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Dynamic Modeling and Control of Doubly Fed Induction Generators Driven by Wind Turbines

Wei Qiao, *Member, IEEE*

Abstract--Two different models are presented and developed in PSCAD/EMTDC to represent a variable-speed wind turbine equipped with a doubly fed induction generator (DFIG). One is the most detailed switching-level (SL) model. The other is a simplified fundamental-frequency (FF) model. The effect of different shaft system representations on the dynamic behavior of the wind turbine generator (WTG) system and the issue of damping low-frequency torsional oscillations are investigated. Dynamic and transient simulation studies are carried out to compare two models with different shaft system representations. Results show that the FF model is sufficient while the lumped-mass shaft model is insufficient to represent the dynamic behavior of the WTG. The FF model with the two-mass shaft representation is therefore recommended to represent the DFIG wind turbines for power system dynamic and transient studies.

Index Terms--Doubly fed induction generator, dynamic model, fundamental-frequency model, shaft system, switching-level model, torsional oscillation, wind turbine

I. INTRODUCTION

WORLDWIDE concern about the environmental pollution and a possible energy crisis has led to increasing interest in technologies for generation of clean and renewable electrical energy. Among various renewable energy sources, wind power is the most rapidly growing one.

During the last decade, the concept of a variable-speed wind turbine equipped with a doubly fed induction generator (DFIG) has received increasing attention due to its noticeable advantages over other wind turbine generator (WTG) concepts [1]-[4]. In the DFIG concept, the induction generator is grid-connected at the stator terminals, but the rotor terminals are connected to the grid via a partial-load variable frequency AC/DC/AC converter (VFC). The VFC only needs to handle a fraction (25-30%) of the total power to achieve full control of the generator.

Much research effort has gone into modeling the DFIG wind turbines and studying their impact on the dynamic performance of the power system [2]-[10]. In these works, the power electronic converter models are simplified as controlled ideal voltage-sources or current-sources. This permits large integration time-steps during transient simulations, which is essential in the representation of large networks. However, in the DFIG wind turbine system, the VFC and its power electronics (IGBT-switches) are the most sensitive part to grid

disturbances. The converter action might determine the operation of the WTG during the transient disturbances in the power grid [2]. A question that arises is whether the simplified models of the VFC adequately represent its behavior during transient conditions.

At the most detailed level, the operation of individual IGBT switches is fully represented [11]. This level of modeling is useful for the detailed study of the power converter and its control strategy, and confirming the results of various simplified models. However, since the IGBT components in the VFC are switched on and off at a high frequency (several kHz or higher), it requires a very small simulation time-step (typically 10-50 μ s) to accurately represent the PWM waveforms. This detailed switching-level (SL) model uses excessive computation time and is unsuitable for dynamic and transient study of large power systems with a high-level penetration of DFIG wind turbines.

This paper presents two different models developed in PSCAD/EMTDC to represent a DFIG wind turbine. One is a detailed SL model, in which the VFC is fully represented by individual IGBT switches with a dc-link capacitor. The other is a simplified fundamental-frequency (FF) model, in which the VFC is represented by two current-controlled voltage sources but takes into account the dc-link dynamics. The other parts of the WTG system, including the wind turbine, shaft system, induction generator, and control system, are modeled or designed with the same level of detail for both the SL and FF models. The effect of different shaft system representations and the issue of damping low-frequency torsional oscillations are also investigated. Simulation studies are carried out for a 3.6 MW DFIG wind turbine to compare the two models with different shaft system representations.

II. WIND TURBINE AND DFIG MODEL

The basic configuration of a DFIG wind turbine is shown in Fig. 1. The wind turbine is connected to the induction generator through a mechanical shaft system, which consists of a low-speed shaft and a high-speed shaft and a gearbox in between. The wound-rotor induction generator in this configuration is fed from both stator and rotor sides. The stator is directly connected to the grid while the rotor is fed through a VFC. In order to produce electrical power at constant voltage and frequency to the utility grid over a wide operating range from subsynchronous to supersynchronous speeds, the power flow between the rotor circuit and the grid

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must be controlled both in magnitude and in direction. Therefore, the VFC consists of two four-quadrant IGBT PWM converters (a rotor-side converter RSC and a grid-side converter GSC) connected back-to-back by a dc-link capacitor. The crow-bar circuit is used to short-circuit the RSC in order to protect it from over-current in the rotor circuit during transient disturbances.

The operation of the DFIG wind turbine is regulated by a control system, which generally consists of two parts: the electrical control of the DFIG and the mechanical control of the wind turbine blade pitch angle. Control of the DFIG is achieved by controlling the VFC, which includes control of the RSC and control of the GSC, as shown in Fig. 1.

Fig. 1. Configuration of a DFIG wind turbine connected to a utility grid.

A. Modeling of the Wind Turbine Aerodynamics

The aerodynamic model of a wind turbine can be characterized by the well-known $C_p\lambda\beta$ curves. C_p is the power coefficient, which is a function of both tip-speed-ratio λ and the blade pitch angle β . The tip-speed-ratio λ is defined by

$$\lambda = \frac{\omega_t R}{v_w} \quad (1)$$

where R is the blade length in m, ω_t is the wind turbine rotational speed in rad/s, and v_w is the wind speed in m/s, and the numerator ($\omega_t R$) represents the blade tip speed in m/s of the wind turbine. The $C_p\lambda\beta$ curves depend on the blade design and are given by the wind turbine manufacturer. In this paper, the mathematical representation of the C_p curves used for the 3.6 MW wind turbine is obtained by curve fitting, given by [12],

$$C_p(\beta, \lambda) = \sum_{i=0}^4 \sum_{j=0}^4 \alpha_{ij} \beta^i \lambda^j \quad (2)$$

where the coefficients α_{ij} are given in Table 4-7 of [12].

Given the power coefficient C_p , the mechanical power that the wind turbine extracts from the wind is calculated by [2]:

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

Where ρ is the air density in kg/m³, $A_r = \pi R^2$ is the area in m² swept by the rotor blades. At a certain wind speed, there is a unique wind turbine rotational speed to achieve the maximum power coefficient, C_{pm} , and thereby the maximum mechanical (wind) power. If the wind speed is below the rated value, the wind turbine operates in the variable speed mode, and the rotational speed is adjusted (by DFIG speed control or active power control) such that C_p remains at the C_{pm} point. In this operating mode, the wind turbine pitch control is deactivated and the pitch angle β is fixed. However, if the wind speed

increases above the rated value, the pitch control is activated to increase the wind turbine pitch angle to reduce the mechanical power extracted from the wind.

The wind turbine aerodynamic model is represented by a custom component in PSCAD/EMTDC.

B. Modeling of the Shaft System

The shaft system of the WTG can be represented either by a two-mass system or by a single lumped-mass system [2], [12], [13]. In the two-mass model, separate masses are used to represent the low-speed turbine and the high-speed generator, and the connecting resilient shaft is modeled as a spring and a damper, as shown in Fig. 2. The electromechanical dynamic equations are then given by

$$2H_t p\omega_t = T_m - D_t \omega_t - D_{tg}(\omega_t - \omega_r) - T_{tg} \quad (4)$$

$$2H_g p\omega_r = T_{tg} + D_{tg}(\omega_t - \omega_r) - D_g \omega_r - T_e \quad (5)$$

$$pT_{tg} = K_{tg}(\omega_t - \omega_r) \quad (6)$$

where $p = d/dt$; ω_t and ω_r are the turbine and generator rotor speed, respectively; T_m and T_e are the mechanical torque applied to the turbine and the electrical torque of the generator, respectively; T_{tg} is an internal torque of the model; H_t and H_g are the inertia constants of the turbine and the generator, respectively; D_t and D_g are the damping coefficients of the turbine and the generator, respectively; D_{tg} is the damping coefficient of the flexible coupling (shaft) between the two masses; K_{tg} is the shaft stiffness. In Fig. 2, N_t/N_g is the gear ratio of the gearbox. The standard multi-mass component model in the PSCAD/EMTDC library is used to model the two-mass system.

As in [3], [5], [7], [10], the shaft system is simply modeled as a single lumped-mass system with the lumped inertia constant H_m , calculated by.

$$H_m = H_t + H_g \quad (7)$$

The electromechanical dynamic equation is then given by

$$2H_m p\omega_m = T_m - T_e - D_m \omega_m \quad (8)$$

where ω_m is the rotational speed of the lumped-mass system and $\omega_m = \omega_t = \omega_r$, D_m is the damping of the lumped system.

Fig. 2. DFIG wind turbine shaft system represented by a two-mass model.

C. Modeling of the Induction Generator

The induction generator in this study is a single-cage wound rotor induction machine. In terms of the instantaneous variables shown in Fig. 1, the stator and rotor equations can be written as follows in matrix form

$$v_{sabc} = r_s i_{sabc} + p \lambda_{sabc} \quad (9)$$

$$v_{rabc} = r_r i_{rabc} + p \lambda_{rabc} \quad (10)$$

Applying synchronously rotating reference frame transformation [14] to (9) and (10), the voltage equations become

$$v_{ds} = r_s i_{ds} - \omega_s \lambda_{qs} + p \lambda_{ds} \quad (11)$$

$$v_{qs} = r_s i_{qs} + \omega_s \lambda_{ds} + p \lambda_{qs} \quad (12)$$

$$v_{dr} = r_r i_{dr} - (\omega_s - \omega_r) \lambda_{qr} + p \lambda_{dr} \quad (13)$$

$$v_{qr} = r_r i_{qr} + (\omega_s - \omega_r) \lambda_{dr} + p \lambda_{qr} \quad (14)$$

where ω_s is the rotational speed of the synchronous reference frame, ω_r is the rotor speed, and the flux linkages are given by

$$\lambda_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr} \quad (15)$$

$$\lambda_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr} \quad (16)$$

$$\lambda_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr}) = L_m i_{ds} + L_r i_{dr} \quad (17)$$

$$\lambda_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) = L_m i_{qs} + L_r i_{qr} \quad (18)$$

where $L_s = L_{ls} + L_m$, $L_r = L_{lr} + L_m$; L_{ls} , L_{lr} and L_m are the stator leakage, rotor leakage and mutual inductances, respectively.

In order for the rotor mmf to be in synchronism with the stator mmf, the frequency of the rotor current, ω_{rf} , must satisfy the slip frequency constraint

$$\omega_{rf} = \omega_s - \omega_r = s \omega_s \quad (19)$$

The per-unit electromagnetic torque equation is given by

$$T_e = \lambda_{ds} i_{qs} - \lambda_{qs} i_{ds} = \lambda_{qr} i_{dr} - \lambda_{dr} i_{qr} = L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \quad (20)$$

Neglecting the power losses associated with the stator and rotor resistances, the active and reactive stator powers are:

$$P_s = \frac{3}{2} (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (21)$$

$$Q_s = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) \quad (22)$$

and the active and reactive rotor powers are given by

$$P_r = \frac{3}{2} (v_{dr} i_{dr} + v_{qr} i_{qr}) \quad (23)$$

$$Q_r = \frac{3}{2} (v_{qr} i_{dr} - v_{dr} i_{qr}) \quad (24)$$

The PSCAD/EMTDC software library provides the standard model of the wound rotor induction machine, which is used in this study.

D. Modeling of the Variable-Frequency Converter

Two different models are used to represent the dynamics of the VFC, one is a detailed SL model and the other is a simplified FF model.

1) *SL Model*: The VFC is represented by two four-quadrant IGBT PWM converters connected back-to-back by a dc-link capacitor. Both converters are fully represented by individual IGBT switches and the switching frequency is 2 kHz, as shown in Fig. 1. The IGBT switches, dc-link capacitor, and other components of the VFC are built from the standard component models from the PSCAD/EMTDC library

2) *FF Model*: The VFC is simply represented by two current-controlled voltage sources which take into account the dc-link dynamics, as shown in Fig. 3. The RSC injects the current $i_1 = P_r / v_{dc}$ into the dc-link, while the GSC injects $i_2 = P_g / v_{dc}$ into the dc-link. Neglecting the switching and conduction losses in the converters and the power losses in the dc-link, the dc-link dynamics are given by

$$i_{dc} = i_1 - i_2 = C p v_{dc} \quad (25)$$

At steady state, $P_r = P_g$ and $i_1 = i_2$, thereby the dc-link voltage, v_{dc} , is constant. However, when a disturbance occurs, the relationship, $P_r = P_g$, is broken; and the current flowing through the dc-link capacitor, $i_{dc} = i_1 - i_2 \neq 0$, which results in fluctuations of the dc-link voltage v_{dc} .

Fig. 3. FF model of the VFC.

III. DESIGN OF THE CONTROL SYSTEM

The objective of the RSC is to govern both the stator-side active and reactive powers independently; while the objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The GSC control scheme can also be designed to regulate the reactive power. The reactive power control by the RSC and GSC is necessary to keep the voltage within the desired range, when the DF IG feeds into a weak power system with insufficient local reactive compensation. The wind turbine controller controls the pitch angle of the blades, which determine the mechanical power that the turbine extracts from the wind.

A. Design of the RSC Controllers

The RSC control scheme consists of two cascaded control loops. The inner current control loops regulate independently the d -axis and q -axis rotor current components, i_{dr} and i_{qr} , according to some synchronously rotating reference frame. The stator-flux oriented reference frame [14] is the most commonly used one. The outer control loops regulate both the stator active power (or the generator rotor speed) and reactive power independently.

In the stator-flux oriented reference frame, the d -axis is aligned with the stator flux linkage vector λ_s , namely, $\lambda_{ds} = \lambda_s$ and $\lambda_{qs} = 0$. This gives the following relationships

$$i_{qs} = -L_m i_{qr} / L_s \quad (26)$$

$$i_{ds} = L_m (i_{ms} - i_{dr}) / L_s \quad (27)$$

$$P_s = -\frac{3}{2} \omega_s L_m^2 i_{ms} i_{qr} / L_s \quad (28)$$

$$Q_s = \frac{3}{2} \omega_s L_m^2 i_{ms} (i_{ms} - i_{dr}) / L_s \quad (29)$$

$$v_{dr} = r_r i_{dr} + \sigma L_r p i_{dr} - s \omega_s \sigma L_r i_{qr} \quad (30)$$

$$v_{qr} = r_r i_{qr} + \sigma L_r p i_{qr} + s \omega_s (\sigma L_r i_{dr} + L_m^2 i_{ms} / L_s) \quad (31)$$

where

$$i_{ms} = \frac{v_{qs} - r_s i_{qs}}{\omega_s L_m} \quad (32)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (33)$$

Equations (28) and (29) indicate that P_s and Q_s can be controlled independently by regulating the rotor current components, i_{qr} and i_{dr} , respectively. Consequently, the reference values of i_{dr} and i_{qr} can be determined from the outer power control loops.

1) *Design of the Inner Current Control Loops in Fig. 4*: Let

$$v_{dr1} = r_r i_{dr} + \sigma L_r p i_{dr} \quad (34)$$

$$v_{qr1} = r_r i_{qr} + \sigma L_r p i_{qr} \quad (35)$$

representing parts of (30) and (31), then (34) and (35) can be rewritten into a matrix form as

$$p \begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} = -\frac{r_r}{\sigma L_r} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} i_{dr} + \frac{1}{\sigma L_r} \begin{bmatrix} v_{dr1} \\ v_{qr1} \end{bmatrix} \quad (36)$$

Equation (36) indicates that i_{dr} and i_{qr} respond to v_{dr1} and v_{qr1} respectively, through a first-order transfer function without cross-coupling. It is therefore possible to design the following feedback loops and PI controllers

$$v_{dr1} = \left(k_{pr} + \frac{k_{ir}}{s} \right) (i_{dr}^* - i_{dr}) \quad (37)$$

$$v_{qr1} = \left(k_{pr} + \frac{k_{ir}}{s} \right) (i_{qr}^* - i_{qr}) \quad (38)$$

Substituting (37) and (38) into (30) and (31) gives

$$v_{dr} = \left(k_{pr} + \frac{k_{ir}}{s} \right) (i_{dr}^* - i_{dr}) - s\omega_s \sigma L_r i_{qr} \quad (39)$$

$$v_{qr} = \left(k_{pr} + \frac{k_{ir}}{s} \right) (i_{qr}^* - i_{qr}) + s\omega_s \left(\sigma L_r i_{dr} + \frac{L_m^2}{L_s} i_{ms} \right) \quad (40)$$

2) *Design of the Speed Controller:* The shaft system model has a significant impact on the dynamic behavior of the WTG and the design of the speed controller. In terms of (4)-(6), the transfer function from the EM torque, T_e , to rotor speed, ω_r , for the two-mass shaft system (with $D_t = D_g = 0$) is given by

$$\frac{\omega_r}{T_e} = \frac{1}{2(H_t + H_g)s} \frac{1}{s} \frac{2H_t s^2 + D_{tg}s + K_{tg}}{2H_t H_g s^2 + D_{tg}s + K_{tg}} \quad (41)$$

which can be viewed as a lumped-mass system, $1/[2(H_t + H_g)s]$, on the left and a bi-quadratic function on the right. PI controllers are normally designed to control the lumped-mass system. The bi-quadratic function causes instability by altering the phase and gain of the lumped-mass system [15]. On most practical machines, the damping coefficient, D_{tg} , is small so that both the numerator and denominator of the bi-quadratic function exhibit lightly damped torsional oscillation modes, if no specifically designed damping control is present in the WTG control system. The frequencies of these torsional oscillation modes are given by:

$$\omega_1 = \sqrt{\frac{K_{tg}}{2H_t}}, \quad \omega_2 = \sqrt{\frac{K_{tg}}{2H_t H_g / (H_t + H_g)}} \quad (42)$$

where $\omega_1 < \omega_2$. The value of ω_1 is typically less than several Hz on most practical WTG system. In order to improve the damping of the low-frequency torsional oscillations of the two-mass system, the speed controller has to be designed so that the closed-loop system has a sufficiently low bandwidth less than ω_1 . The speed controller acts as a low-pass filter to reduce the gains at oscillating frequencies.

For the lumped-mass model, the transfer function from T_e to ω_m , according to (8) (with $D_m = 0$), is given by

$$\frac{\omega_m}{T_e} = \frac{1}{2H_m s} \quad (43)$$

which is the same as the lumped-mass part in (41). In such a model, there are no low-frequency oscillating components, and the speed controller therefore can be designed with a higher bandwidth. However, the lumped-mass model might be insufficient to represent the dynamic behavior of the WTG system. The effect of the shaft system model on the dynamic behavior of the WTG and the speed controller is further investigated by simulation studies in Section IV.

Fig. 4 shows the overall vector control scheme of the RSC. In the SL model, the compensated outputs of the two current controllers, v_{dr} and v_{qr} , are used by the PWM module to generate the IGBT gate control signals to drive the IGBT converter. In the FF model, v_{dr} and v_{qr} are used to determine the RSC ac-side voltages v_{ra} , v_{rb} and v_{rc} (Fig. 3) directly by applying the inverse transformation of the stator-flux oriented synchronously rotating reference frame transformation.

Fig. 4. Overall vector control scheme of the RSC. $v_{dr2} = -s\omega_s \sigma L_r i_{qr}$, $v_{qr2} = s\omega_s (\sigma L_r i_{dr} + L_m^2 i_{ms} / L_s)$.

B. Design of the GSC Controllers

The GSC control scheme also consists of two cascaded control loops. The inner current control loops regulate independently the d -axis and q -axis GSC ac-side current components, i_{dg} and i_{qg} , in the synchronously rotating reference frame. The outer control loops regulate the dc-link voltage and the reactive power exchanged between the GSC and the grid.

1) *Design of the Inner Current Control Loops in Fig. 5:* In Figs. 1 and 3, the ac-side circuit equations of the GSC can be written as

$$p i_{gabc} = -\frac{r_g}{L_g} i_{gabc} + \frac{1}{L_g} (v_{gabc} - v_{sabc}) \quad (44)$$

Applying the synchronously rotating reference frame transformation to (44) with the d -axis aligned to the grid voltage vector v_s ($v_s = v_{ds}$, $v_{qs} = 0$), the following d - q vector representation can be obtained for modeling the GSC ac-side

$$v_{dg} = r_g i_{dg} + L_g p i_{dg} - \omega_s L_g i_{qg} + v_s \quad (45)$$

$$v_{qg} = r_g i_{qg} + L_g p i_{qg} + \omega_s L_g i_{dg} \quad (46)$$

Following the same procedure as in (34)-(38), v_{dg} and v_{qg} can be obtained by the following feedback loops and PI controllers

$$v_{dg} = \left(k_{pg} + \frac{k_{ig}}{s} \right) (i_{dg}^* - i_{dg}) - \omega_s L_g i_{qg} + v_s \quad (47)$$

$$v_{qg} = \left(k_{pg} + \frac{k_{ig}}{s} \right) (i_{qg}^* - i_{qg}) + \omega_s L_g i_{dg} \quad (48)$$

where the reference values i_{dg}^* and i_{qg}^* are obtained from the outer control loop.

2) *Design of the Dc-link Voltage Controller:* Neglecting harmonics due to switching and the losses in the GSC, the filtering inductor and the transformer (Figs. 1 and 3), the power balance equation is given by

$$P_r - P_g = v_{dc} i_{dc} = C v_{dc} p v_{dc} \quad (49)$$

Let

$$v_{dc} = v_{dc0} + \Delta v_{dc} \quad (50)$$

where v_{dc0} ($= v_{dc}^*$) is the dc component of v_{dc} , Δv_{dc} is the ripple component of v_{dc} . Substituting (50) into (49) gives

$$P_r - P_g = C v_{dc0} p v_{dc} + C \Delta v_{dc} p v_{dc} \quad (51)$$

Since $\Delta v_{dc} \ll v_{dc0}$, (51) can be written as

$$P_r - P_g \approx C v_{dc0} p v_{dc} \quad (52)$$

Therefore, the transfer function from P_g to v_{dc} is given by

$$\frac{v_{dc}(s)}{P_g(s)} = \frac{1}{C v_{dc0} s} \quad (53)$$

Since

$$P_g = \frac{3}{2} v_{ds} i_{dg} = \frac{3}{2} v_s i_{dg} \quad (54)$$

(53) becomes

$$\frac{v_{dc}(s)}{i_{dg}(s)} = \frac{\frac{3}{2} v_s}{C v_{dc0} s} \quad (55)$$

Therefore, it is possible to design a feedback loop and PI controller to generate the reference value of i_{dg} as follows

$$i_{dg}^* = \left(k_{pv} + \frac{k_{iv}}{s} \right) (v_{dc}^* - v_{dc}) \quad (56)$$

3) *Reactive Power Control:* The reactive power exchanged between the GSC and the grid is given by

$$Q_g = -\frac{3}{2} v_{ds} i_{qg} = -\frac{3}{2} v_s i_{qg} \quad (57)$$

Therefore, the reference value of i_{dg} can be determined directly from the reactive power command.

Fig. 5 shows the overall control scheme of the GSC.

Fig. 5. Overall vector control scheme of the GSC.

C. Design of the Pitch Angle (β) Controller

The pitch angle controller is only activated at high wind speeds. In such situations, the rotor speed can no longer be

controlled within its limits by increasing the generated power, as this would lead to overloading of the generator and/or the converter. Therefore, the blade pitch angle is controlled to reduce the mechanical power that the wind turbine extracts from the wind as well as to prevent over-speeding of the WTG. Fig. 6 shows the structure of the pitch angle controller [11]. P_e is the total output active power from the DFIG.

In this paper, all the PI controllers are equipped with the anti-windup design as discussed in [11].

Fig. 6. Wind turbine pitch angle controller.

IV. SIMULATION RESULTS

To verify and compare the proposed models, a single machine infinite bus (SMIB) power system as shown in Fig. 7 is used for simulation studies in PSCAD/EMTDC. The WTG represents a 3.6 MW a DFIG wind turbine system [5], [11], [12]. It is connected to the grid through a step-up transformer and two parallel lines. A three-phase balanced electric load at the sending-end bus is modeled as a constant impedance load. The parameters of the DFIG wind turbine and the power network are given in the Appendix.

The wind turbine operates at a specific operating point with the wind speed $v_w = 11.0$ m/s, generator rotor speed $\omega_r = 1.2$ pu, output active power $P_t = 0.94$ pu, and output reactive power $Q_t = 0$. The RSC and GSC reactive power commands are set at $Q_s^* = 0$ and $Q_g^* = 0$, respectively. The speed control instead of the active power is applied to the RSC. If not specified, the two-mass model is used to represent the WTG shaft system.

Fig. 7. A DFIG wind turbine connected to a SMIB power system.

Fig. 8. DFIG acceleration through synchronous speed: DFIG rotor speed ω_r and rotor phase current i_{ra} .

Fig. 9. A 200 ms three-phase short circuit: network voltage V_t , DFIG rotor speed ω_r , output power P_e , rotor currents i_{dr} and i_{qr} , and dc-link voltage v_{dc} .

A. Case I: DFIG Acceleration through Synchronous Speed

The DFIG initially operates with the rotor speed at $\omega_r = 0.9$ pu. From 10 s, the speed command ω_r^* is gradually increased

from 0.9 pu to 1.2 pu in 5 seconds. During the entire test, the wind speed is assumed to be constant. Fig. 8 compares the results of the DFIG rotor speed ω_r and rotor phase current i_{ra} when using the SL model and the FF model. The two models provide the same results and a smooth transition of the rotor currents from subsynchronous to supersynchronous modes.

B. Case II: Three-Phase Short Circuit Test at the Infinite Bus

A 200 ms three-phase short circuit is applied to the infinite bus at $t = 10$ s. Fig. 9 shows the results of the network voltage V_t , DFIG rotor speed ω_r , output active power P_e , rotor currents i_{dr} and i_{qr} , and dc-link voltage v_{dc} . This fault causes a voltage sag in V_t at the grid connection point of the WTG. This sag results in an imbalance between the turbine input power and the DFIG output power and therefore a high current in the DFIG stator windings. Because of the magnetic coupling between stator and rotor, this current also flows in the rotor circuit and the converter. Due to the stator flux oscillations during this transient state, the rotor currents oscillate with a frequency near the synchronous frequency [2], as can be seen from the waveforms of i_{dr} and i_{qr} . These results show that the simplified FF model provides the same model accuracy as the SL model, even for this severe disturbance.

C. Case III: Step Change in Wind Speed

The wind speed is assumed to change from 11 m/s to 14 m/s at $t = 10$ s. In this case, the pitch angle controller is activated to increase the blade pitch angle to shed some part of the wind power. The turbine pitch angle β , DFIG rotor speed ω_r , output active power P_e , rotor currents i_{dr} and i_{qr} , and dc-link voltage v_{dc} are compared in Fig. 10 for the SL and FF models. The pitch angle changes from 0° to about 8° to prevent the WTG from overloading in such a strong wind. As a result, the DFIG rotor speed ω_r and the output active power P_e are controlled at their rated values of 1.2 pu and 3.6 MW, respectively, after the system returns to the steady state condition. The same level of accuracy is achieved by using the two different models.

D. Case IV: Effect of Speed Controller PI Gains When Using Two-Mass Shaft Model

Based on the results in Sections IV-A, B and C, the FF model is accurate enough for modeling the DFIG and its VFC, and therefore, is used for further simulation studies. During the rest simulation study, the turbine pitch angle and the DFIG speed reference are set at 7.5° and 1.2 pu, respectively.

Grid disturbances may excite shaft torsional oscillations, primarily, in the shaft system equipped a gearbox. These torsional oscillations can be seen in the fluctuations of the generator rotor speed as well as the electrical parameters of the generator, such as the electrical power and rotor current. When the torsional oscillations are insufficiently damped, the WTG might have to be disconnected. As discussed in Section III-A, in order to damp the low-frequency torsional oscillations, the gain and bandwidth of the DFIG speed controller must be properly designed.

Assuming that the wind speed is step changed from 10 m/s to 13.5 m/s at $t = 10$ s, Fig. 11 shows the responses of the DFIG output active power P_e when using different integral

gains, where $k_{i1} < k_{i2} < k_{i3} < k_{i4}$ ($k_{i1} = 0.1$, $k_{i2} = 0.2$, $k_{i3} = 1.0$, and $k_{i4} = 4.0$). A larger integral gain yields a higher bandwidth for the closed-loop system. These results indicate that the smallest gain k_{i1} should be used. It provides the closed-loop system with a sufficient low bandwidth so that the low-frequency torsional oscillations are sufficiently damped.

Fig. 10. Test during strong wind: blade pitch angle β , DFIG rotor speed ω_r , output active power P_e , rotor currents i_{dr} and i_{qr} , and dc-link voltage v_{dc} .

Now the integral gain is fixed at $k_i = 0.1$. The same step change as in Fig. 11 is applied to the wind speed at $t = 10$ s. Fig. 12 shows the responses of P_e when using different proportional gains for the speed controller, where $k_{p1} < k_{p2} <$

$k_{p3} < k_{p4}$ ($k_{p1} = 0.01$, $k_{p2} = 0.04$, $k_{p3} = 0.1$, and $k_{p4} = 0.5$). The best damping is achieved by using the gain k_{p3} .

Fig. 13 shows the results of using different pairs of PI gains for the same tests in Figs. 11 and 12, where $k_{p1} < k_{p2} < k_{p3} < k_{p4}$, $k_{i1} < k_{i2} < k_{i3} < k_{i4}$ ($k_{i1} = 0.1$, $k_{i2} = 0.2$, $k_{i3} = 1.0$, and $k_{i4} = 4.0$), and the ratio k_{pn}/k_{in} ($n = 1, 2, 3, 4$) is constant. The dynamic performance of the WTG system degrades with the increase of the PI gains. The smallest pair of PI gains k_{p1} and k_{i1} provides the best damping performance, which are the same as those chosen from the previous tests in Figs. 11 and 12

Fig. 11. Effect of the speed controller integral gain ($k_{i1} < k_{i2} < k_{i3} < k_{i4}$) when using the two-mass shaft model: DFIG output active power P_e .

Fig. 12. Effect of the speed controller proportional gain ($k_{p1} < k_{p2} < k_{p3} < k_{p4}$) when using the two-mass shaft model: DFIG output active power P_e .

Fig. 13. Effect of the speed controller PI gains ($k_{p1} < k_{p2} < k_{p3} < k_{p4}$, $k_{i1} < k_{i2} < k_{i3} < k_{i4}$, and the ratio k_{pn}/k_{in} is constant for $n = 1, 2, 3, 4$) when using the two-mass shaft model: DFIG output active power P_e .

E. Case V: Effect of Speed Controller PI Gains When Using Lumped-Mass Shaft Model

The same PI gains and tests as used for the two-mass shaft system in Fig. 13 are now used for the lumped-mass shaft system and the results are shown in Fig. 14. These results

indicate that the lumped-mass shaft model provides the WTG system with a different dynamic behavior from the two-mass shaft model. As shown in Fig. 14, there are no low-frequency oscillations when using any pairs of PI gains, and therefore, the speed controller can be designed with a higher bandwidth by using the largest PI gains k_{p4} and k_{i4} . This pair of PI gains however causes large oscillations in the DFIG output active power P_e , when using the two-mass shaft model, as shown in Fig. 14. Therefore, the lumped-mass model is not sufficient to represent the dynamic behavior of the WTG system and provides a wrong model for designing the WTG controllers.

Fig. 14. Effect of the speed controller PI gains ($k_{p1} < k_{p2} < k_{p3} < k_{p4}$, $k_{i1} < k_{i2} < k_{i3} < k_{i4}$, and the ratio k_{pn}/k_{in} is constant for $n = 1, 2, 3, 4$) when using the lumped-mass shaft model: DFIG output active power P_e .

V. CONCLUSION

Two different models have been presented and developed in PSCAD/EMTDC to represent a wind turbine equipped with a doubly fed induction generator (DFIG). One is a detailed switching-level (SL) model, in which the variable frequency converter (VFC) is fully represented by individual IGBT switches and a dc-link capacitor. The other is a simplified fundamental-frequency (FF) model, in which the VFC is represented by two current-controlled voltage sources which take into account the dc-link dynamics. The other parts of the wind turbine generator (WTG) system, including the wind turbine, shaft system, induction generator, DFIG controller and pitch angle controller, have been modeled or designed in the same level of detail for both models. Simulation studies have been carried out for a 3.6 MW DFIG wind turbine using both the SL model and the FF model, and taking into account different shaft system representations. Results have shown that the SL and FF models provide the same level of accuracy. Therefore, the FF model should be used in order to speed up the simulation process of the power system equipped with DFIG wind turbines.

Moreover, the effect of different shaft system models (two-mass or lumped-mass) on the dynamic behavior and control of the WTG has been investigated based on both analytical and transient simulation studies. When using the lumped-mass model, the WTG does not exhibit any low-frequency torsional oscillations that exist in the practical system and in the two-mass shaft model. Therefore, the two-mass shaft model should be used for the study of power system transient dynamics. The torsional oscillations can be sufficiently damped by using a suitably designed DFIG speed controller.

APPENDIX

Wind turbine: rated capacity = 3.6 MW, number of blades = 3, rotor diameter = 104 m, swept area = 8495 m², rotor speed (variable) = 8.5-15.3 rpm.

Mechanical shaft system (base power = 3.6 MW): $H_t = 4.29$ s, $H_g = 0.9$ s, $D_t = D_g = 0$, $D_{tg} = 1.5$ pu, $K_{tg} = 296.7$ pu.

Wound-rotor induction generator: rated power = 3.6 MW, rated stator voltage = 4.16 kV, power factor $pf = -0.9 \sim +0.9$, $r_s = 0.0079$ pu, $r_r = 0.025$ pu, $r_m = 66.57$ pu, $L_{ls} = 0.07937$ pu, $L_{lr} = 0.40$ pu, $L_m = 4.4$ pu, base frequency $f = 60$ Hz.

Power network in Fig. 7 (base power = 3.6 MVA, base voltage = 34.5 kV): $r_{l1} = r_{l2} = 0.014$ pu, $x_{l1} = x_{l2} = 0.08$ pu, constant impedance load $Z_L = 2.6 + j1.5$ pu.

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