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Steady State and Transient Analysis of Grid Connected Doubly Fed Induction Generator Under Different Operating Conditions

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ABSTRACT

This paper present steady state and dynamic (Transient) models of the doubly fed induction generator connected to grid. The steady state model of the DFIAG (doubly fed asynchronous induction generator) has been constructed by referring all the rotor quantities to stator side. With the help of MATLAB programming simulation results are obtained to depict the steady state response of electromechanical torque, rotor speed, stator and rotor currents, stator and rotor fluxes, active and reactive drawn and delivered by Doubly Fed Asynchronous Induction Machine (DFAIM) as it is operating in two modes i.e. generator and motor. The mathematical steady state and transient model of the DFIAM is constructed for three basic reference frames such as rotor, stator and synchronously revolving reference frame using first order deferential equations. The effect of unsaturated and saturated resultant flux on the mutual inductance is also taken into account to deeply understand the dynamic response of the machine. The steady state and dynamic response of the DFAIG are compared for different rotor voltage magnitudes. Also, the effect of variations in mechanical input torque, stator voltage variations are simulated to predict the stator and rotor currents, active and reactive power, electromagnetic torque and rotor speed variations.

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1. INTRODUCTION

Doubly fed induction generators is also known as Doubly Fed Asynchronous Machine (DFIAM) with wound rotor construction. Now days DFIAMs are most popular machines for wind turbines as generator due to the applicability in the wide range of speed variations. The fixed speed i.e. synchronous generator the power control (active and reactive) electronic equipment required should be of 100% rating of synchronous generator. The power control equipment is generally installed to the stator side to control the voltage profile pertaining to the contingencies due to on load and off load variations. The voltage stability control is mainly linked with the reactive power control. It may be provided either by the control of the reactive power given by capacitor banks on the basis of error signal generated through comparator between a specified voltage reference and the measured voltage of the grid side phase to phase or phase to ground per unit voltage. So, the power control equipment employed for synchronous fixed speed generator is still very costlier which would take major part of the total cost of the Synchronous generator based wind turbine installation. On the other hand in the case of doubly fed asynchronous induction generator has the wider control options i.e. from stator and rotor side control. It also has pitch angle control of the wind turbine which controls the angular blade movement depends on the error signal generated due the difference between the preset reference speed and generator's shaft speed when wind turbine undergo different wind patterns with respect to variable time durations. The main advantage of the DFIAM is that near about 70% of power control is directly through stator side with FACT (flexible AC transmission) devices such as static synchronous compensator (STATCOM)-controls voltage, static VAR compensator (SVC)–Controls voltage. The operational difference between a STATCOM and an SVC is that a STATCOM works as a convenient under control voltage source on the other hand a SVC works on the principle of dynamically regulated the magnitude of reactance connected in parallel with DIAM's Stator. STATCOM has the provision of maximum reactive power feed to grid at under voltage conditions [1, 2]. The rest of the 30% power is fed to the grid with the help of power electronic converter connected to rotor side so; its rating is only 25%-30% of DFAIG's 100% power rating and as compared to fixed speed synchronous generator [2-5].

As the DFIG or DFIAM is an important component of wind turbine based power system so it require very steak and an accurate dynamic mathematical model to study and predict the response of the DFIAM under abnormal loading conditions and at switching instants. Dynamic model to global rotating reference frame of the DFIG system by a d (direct) and q (quardrature)-axis rotating at the angular frequency of ωs [6]. The classical d–q magnetization of the squirrel cage induction generator was modeled with non zero rotor voltage in the Park reference frame [7]. Presented steady state and dynamic models and control strategies of wind turbine generators. [8], [9]. Dynamic time domain DFIG model with synchronously rotating reference frame was made [10], [11]. A brushless model of DFIG was used [12]. However there are many techniques to develop dynamic models of DFIAM but still there is need to study and explore the dynamic models with time domain and z-domain by consideration of effect of magnetic saturation. Implementation of different discrete models to show the simulation work much near to the practical condition. In this paper steady state and dynamic models are implemented. Discrete dynamic models are implemented based on various z-domain methods. The mathematical steady state and transient model of the DFIAM is constructed for three basic reference frames such as rotor, stator and synchronously revolving reference frame using first order deferential equations. The steady state and dynamic response of the DFAIG are compared for different rotor voltage magnitudes. Also, the effect of variations in mechanical input torque, stator voltage variations are simulated in MATLAB simulator to predict the stator and rotor currents, active and reactive power, electromagnetic torque and rotor speed variations.

2. STEADY STATE MODEL OF DFIAM

The steady state model of the three phase DFIAM machine is obtained from an equivalent circuit diagram as shown in the Figure 1-3. The mutual reactance X_m is moved to stator voltage supply source V_s and the simplified model of the induction machine is shown by the Figure 3. To obtain the torque equation from the equivalent circuit, the rotor current Ir is expressed as the following set of equations as [8].

$$I^r_{std} = \frac{V^s_{std} - V^r_{std} / s^{slip}}{(R_s + \frac{R_r^{'}}{s^{slip}}) + j(X_{ls} + X_{lr}^{'})} \tag{1}$$

The electromagnetic torque in an induction machine is the sum of air gap power and rotor fed power.
where;
$V^s{}_{std}$=Stator steady state voltage (p.u); X_{ls}=Stator reactance (p.u);
$V^r{}_{std}$=Stator steady state voltage (p.u); X'_{lr}=Rotor reactance (p.u);
R_s=Stator resistance (p.u); R_r=Stator resistance (p.u);
S^{slip}=s=Slip (Stator's flux speed-Rotor's speed)/ Stator's flux speed
$T\_e^{sator}{}_{std}$=Electromechanical torque from stator side (p.u).
Ψ_s^{flux}=Stator side flux (p.u.) Ψ_s^{flux}=Rotor side flux (p.u.)
P_R=Rotor fed active power.

$$T^s_{e\_std} = \left((I^r_{std})^2 * \left(\frac{R_r^{'}}{s^{slip}} + R_s \right) \right) + P_R \tag{2}$$

Rotor fed active power.

$$P_R = \frac{V_r^{'}}{s^{std}} * I_{std}^{r} * \cos \varphi_p \quad (3)$$

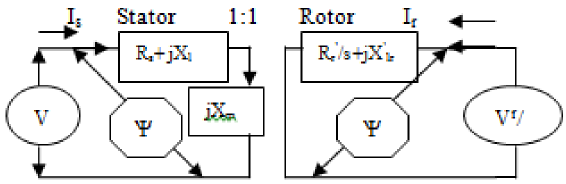


Figure 1. Equivalent Circuit of DFIAM with Stator and Rotor side

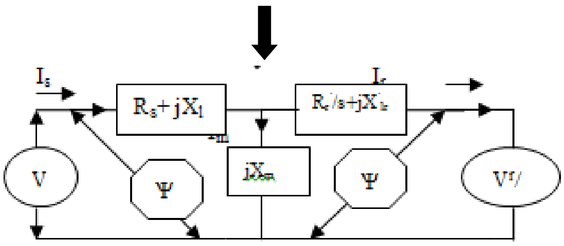


Figure 2. Equivalent Circuit of DFIAM as rotor side is referred to stator

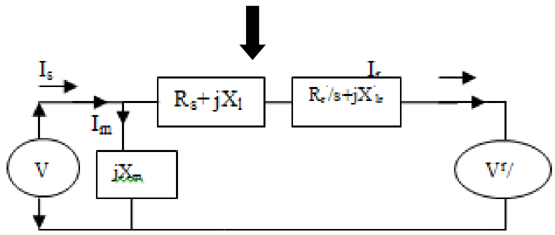


Figure 3. Steady state equivalent circuit of DFIAM as rotor is referred to stator

$$T_{e\_std}^{s} = \left(\frac{\{s*(V_{std}^{s})^2 - V_{std}^{r'} * V_{std}^{s}\}*(s^{slip} * R_s + R_r^{'})}{(s*R_s + R_r^{'})^2 + (s^{slip})^2 (X_{ls} + X_{lr}^{'})^2} \right) \quad (4)$$

$$I_m^s = \frac{V_{std}^s}{X_m} \quad (5)$$

$$I_{std}^s = I_m^s + I_r^s \quad (6)$$

$$\Psi_m^s = L_{ls} * I_{std}^s + L_m * (I_{std}^s - I_{std}^r) \quad (7)$$

Stator's active power

$$P_{std}^s = V_{std}^s * I_{std}^s \cos \Theta_s \quad (8)$$

Where

$$\Theta_s = \cos^{-1}\left(\frac{-\{X_m * (s^{slip} * Rs + R_r^{'})^2 + s^{slip}(X_s + X_r^{'}) * \left[X_m (X_s + X_r^{'}) + 1 \right]\}}{s^{slip} * Rs + R_r^{'}} \right) \quad (9)$$

Alternatively electromagnetic torque is given by [8] the following equation:

$$T_{em}^{s} = 3\frac{p_{pair} R_r^{'} I_r^{'2}}{s^{slip}\omega_{syn}} \tag{10}$$

where;

L_{ls}	=	Stator leakage self inductance (p.u);
L_m	=	Mutual inductance from Stator side (p.u);
ω_{syn}	=	Synchronous or angular speed at supply frequency (p.u);
S^{slip}=s	=	Slip (Stator’s flux speed-Rotor’s speed)/ Stator’s flux speed
$T\_e^{sator}_{std}$	=	Electromechanical torque from stator side (p.u).
Ψ_s^{flux}	=	Stator side flux (p.u.) Ψ_s^{flux}=Rotor side flux (p.u.)
Ψ_m^{flux}	=	Equivalent magnetic flux from stator.
Θ_s	=	power factor of the equivalent ckt. As shown in Figure 3.

Steady state simulation analysis pertaining to the above given mathematical equations of a 1.5 MW DFIAM whose circuit constant values are tabulated in Appendix-A. The following figures show the steady state response of the induction machine for (1)-(10). Figure 4 shows the steady state variations of electro-magnetic torque corresponding to different rotor fed voltages and slip factors. Operating region of the doubly fed Asynchronous machine lies between the slip factors 0.2 and -0.2.

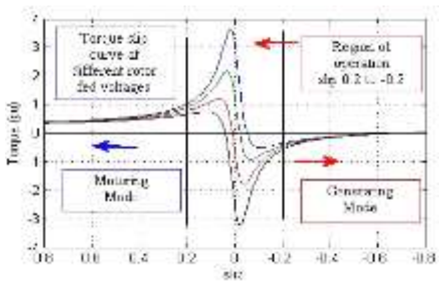


Figure 4. Steady state electromagnetic torque versus slip curves for different rotor voltages

Figure 5 shows the rotor current variations for different voltages corresponds to the different slip factors. The rotor current follows (1).

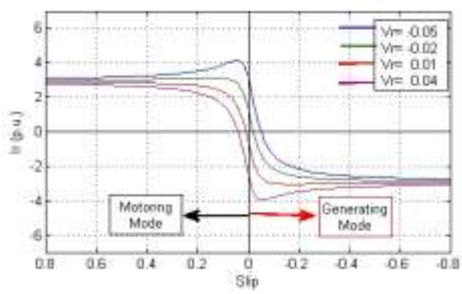


Figure 5. Rotor current versus slip to different rotor voltages (p.u.)

The variations of rotor active and reactive power as per rotor voltage magnitudes for slip factors are shown in Figure 6 and Figure 7.

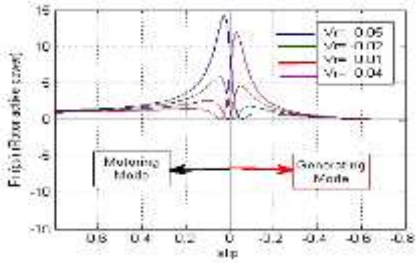


Figure 6. Rotor active power (I^2*R_r) versus slip to different rotor voltages

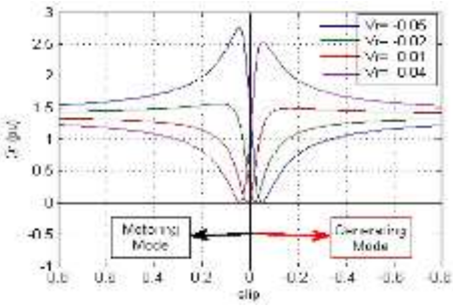


Figure 7. Rotor reactive power (I^2*X_{lr}) versus slip to different rotor voltages

Figure 8 shows that magnetizing current remains constant over slip and rotor voltage variations. The magnetizing reactance considered to be constant i.e. unsaturated 2.9(p.u.). The angular speed is considered to be 1(p.u).

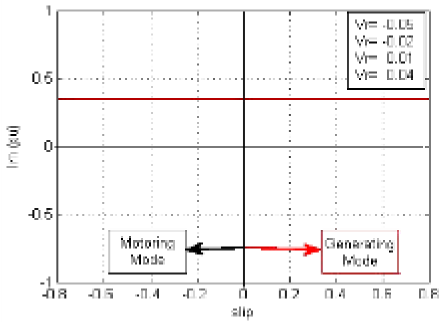


Figure 8. Magnetizing current versus slip for different voltages and

The stator's flux variations correspond to different rotor fed voltages and slip values are shown in Figure 9.

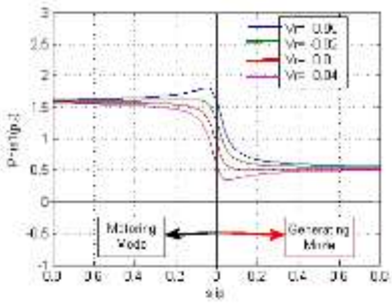


Figure 9. Stator's flux versus slip for different rotor voltages

3. TRANSIENT MODEL OF DFIAM WITH VARIOUS REFERENCE FRAMES.

The per unit dynamic model of the three phase doubly fed asynchronous machine is derived by the transformation of three variable phase quantities to a set of two stationary vectors known as α-axis and β-axis (clark's transformation). Then these stationary vectors are transformed to rotating frame with d-axis and q-axis coordinates. The three phase supply voltages are alternating quantities which are transformed to α and β-axis with the help of Clark's transformation (stationary reference frame) is as follows.

a. abc to αβo (stationary):

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \begin{bmatrix} 2/3 & -1/3 & -1/3 \\ 0 & 1/\sqrt{3} & -1/\sqrt{3} \\ 1/3 & 1/3 & 1/3 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (11)$$

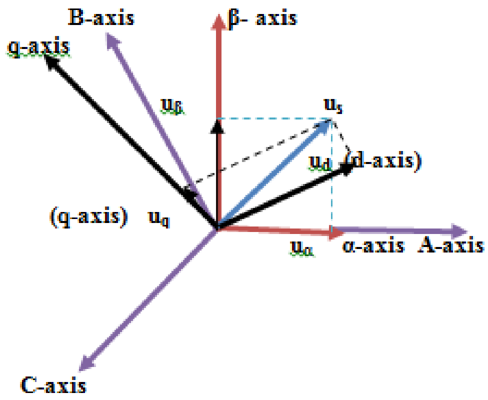


Figure 10. Stator's phase voltages along dq and αβ axis

b. αβo(stationary) to dqo reference:

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \begin{bmatrix} \sin wt & -\cos wt & 0 \\ \cos wt & \sin wt & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} \quad (12)$$

c. αβo(stationary) to dqo reference:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} \sin wt & \cos wt & 1 \\ \sin(wt-2\pi/3) & \cos(wt-2\pi/3) & 1 \\ \sin(wt+2\pi/3) & os(wt-2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} \quad (13)$$

Assumptions for the Dynamic Model:

a. No magnetic flux saturation so the mutual inductance is constant i.e unsaturated.
b. Machine windings are connected in star configuration on stator and rotor hence no (0) component.
c. Va=Vph sinwt (i), Vb=Vphsin (wt-120) (ii), Vc=Vph sin (wt+120) balanced three phase voltages.

As per park's transformation the three phase stator and rotor voltages transformed to a dqo rotating frame is given the following equations:

$$\begin{bmatrix} v_s^a \\ v_s^b \\ v_s^c \end{bmatrix} = \begin{bmatrix} \sin\theta_s & \cos\theta_s & 1 \\ \sin(\theta_s-2\pi/3) & \cos(\theta_s-2\pi/3) & 1 \\ \sin(\theta_s-4\pi/3) & \cos(\theta_s-4\pi/3) & 1 \end{bmatrix} \begin{bmatrix} V_{qs} \\ V_{ds} \\ V_{0s} \end{bmatrix} \quad (14)$$

In terms of line voltages

$$\begin{bmatrix} V_{d_s} \\ V_{q_s} \end{bmatrix} = 1/3 \begin{bmatrix} (\sqrt{3}\sin\theta_s + \cos\theta_s)v_{ab_s} + 2\cos\theta_s v_{bc_s} \\ (-\sqrt{3}\cos\theta_s + \sin\theta_s)v_{ab_s} + 2\sin\theta_s v_{bc_s} \end{bmatrix} \quad (15)$$

$$\begin{bmatrix} v_d^{r'} \\ v_q^{r'} \end{bmatrix} = 1/3 \begin{bmatrix} (\sqrt{3}\sin\Gamma + \cos\Gamma)v_{ab_r} + 2\cos\Gamma v_{bc_r} \\ (-\sqrt{3}\cos\Gamma + \sin\Gamma)v_{ab_r} + 2\sin\Gamma v_{bc_r} \end{bmatrix} \quad (16)$$

$$\Gamma = \theta_s - \theta_r \quad (17)$$

θ_s angle of reference frame and Γ is the angle between reference frame and position of rotor. As w_s is the speed of stator flux and w_s-w_r is the relative speed between stator's flux and rotor's actual angular speed. So the W speed (p.u.) matrix for stator and rotor ckt is given by (18):

$$W = \begin{bmatrix} 0 & -w_s & 0 & 0 \\ w_s & 0 & 0 & 0 \\ 0 & 0 & 0 & -(w_s - w_r) \\ 0 & 0 & (w_s - w_r) & 0 \end{bmatrix} \quad (18)$$

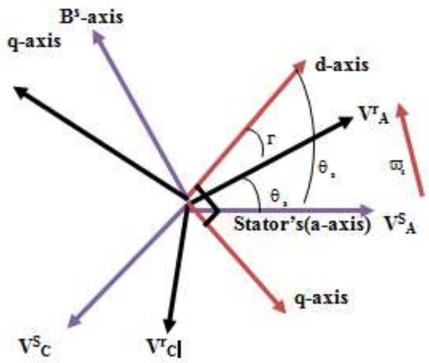


Figure 11. Stator and rotor phase voltages along dq-axis for rotor reference frame

4. ROTOR REFERENCE FRAME

In this reference frame $\theta_s = \theta_r$, $\Gamma = \theta_r - \theta_r = 0$ stator and rotor dq component corresponds to line voltage given by equation (19) and (20). θ_r =the position of phase 'a' of rotor abc frame in electrical degree w.r.t phase 'a' of stator abc reference frame.

Stator voltage equations:

$$\begin{bmatrix} V_{d_s} \\ V_{q_s} \end{bmatrix} = 1/3 \begin{bmatrix} (\sqrt{3}\sin\theta_r + \cos\theta_r)v_{ab_S} + 2\cos\theta_r v_{bc_S} \\ (-\sqrt{3}\cos\theta_r + \sin\theta_r)v_{ab_S} + 2\sin\theta_r v_{bc_S} \end{bmatrix} \quad (19)$$

Rotor voltage equations:

$$\begin{bmatrix} v_{dr'} \\ v_{qr'} \end{bmatrix} = 1/3 \begin{bmatrix} v_{ab_R} + 2v_{bc_r} \\ (-\sqrt{3})v_{ab_r} \end{bmatrix} \quad (20)$$

For rotor ref. frame (w_s=w_r) for pu system w_s=1 p.u.

$$W=\begin{bmatrix}0 & -w_r & 0 & 0\\ w_r & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix} \tag{21}$$

In general stator's dqo components in terms of voltage drops are as follows:

$$\begin{Bmatrix} V_{ds}=\frac{d\phi_{ds}}{dt}-\omega_s\phi_{qs}+R_S i_{ds}\\ V_{qs}=\frac{d\phi_{qs}}{dt}+\omega_s\phi_{ds}+R_S i_{qs}\\ V_{qs}=\frac{d\phi_{0s}}{dt}+R_S i_{0s}\end{Bmatrix} \tag{22}$$

Also, rotor dqo components in terms of voltage drops are as follows:

$$\begin{Bmatrix} V_{dr'}=\frac{d\phi_{dr'}}{dt}-(\omega_s-\omega_r)\phi_{qr'}+R_{r'}i_{dr'}\\ V_{qr'}=\frac{d\phi_{qr'}}{dt}+(\omega_s-\omega_r)\phi_{dr'}+R_{r'}i_{qr'}\\ V_{qr'}=\frac{d\phi_{0r'}}{dt}+R_{r'}i_{0r'}\end{Bmatrix} \tag{23}$$

From (21) - (23) stator and rotor voltages for Rotor reference frame are as follows:

Stator and rotor dqo voltages are:

$$\begin{Bmatrix} V_{ds}=\frac{d\phi_{ds}}{dt}-\omega_r\phi_{qs}+R_S i_{ds}\\ V_{qs}=\frac{d\phi_{qs}}{dt}+\omega_r\phi_{ds}+R_S i_{qs}\\ V_{qs}=\frac{d\phi_{0s}}{dt}+R_S i_{0s}\end{Bmatrix} \tag{24}$$

$$\begin{Bmatrix} V_{dr'}=\frac{d\phi_{dr'}}{dt}+R_{r'}i_{dr'}\\ V_{qr'}=\frac{d\phi_{qr'}}{dt}+R_{r'}i_{qr'}\\ V_{0r'}=\frac{d\phi_{0r'}}{dt}+R_{r'}i_{0r'}\end{Bmatrix} \tag{25}$$

$$\begin{bmatrix}\dot{\phi}_{ds}(t)\\ \dot{\phi}_{qs}(t)\\ \dot{\phi}_{dr'}(t)\\ \dot{\phi}_{qr'}(t)\end{bmatrix}=\begin{bmatrix}V_{ds}\\ V_{qs}\\ V_{dr'}\\ V_{qr'}\end{bmatrix}-\begin{bmatrix}0 & -\omega_r & 0 & 0\\ \omega_r & 0 & 0 & 0\\ 0 & 0 & 0 & 0\\ 0 & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}\phi_{ds}(t)\\ \phi_{qs}(t)\\ \phi_{dr'}(t)\\ \phi_{qr'}(t)\end{bmatrix}-\begin{bmatrix}R_s & 0 & 0 & 0\\ 0 & R_s & 0 & 0\\ 0 & 0 & R_{r'} & 0\\ 0 & 0 & 0 & R_{r'}\end{bmatrix}\begin{bmatrix}i_{ds}(t)\\ i_{qs}(t)\\ i_{dr'}(t)\\ i_{qr'}(t)\end{bmatrix} \tag{26}$$

Where the relation between flux and current is given by:

$$\begin{bmatrix} i_{ds}(t) \\ i_{qs}(t) \\ i_{dr'}(t) \\ i_{qr'}(t) \end{bmatrix} = \begin{bmatrix} L_{ls}+L_M & 0 & L_M & 0 \\ 0 & L_{ls}+L_M & 0 & L_M \\ L_M & 0 & L_{lr'}+L_M & 0 \\ 0 & L_M & 0 & L_{lr'}+L_M \end{bmatrix}^{-1} \begin{bmatrix} \phi_{ds}(t) \\ \phi_{qs}(t) \\ \phi_{dr'}(t) \\ \phi_{qr'}(t) \end{bmatrix} \quad (27)$$

By putting (27) into (26) gives a relation of flux that

$$\text{Fluxes: } \dot{\phi}_{dq_{sr}}(t) = [V_{dq}r,s]+(-[W]-[L^{-1}*R])\,\phi_{dq_{Sr}}(t)$$
$$\phi_{dq_{sr}}(t) = \int [V_{dq}r,s]+(-[W]-[L^{-1}*R])\,\phi_{dq_{RS}}(t)\,dt \quad (28)$$

Flux is derived from the equation (28), Electromagnetic torque and mechanical model are given by the same set of equations (43)-(45).

5. STATOR OR STATIONARY REFERENCE FRAME

For stationary frame phase A of the stator voltage is in phase with the d-axis so, $\theta_s = 0$, $\Gamma = -\theta_r$ and stator and rotor voltages to dq component are given by equation (29) and equation (30). θ_r =the position of phase 'a'of rotor abc frame in electrical degree w.r.t phase 'a' of stator abc reference frame. Stator voltage eqns:

$$\begin{bmatrix} V_{d_s} \\ V_{q_s} \end{bmatrix} = 1/3 \begin{bmatrix} v_{ab_S} + 2v_{bc_S} \\ (-\sqrt{3})v_{ab_S} \end{bmatrix} \quad (29)$$

Rotor voltage are given by equation (30) as :

$$\begin{bmatrix} V_{d_r} \\ V_{q_r} \end{bmatrix} = 1/3 \begin{bmatrix} (-\sqrt{3}\sin\theta_r + \cos\theta_r)v_{ab_r} + 2\cos\theta_r v_{bcr} \\ (-\sqrt{3}\cos\theta_r - \sin\theta_r)v_{ab_r} - 2\sin\theta_r v_{bc_r} \end{bmatrix} \quad (30)$$

As w_s is the speed of stator flux and w_s-w_r is the relative speed between stator's flux and rotor's actual speed. So the W speed matrix for stator and rotor ckt is given by equation (31). For stationary ref. frame (w_s=0) for pu system

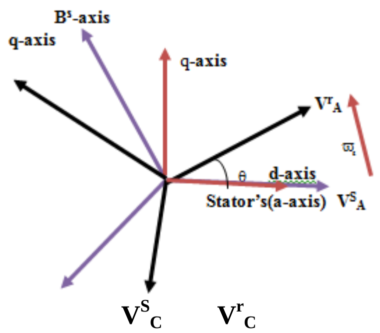


Figure 12. Stator and rotor phase voltages along dq axis for a stationary reference frame

$$W = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & (w_r) \\ 0 & 0 & (-w_r) & 0 \end{bmatrix} \quad (31)$$

The stator dqo voltages:

$$\begin{Bmatrix} V_{ds} = \dfrac{d\phi_{ds}}{dt} + R_S i_{ds} \\ V_{qs} = \dfrac{d\phi_{qs}}{dt} + R_S i_{qs} \\ V_{0s} = \dfrac{d\phi_{0s}}{dt} + R_S i_{0s} \end{Bmatrix} \quad (32)$$

$$\begin{Bmatrix} V_{dr'} = \dfrac{d\phi_{dr'}}{dt} + \omega_r \phi_{qs} + R_{r'} i_{dr'} \\ V_{qr'} = \dfrac{d\phi_{qr'}}{dt} + (-\omega_r)\phi_{dr'} + R_{r'} i_{qr'} \\ V_{0r'} = \dfrac{d\phi_{0r'}}{dt} + R_{r'} i_{0r'} \end{Bmatrix} \quad (33)$$

Stator and rotor fluxes are given by:

$$\begin{bmatrix} \dot{\phi}_{ds}(t) \\ \dot{\phi}_{qs}(t) \\ \dot{\phi}_{dr'}(t) \\ \dot{\phi}_{qr'}(t) \end{bmatrix} = \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr'} \\ V_{qr'} \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & wr \\ 0 & 0 & -w_r & 0 \end{bmatrix} \begin{bmatrix} \phi_{ds}(t) \\ \phi_{qs}(t) \\ \phi_{qr'}(t) \\ \phi_{dr'}(t) \end{bmatrix} - \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_{r'} & 0 \\ 0 & 0 & 0 & R_{r'} \end{bmatrix} \begin{bmatrix} i_{ds}(t) \\ i_{qs}(t) \\ i_{dr'}(t) \\ i_{qr'}(t) \end{bmatrix} \quad (34)$$

From (27)

$$\begin{bmatrix} \dot{\phi}_{ds}(t) \\ \dot{\phi}_{qs}(t) \\ \dot{\phi}_{dr'}(t) \\ \dot{\phi}_{qr'}(t) \end{bmatrix} = \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr'} \\ V_{qr'} \end{bmatrix} - \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & w_r \\ 0 & 0 & -w_r & 0 \end{bmatrix} \begin{bmatrix} \phi_{ds}(t) \\ \phi_{qs}(t) \\ \phi_{qr'}(t) \\ \phi_{dr'}(t) \end{bmatrix} - \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_{r'} & 0 \\ 0 & 0 & 0 & R_{r'} \end{bmatrix} \begin{bmatrix} L_{ls}+L_M & 0 & L_M & 0 \\ 0 & L_{ls}+L_M & 0 & L_M \\ L_M & 0 & L_{lr'}+L_M & 0 \\ 0 & L_M & 0 & L_{lr'}+L_M \end{bmatrix}^{-1} \begin{bmatrix} \phi_{qs}(t) \\ \phi_{ds}(t) \\ \phi_{qr'}(t) \\ \phi_{dr'}(t) \end{bmatrix} \quad (35)$$

Flux is derived from (28), Electromagnetic torque model are given by the same set of equations (43)-(45).

6. SYNCHRONOUSLY ROTATING FRAME

In this frame $\theta_s = \theta_e$, $\Gamma = \theta_e - \theta_r$ stator and rotor dq component corresponds to line voltage given by the set equation (37) and (39). θ_r =the position of phase ‘a’of rotor abc frame in electrical degree w.r.t phase ‘a’ of stator abc reference frame.

Stator voltage equations:

$$\begin{bmatrix} V_{d_s} \\ V_{q_s} \end{bmatrix} = 1/3 \begin{bmatrix} (\sqrt{3}\sin\theta_e + \cos\theta_e)v_{ab_r} + 2\cos\theta_e v_{bcr} \\ (-\sqrt{3}\cos\theta_e + \sin\theta_e)v_{ab_r} + 2\sin\theta_e v_{bc_r} \end{bmatrix} \quad (36)$$

Rotor voltage equations:

$$\begin{bmatrix} V_{d_r} \\ V_{q_r} \end{bmatrix} = 1/3 \begin{bmatrix} (\sqrt{3}\sin(\theta_e - \theta_r) + \cos(\theta_e - \theta_r)v_{ab_r} + 2\cos(\theta_e - \theta_r)v_{bcr} \\ (-\sqrt{3}\cos(\theta_e - \theta_r) + \sin(\theta_e - \theta_r)v_{ab_r} + 2\sin(\theta_e - \theta_r)_r v_{bc_r} \end{bmatrix} \quad (37)$$

As w_s is the speed of stator flux and w_s-w_r is the relative speed between stator's flux and rotor's actual speed. For synchronously rotating ref. frame (w_s=1) for pu system w_s=1 p.u.Matrix w is given by:

$$W = \begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -(1-w_r) \\ 0 & 0 & (1-w_r) & 0 \end{bmatrix} \quad (38)$$

Stator dqo voltages:

$$\begin{Bmatrix} V_{ds} = \dfrac{d\phi_{ds}}{dt} - \phi_{qs} + R_S i_{ds} \\ V_{qs} = \dfrac{d\phi_{qs}}{dt} + \phi_{ds} + R_S i_{qs} \\ V_{qs} = \dfrac{d\phi_{0s}}{dt} + R_S i_{0s} \end{Bmatrix} \quad (39)$$

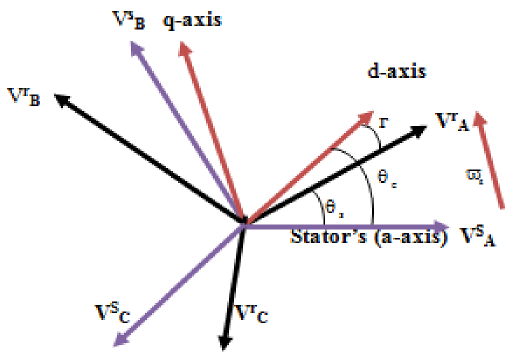


Figure 13. Stator and rotor phase voltages along dq axis for a stationary reference frame

where;

Te	=	Electromagnetic torque (p.u)
H	=	Damping constant (p.u)
F	=	Friction constant (p.u)
p	=	Pair of poles.
w_m	=	Generator shaft speed (p.u)
T_m	=	Mechanical torque (p.u)
θ_r	=	Rotor angle electrical radian

Rotor dqo voltages:

$$\begin{cases} V_{dr'} = \dfrac{d\phi_{dr'}}{dt} - (1-\omega_r)\phi_{qs} + R_{r'}.i_{dr'} \\ V_{qr'} = \dfrac{d\phi_{qr'}}{dt} + (1-\omega_r)\phi_{dr'} + R_{r'}.i_{qr'} \\ V_{qr'} = \dfrac{d\phi_{0r'}}{dt} + R_{r'}.i_{0r'} \end{cases} \tag{40}$$

Stator and Rotor fluxes:

$$\begin{bmatrix} \dot{\phi}_{ds}(t) \\ \dot{\phi}_{qs}(t) \\ \dot{\phi}_{dr'}(t) \\ \dot{\phi}_{qr'}(t) \end{bmatrix} = \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr'} \\ V_{qr'} \end{bmatrix} + \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & (1-w_r) \\ 0 & 0 & -(1-w_r) & 0 \end{bmatrix} \begin{bmatrix} \phi_{ds}(t) \\ \phi_{qs}(t) \\ \phi_{qr'}(t) \\ \phi_{dr'}(t) \end{bmatrix} - \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_{r'} & 0 \\ 0 & 0 & 0 & R_{r'} \end{bmatrix} \begin{bmatrix} i_{ds}(t) \\ i_{qs}(t) \\ i_{dr'}(t) \\ i_{qr'}(t) \end{bmatrix} \tag{41}$$

From (27)

$$\begin{bmatrix} \dot{\phi}_{ds}(t) \\ \dot{\phi}_{qs}(t) \\ \dot{\phi}_{dr'}(t) \\ \dot{\phi}_{qr'}(t) \end{bmatrix} = \begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr'} \\ V_{qr'} \end{bmatrix} + \begin{bmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & (1-w_r) \\ 0 & 0 & -(1-w_r) & 0 \end{bmatrix} \begin{bmatrix} \phi_{ds}(t) \\ \phi_{qs}(t) \\ \phi_{qr'}(t) \\ \phi_{dr'}(t) \end{bmatrix} - \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_{r'} & 0 \\ 0 & 0 & 0 & R_{r'} \end{bmatrix} \begin{bmatrix} L_{ls}+L_M & 0 & L_M & 0 \\ 0 & L_{ls}+L_M & 0 & L_M \\ L_M & 0 & L_{lr'}+L_M & 0 \\ 0 & L_M & 0 & L_{lr'}+L_M \end{bmatrix}^{-1} \begin{bmatrix} \phi_{qs}(t) \\ \phi_{ds}(t) \\ \phi_{qr'}(t) \\ \phi_{dr'}(t) \end{bmatrix} \tag{42}$$

Flux is derived from (28), Electromagnetic torque and mechanical model are given by the same set of (43)-(45).

Electromagnetic torque:

$$Te = (\Phi_{ds} i_{qs} - \Phi_{qs} i_{ds}) \tag{43}$$

Mechanical model:

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\omega_m - T_m) \tag{44}$$

$$\begin{aligned} w_r(p.u) = \omega_m &= \int \frac{1}{2H}(T_e - F\omega_m - T_m)dt \\ \theta_r &= \int w_r * web.dt \;\; \text{so}, \;\; \theta_r = \theta_m / p \end{aligned} \tag{45}$$

7. SIMULINK MODEL OF GRID CONNECTED 1.5 MW DFIAM MACHINE

To analyze the transient behavior of the doubly fed asynchronous machine a simulink test model is constructed in the matlab environment. A 1.5MW doubly fed asynchronous induction generator is connected to nominal line to line 575 V grids. A 1.5 MW wind turbine is coupled to the machine through drive train model. The single line diagram of the grid is shown in Figure 14.

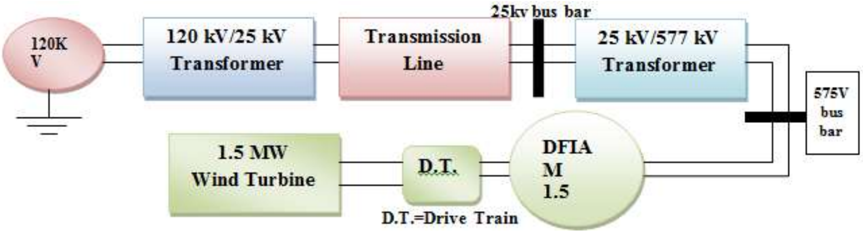


Figure 14. Test model for grid connected standalone DFIAM

The test model shown above is used to test DFIAM performance based on electrical torque, generator's shaft speed, and stator and rotor currents for various operating conditions such as:

Case1.A 0 p.u. Mechanical torque input is applied to the DIAM without the use of Wind turbine to test the output of DIAM. Also, set initial slip s=1 and rotor side line-line rms voltage to zero.

Case2.A 0.1 p.u. Mechanical torque input is applied to the DIAM without the use of Wind turbine to test the output of DIAM. Also, set initial slip s=1 and rotor side line-line rms voltage to zero.

Case3.A -0.1 p.u. Mechanical torque input is applied to the DIAM without the use of Wind turbine to test the output of DIAM. Also, set initial slip s=0 and rotor side line-line rms voltage to zero.

Case4.A -0.1 p.u. Mechanical torque input is applied to the DIAM without the use of Wind turbine to test the output of DIAM. Also, set the initial slip s=-0.2 and rotor side line-line rms voltage to zero.

8. WIND TURBINE MODEL

The wind turbine model is described by the following set of (46)-(48):

8.1. Aerodynamic model

The mechanical power produced by the turbine on interaction with wind depends upon swept area S of the air disk formed by the rotation of the turbine's blades S, power coefficient of performance Cp (depends upon collective blade pitch angle β and tip to speed ratio (λ), air density and wind speed V. The expression for power extracted from wind is given by [13]-[15] following (46)-(48).

$$P_r = \frac{1}{2}\rho C_P(\beta,\lambda) S V^3 \tag{46}$$

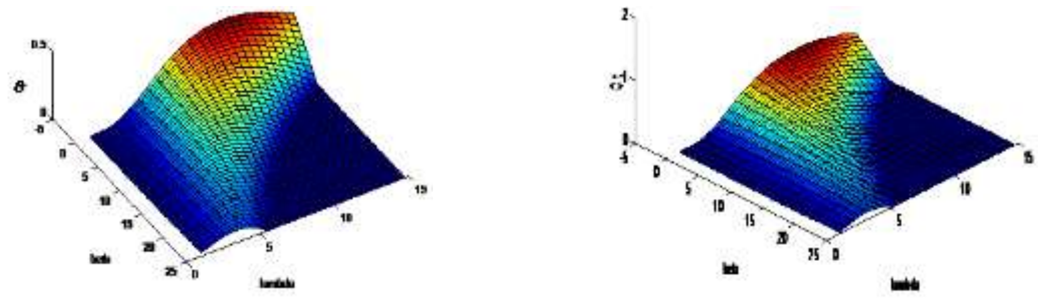
Similarly torque produced is given by the equation as follows.

$$T_r = \frac{1}{2}\rho C_Q R(\beta,\lambda) S V^2 \tag{47}$$

Hence the equation for thrust exerted on the tower Ft is given as follows.

$$F_T = \frac{1}{2}\rho C_T(\beta,\lambda) S V^2 \tag{48}$$

Where Ct thrust coefficient, Cq is the torque coefficient, R is the radius of the rotor.



(a) (b)

Figure 15. (a) and (b) Variations of Cp and Ct

Cq=Cp/ λ and λ=Rwr/V. Where Wrt is the rotor speed of turbine.Figure.1 illustrate the variation of performance coefficients of Cp and Ct.Now, The Wind turbine is coupled to the shaft of DIAM and the performance of the DFIAM is tested with Slip s=0 and s=-0.2.Note that again there is no rotor voltage is applied to the rotor. To control the electromagnetic torque and speed a direct discrete PID controller is implemented to control the pith of the turbine blade. The results show the performance of wind turbine based DFIAM connected to grid.

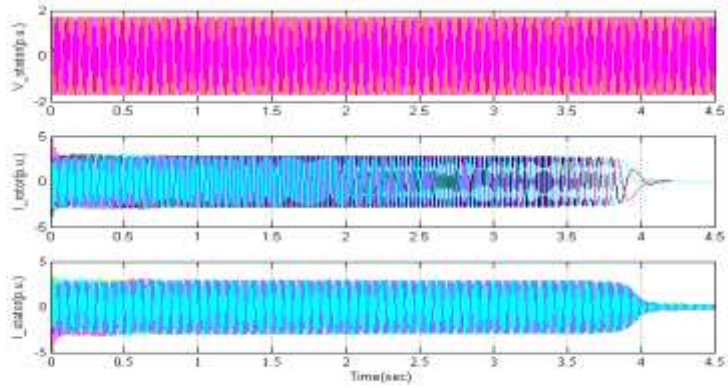
8.2. Proposed PID based pitch controller

A simple proportional gain of discrete PID controller is used which actuates for an error signal generated by reference speed (p.u) and generator's speed (p.u). Then the output of the controller is optimized through limiter having maximum value of the pitch angle is 27 deg.

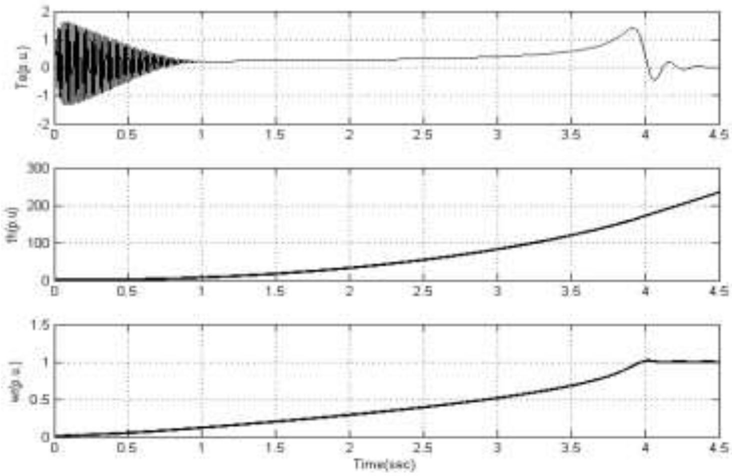
9. RESULTS AND DISCUSSIONS

In this section results of different and case studies are shown and discussed as follows:

CASE 1 When slip s=1, Tm=0, Vr=0.



(a)



(b)

Figure 16. (a) Stator currents, rotor currents and stator voltages (p.u) (b) Transient response of Te (p.u), theta (rad) and generator's speed (p.u)

In this case DFIAM is set to work as squirrel cage induction machine as zero input voltage to the rotor. The mechanical input and load on the shaft is also set to be zero. The machine is working as a motor with slip s=1. Figure 16(a) shows the dynamic response of stator and rotor currents with magnitude of 5p.u at t=0, at t=4s rotor current attain minimum value 0.01p.u and stator current attains steady state value of 0.4p.u.

Figure 16(b) shows the transient response of electromagnetic torque (Te) and generator shaft speed (wr) in p.u.

CASE 2. With slip s=0, Tm=0.1, Vr=0.

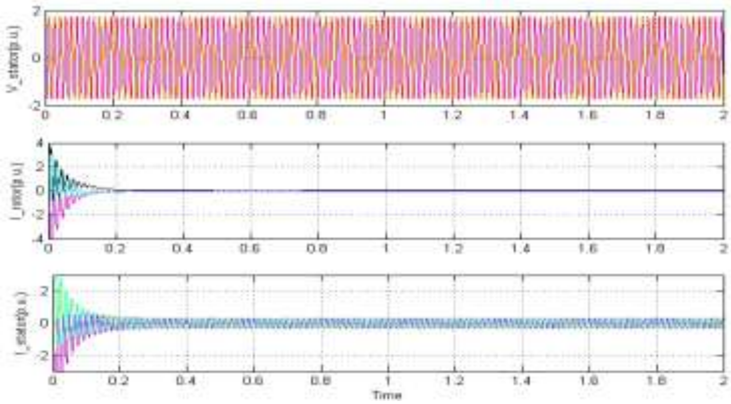


Figure 17. (a) Stator currents, rotor currents and stator voltages (p.u)

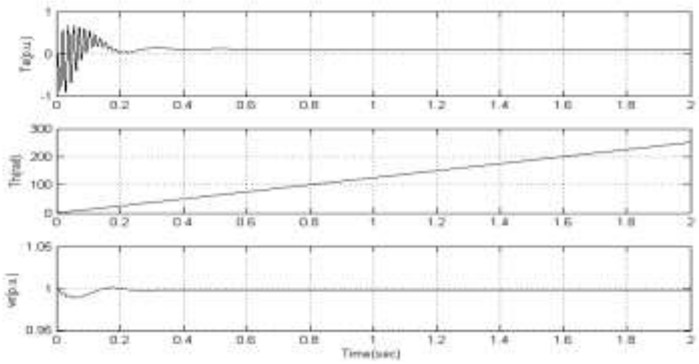
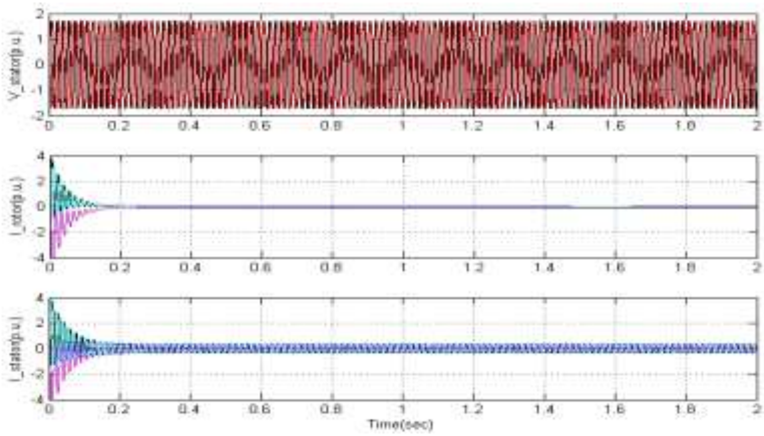


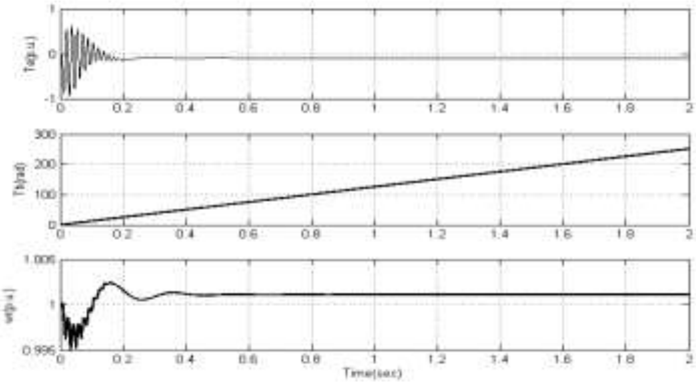
Figure 17. (b) Stator currents, rotor currents and stator voltages (p.u)

Due to the mechanical shaft input is 0.1p.u and the shaft is running at synchronous speed (slip=0) DFIAM is still working as squirrel cage induction motor. The mechanical input helps to reduce the transients in Te and wr at t=0. Figure 17(a) shows the small time period dynamic deviations in the rotor and stator currents before reached to steady state. From Figure.17 (a) and 17(b) it is observed that the machine achieves the steady state response at t=0.2s.

CASE 3. When s=0, Tm=-0.1 and Vr=0.



(a)

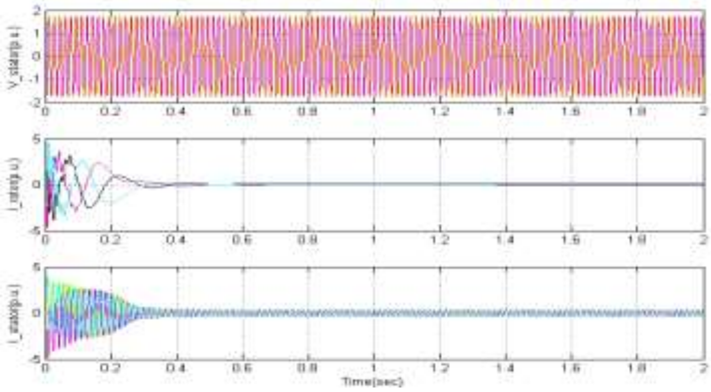


(b)

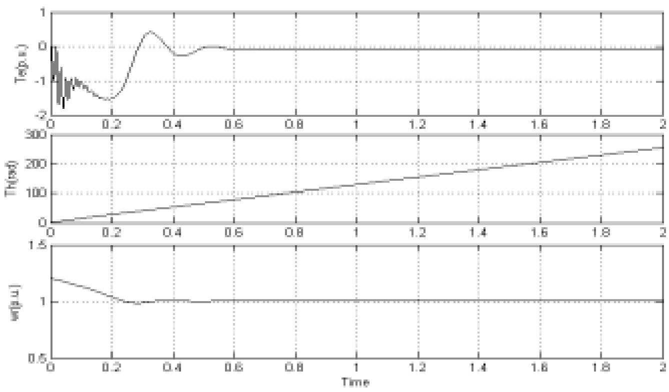
Figure 18. (a) Stator currents, rotor currents and stator voltages (p.u) (b) Transient response of Te(p.u), theta(rad) and generator's speed (p.u)

In this mode DFIAM is working as squirrel cage induction generator as shaft of the machine is running above the synchronous speed. Again the time taken by the machine to attain steady state is 0.3sec. Figure 18(a) shows that stator and rotor currents has some transients during t=0 to t=0.3sec also the response of Te and wr are shown in the Figure 18(b).

CASE 4. When s=-0.2, Tm=-0.1 and Vr=0.



(a)

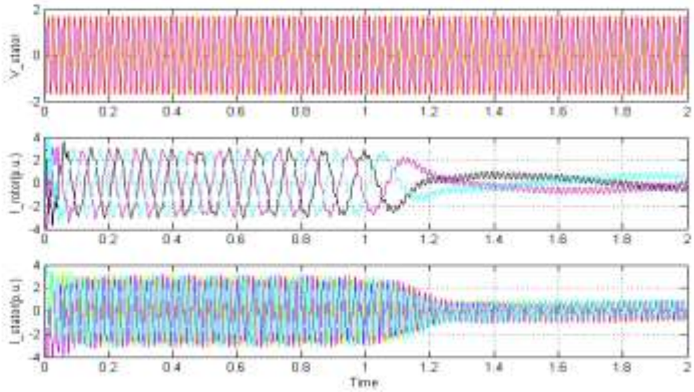


(b)

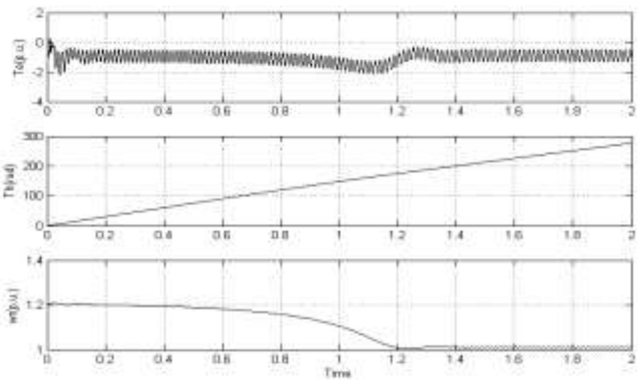
Figure 19. (a) Stator currents, rotor currents and stator voltages(p.u) (b) Transient response of Te (p.u), theta (rad) and generator's speed (p.u)

In this mode DFIAM is working as squirrel cage induction generator. The initial speed of the generator shaft is 1.2p.u. When supply voltage is applied to the stator's terminals the stator and rotor current transients are shown in the figure 19(a) also, the dynamic response of the (Te) and (wr) is shown in the Figure 19(b). At t=0.6 steady state is reached and all the above variables are settle down to steady state.

CASE 5. When s=-0.2, Tm=-0.1 and Vr=0.173V arbitrary taken the values of Vr to show the working of a DFAIM (without any control mechanism)



(a)

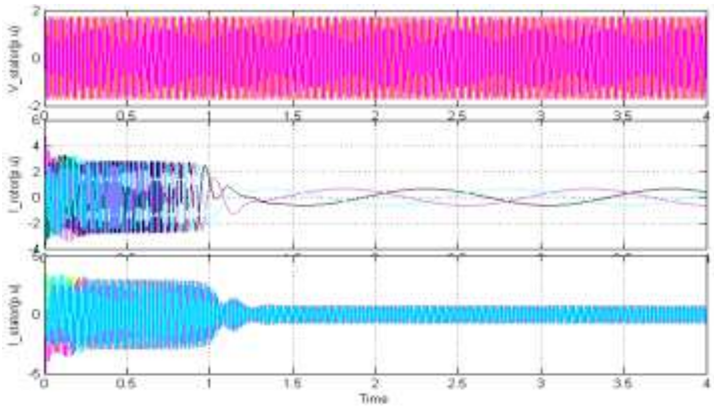


(b)

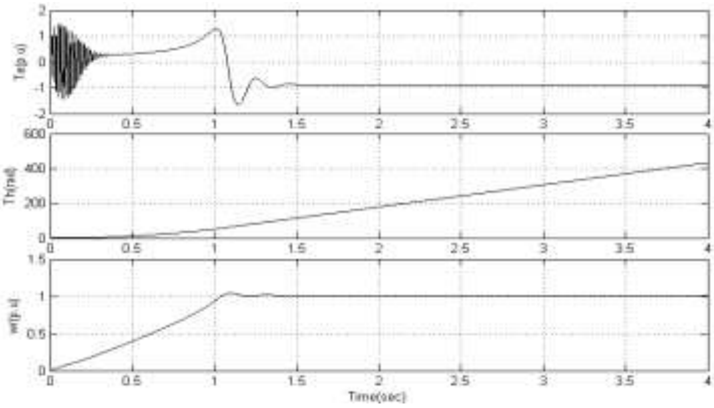
Figure 20. (a) Stator currents, rotor currents and stator voltages (p.u) (b) Transient response of Te (p.u), theta (rad) and generator's speed (p.u)

In this mode DFIAM is working as wound rotor induction generator. The initial speed of the generator shaft is 1.2p.u. When supply voltage is applied to the stator's terminals at t=0s, the stator and rotor current transients are shown in the Figure 20(a) also, the dynamic response of the (Te) and (wr) is shown in the Figure 20(b). At t=0.6 steady state is reached and all the above variables are settle down to steady state. Corresponding to negative mechanical torque the electromagnetic torque is also becomes negative to show the working of DFIAM as generator. As from the Figure 20(b) the Te does not settle down to steady state value which is the major concern for control need to apply to the rotor side.

CASE 6. When s=1, Tm=-0.1 and Vr=0 p.u. to show the transient case as compared to steady state:



(a)

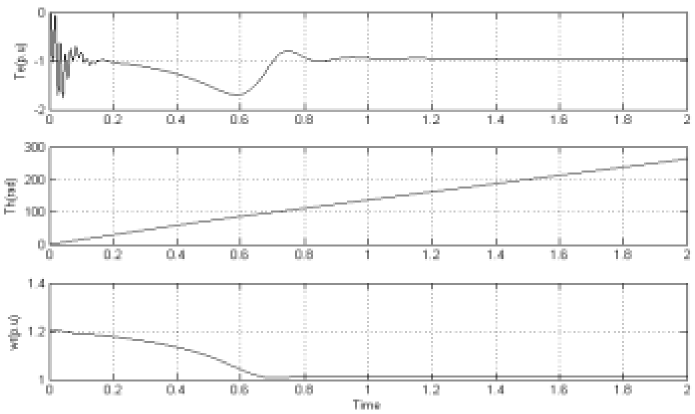


(b)

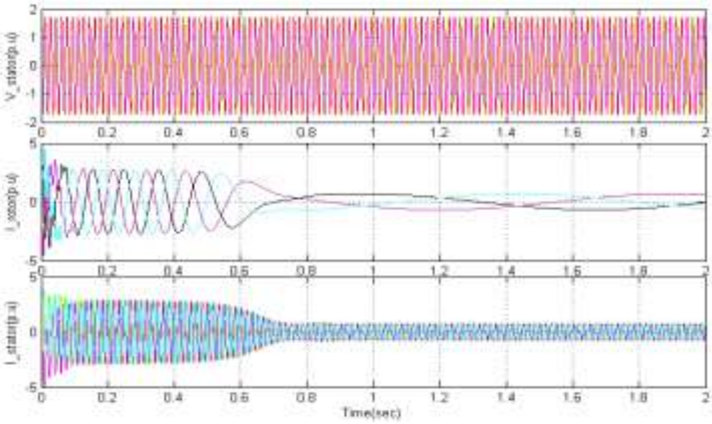
Figure 21. (a) Stator currents, rotor currents and stator voltages (p.u) (b) Transient response of Te (p.u), theta (rad) and generator's speed (p.u)

In this mode DFIAM is working as squirrel rotor induction motor and generator both. The initial speed of the generator shaft is 0. Slip is 1, When supply voltage is applied to the stator's terminals at t=0s, the stator and rotor current transients are shown in the Figure 21(a) also, the dynamic response of the (Te) and (wr) is shown in the Figure 21(b). At t=1.2 motoring mode is shifted to generator mode as the mechanical torque is -1 p.u. and this mode is used to show the comparison of steady state(Figure 3) and transient (Figure 15(b).

Case 7. When 1.5MW wind turbine is coupled with DFIAM and set s=-0.2, Vr=0. A direct PID pitch controller is implemented.



(a)

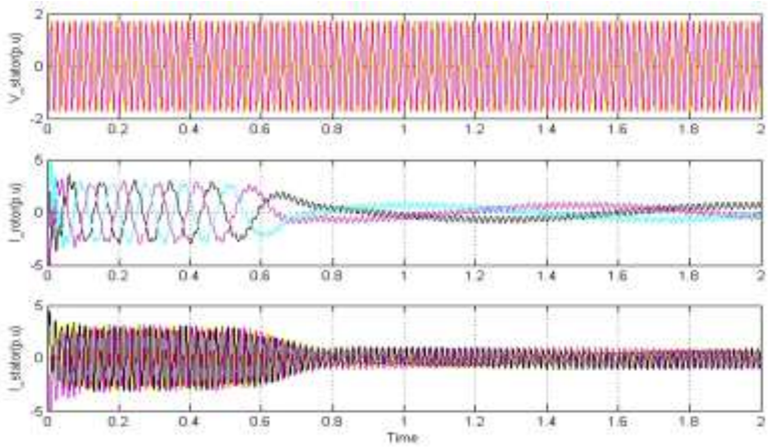


(b)

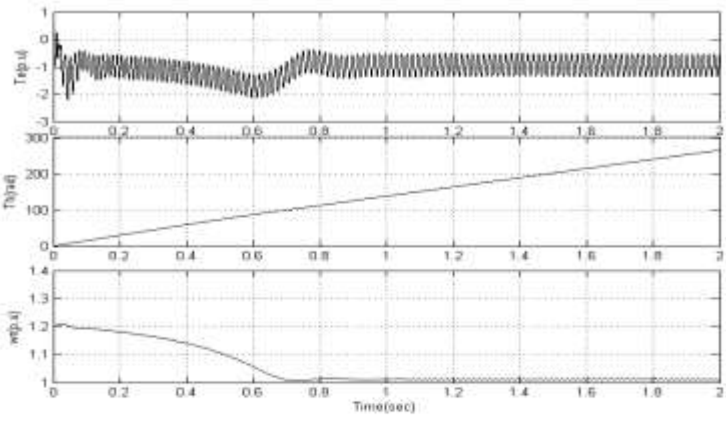
Figure 22. (a) Transient response of Te (p.u), theta (rad) and generator's speed (p.u) (b) Stator currents, rotor currents and stator voltages (p.u)

In this mode initial slip s=-0.2 which shows the initial speed DFIAM is 1.2 p.u. The machine working as squirrel rotor induction motor. When supply voltage is applied to the stator's terminals at t=0s, the stator and rotor current transients are shown in the Figure 22(b) also, the dynamic response of the (Te) and (wr) is shown in the Figure 22(a). At t=0.8 motoring mode reaches to steady state condition.

Case 8. When 1.5MW wind turbine is coupled with DFIAM and set s=-0.2, Vr=0.173v. A direct PID pitch controller is implemented.



(a)

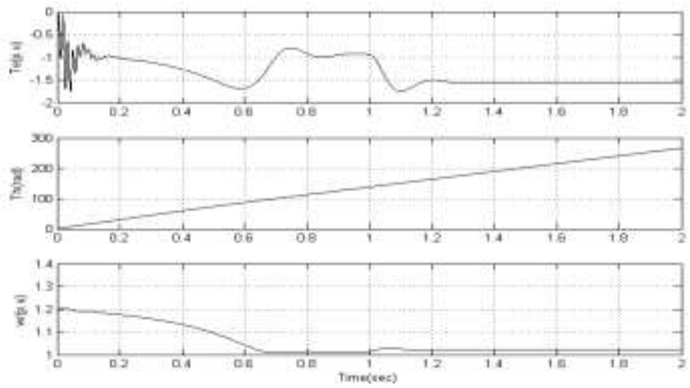


(b)

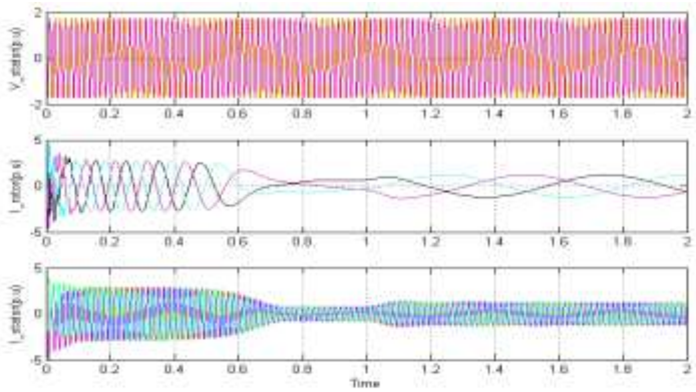
Figure 23. (a) Stator currents, rotor currents and stator voltages (p.u) (b) Transient response of Te (p.u), theta (rad) and generator's speed (p.u)

In this mode rotor voltage of 0.173 p.u. is applied and also the shaft of the generator is coupled with the 1.5MW wind turbine having a simple discrete PID controller for pitch control based on the error signal of generator speed and reference speed. Initial slip s=-0.2 which shows the initial speed DFIAM is 1.2 p.u. The machine working as DFIG rotor induction generator. When supply voltage is applied to the stator's terminals at t=0s, the stator and rotor current transients are shown in the Figure 23(b) also, the dynamic response of the (Te) and (wr) is shown in the Figure 23(a). At t=0.8 motoring mode reaches to steady state condition.

CASE 9. When s=-0.2, wind speed step change from 12m/s to 15 m/s and Vr=0.



(a)

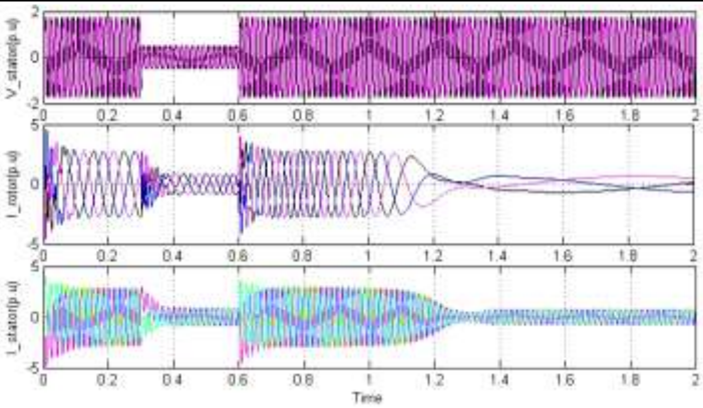


(b)

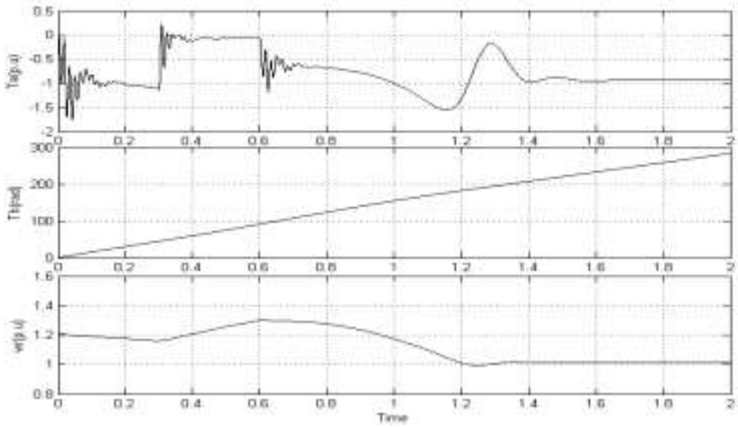
Figure 24. (a) Transient response of Te (p.u), theta (rad) and generator's speed (p.u) (b) Stator currents, rotor currents and stator voltages (p.u)

In this mode rotor voltage is set to 0 and also the shaft of the generator is coupled with the 1.5MW wind turbine having a simple discrete PID controller for pitch control based on the error signal of generator speed and reference speed. Initial slip s=-0.2 which shows the initial speed DFIAM is 1.2 p.u. The step change in wind speed is applied which drift from 12m/s to 15m/s. The machine is working as squirrel cage rotor induction generator. When supply voltage is applied to the stator's terminals at t=0s, the stator and rotor current transients are shown in the Figure 24(b) also, the dynamic response of the (Te) and (wr) is shown in the Figure 24(a). At t=1.8 generating mode reaches to steady state condition.

CASE 10. When s=-0.2, grid voltage changes to 0.3pu, wind speed=12m/s and Vr=0



(a)



(b)

Figure 24. (a) Stator currents, rotor currents and stator voltages (p.u) (b) Transient response of Te (p.u), theta (rad) and generator's speed (p.u)

In this mode rotor voltage is set to 0 and the stator voltage dip of 0.3p.u is applied at t=0.3s to t=0.6s. The shaft of the generator is coupled with the 1.5MW wind turbine having a simple discrete PID controller for pitch control based on the error signal of generator speed and reference speed. Initial slip s=-0.2 which shows the initial speed DFIAM is 1.2 p.u. The machine is working as squirrel cage rotor induction generator. When supply voltage is applied to the stator's terminals at t=0s, the stator and rotor current transients are shown in the Figure 24(a) also, the dynamic response of the (Te) and (wr) is shown in the Figure 24(b). At t=1.4 generating mode reaches to steady state condition.

10. CONCLUSIONS AND FUTURE SCOPE

In this work a fourth ordered continuous dynamic model of DFIAM is constructed using first order differential conditions. The steady state and dynamic performance of the macine is tested and compared. The various state space models of (DFIAM continuous type) based on rotor reference frame, stationary reference and synchronously rotation frames has been made. The simulation results shows that when DFIG is connected to grid with rotor voltage input at t=0, under various conditions when DFIAM is acting as squirrel cage motor and generator also, conditions are applied to test the model for wound rotor generators. From the results obtained for wound rotor generator when rotor input is given at slip s=-0.2 there is stability problems for rotor currents and electromagnetic torque Te as the transients are present in the curves. These variations in the torque at steady state need to be controlled. In this paper only the steady state and dynamic response is represented. The control aspects and various uncertainties are to be discussed in the coming research papers. Results show the performance of a standalone DFIAM connected to grid for the various cases of section VIII. Also the analysis of wind turbine based DFIAM for step change in wind speed and voltage dip is covered.

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REFERENCES

[1] Amaris, Hortensia et.al., "Reactive Power Management of Power Networks with Wind Generation," Lecture Notes in Energy, Springer-Verlag London, vol. 5, pp. 9-28, 2013.
[2] J. S. Lather, S. S Dhillon, S. Marwaha, "Modern control aspects in dfig based power sytstems: A review," *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, vol. 2, no. 6, pp. 2149-2161, June 2013.
[3] B. P. Roberts and C. Sandberg, "The Role of Energy Storage in Development of Smart Grids," in *Proceedings of the IEEE*, vol. 99, no. 6, pp. 1139-1144, June 2011.
[4] L. Qu and W. Qiao, "Constant Power Control of DFIG Wind Turbines With Supercapacitor Energy Storage," in *IEEE Transactions on Industry Applications*, vol. 47, no. 1, pp. 359-367, Jan.-Feb. 2011.
[5] J. A. Baroudi, V. Dinavahi and A. M. Knight, "A review of power converter topologies for wind generators," *IEEE International Conference on Electric Machines and Drives, 2005.*, San Antonio, TX, 2005, pp. 458-465.
[6] M. Zamanifar, B. Fani, M.E.H. Golshan, H.R. Karshenas, "Dynamic modeling and optimal control of DFIG wind energy systemsusing DFT and NSGA-II," *Electric Power Systems Research* vol. 108 , pp50– 58, 2014.
[7] Ahmed M. Kassem, Khaled M. Hasaneen, Ali M. Yousef, "Dynamic modeling and robust power control of DFIG driven by wind turbine at infinite grid," *Electrical Power and Energy Systems*, vol.44, pp. 375–382, 2013.
[8] Nolan D. Caliao, "Dynamic modelling and control of fully rated converter wind turbines," Renewable Energy, vol. 36, pp. 2287-2297, 2011.
[9] Hee-Sang Koa, Gi-Gab Yoon, Nam-Ho Kyunga, Won-Pyo Hong, "Modeling and control of DFIG-based variable-speed wind-turbine," *Electric Power Systems Research*, vol.78, pp. 1841–1849, 2008.
[10] Jiabing Hu, Yikang He, "Modeling and enhanced control of DFIG under unbalanced grid voltage conditions," *Electric Power Systems Research*, vol.79, pp. 273–281, 2009.
[11] C. Belfedala, S. Gherbia, M. Sedraouia, S. Moreau, "Robust control of doubly fed induction generator for stand-alone applications," *Electric Power Systems Research*, vol.80, pp. 230–239, 2010.
[12] Izaskun Sarasola, Javier Poza, Miguel. Rodriguez, Gonzalo Abad, "Direct torque control design and experimental evaluation for the brushless doubly fed machine," *Energy Conversion and Management,* vol.52, pp. 1226–1234, 2011.
[13] S. Heier, "Grid Integration of Wind Energy Conversion Systems," John Wiley & Sons, Ltd. 2006.
[14] Bianchi, F.D. et.al., "Wind Turbine Control Systems Principles, Modelling and Gain Scheduling Design," London: Springer-Verlag, 2007.
[15] N. W. Miller, J. J. Sanchez-Gasca, W. W. Price and R. W. Delmerico, "Dynamic modeling of GE 1.5 and 3.6 MW wind turbine-generators for stability simulations," *2003 IEEE Power Engineering Society General Meeting (IEEE Cat. No.03CH37491)*, Toronto, Ont., 2003, pp. 1977-1983 Vol. 3.