.5s as shown in Fig. 8(b). While pitch angle is changed, the mechanical power of the wind turbine is increased as shown in Fig. 8(c). With reference to the electrical power curve shown in Fig. 4, the DFIG mechanical power is larger than the electrical power. While the operating point shifts from A to B, the rotor speed and electrical power is driven to increase slowly as shown in Figs. 8(d) and 8(e). For the increasing DFIG electrical power and system frequency, the synchronous machine output electrical power and mechanical power both slowly decreases as shown in Fig. 8(f) and 8(g).

Owing to the slow response of the wind plant, the synchronous generator must pick up most of the load increase at the beginning and the lowest system frequency (58.6 Hz) is almost the same as with no pitch angle control (58.4 Hz). While the wind plant output active power slowly increases to the new value of 1.06 MW shown in Fig. 8(e), the synchronous machine output slowly decreases, as seen in Fig. 8(f).

Based on simulation results, we can draw the conclusion that the wind plant can increase its output active power and help in system long time primary frequency control by means of a pre-defined pitch angle control.



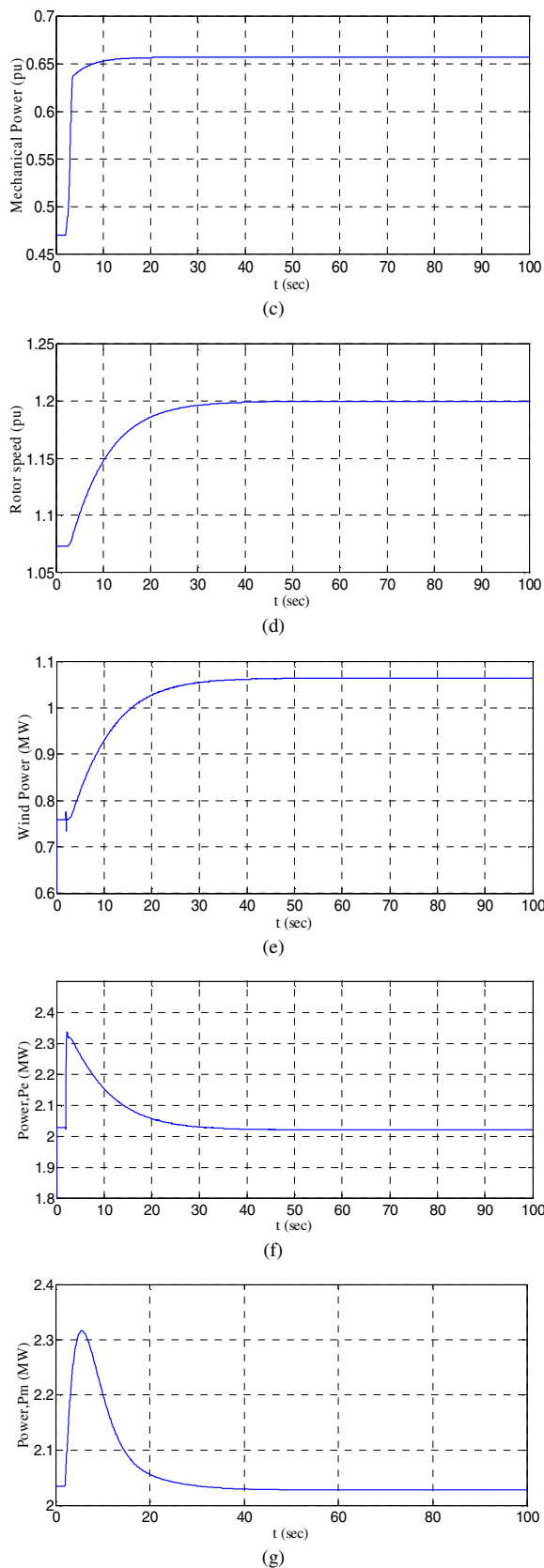


Fig. 8 Pitch angle control of the wind turbine. (a) System frequency. (b) Pitch angle (c) DFIG mechanical power (d) Rotor speed of DFIG (e) DFIG output active power (f) Synchronous generator output active power (g) Synchronous generator mechanical power.

## VI. CONCLUSION

Both the inertial response and the pitch angle control methods are able to help improve the system frequency after a disturbance. With the inertia control strategy, the kinetic energy on the wind turbine assembly can be extracted to help system minimum frequency; however, the trade off is long-term dynamic performance of the wind plant. Pitch angle control requires that the wind turbine be de-loaded. Thus, it can help the system in long time primary frequency control, although it falls short in the initial stages of a frequency change because of the slow mechanical response.

## VII. APPENDIX

### DFIG parameters

Nominal power  $S_n=1.5/0.9$  MVA, Rated voltage  $V_n=575$  V, Rated slip  $s=0.2$ , Inertia constant  $H=5s$ ,  $R_s=0.00706$  pu,  $L_s=0.171$  pu,  $R_r=0.005$  pu,  $L_r=0.156$  pu,  $L_m=2.9$  pu

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## IX. BIOGRAPHIES

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