Steady State and Dynamic Modeling of DFIG

4.1 Introduction to DFIG

DFIG is also known as doubly fed induction asynchronous machine (DFIAM) with wound rotor construction. Recently, DFIAM has become more popular WECS as it provides variable speed operations. The fixed speed WECS were based on synchronous generator with rating of control equipment as that of generator. The power control equipment is required to provide active and reactive power compensation during load/demand fluctuations. The full rating power electronic converter employed to regulate active and reactive power is very expensive for fixed speed WECS as compared to that of DFIG-WT system where power converter with 30% rating of DFIG/DFIAM is required [5]-[8]. The voltage stability control is supplemented with reactive power error control. DFIG/DFIAMs have control options from stator as well as rotor side. A blade pitch angle control mechanism is also required to control and maximize mechanical power output of the wind turbine under different wind speed range. Pitch angle controller actuates on the basis of error signal between reference wind turbine speed and generator measured speed [7]-[12].

The major advantage of DFIAM is that about 70% of power is transferred directly through stator side with Flexible AC Transmission system (FACTs) devices like Static Synchronous Compensator (STATCOM) installed at PCC. The FACTs devices work on the principle of dynamically regulated the magnitude of reactance connected in parallel with DFIAM’s Stator [5]-[10]. The rest of the 30% power is fed to the grid with the help of power electronic converter connected to rotor side with rating about 25%-30% of
DFIG’s power rating in contrast to fixed speed synchronous generator [7],[53]. DFIG demands for its accurate dynamic mathematical model for predicting its response under various conditions. Different models in dq-reference frame of the DFIG system and at the angular speed of $\omega_{syn}$ exist in literature [7]-[12],[54],[51]. Dynamic time domain DFIG model with synchronously rotating reference frame was made [7]-[12]. Steady state and dynamic models with their control strategies were proposed for wind turbine generators [7],[54]. Steady state and dynamic mathematical models were implemented in [31]-[55]. In this chapter, the mathematical DFIAM was constructed in mainly two reference frames such as rotor and stationary frame using first order differential equations. The steady state and dynamic response of the DFIAM are analyzed for different operating conditions. Also, Inertia emulation model for DFIG is derived for frequency support.

4.1.1 Steady State model of DFIAM

The steady state model of three phase DFIAM machine is obtained from an equivalent circuit diagram as shown in Figure 4.1(a) and 4.1(b) [12],[47],[149]. Here, the mutual reactance $X_m$ is referred onto stator voltage supply source $V_{std}$ side and the simplified model of the induction machine is as shown in Figure 4.1(b). To obtain the torque equation from the equivalent circuit, the rotor current $I_r$ is expressed as [6]-[10],[12],[46],[47].

$$I_{std}' = \frac{V_{std}' - V_{rd}' I_{std}' s_{slip}}{(R_s + \frac{R_r}{s_{slip}}) + j(X_{ls} + X_{lr})} \quad (4.1)$$

where, $V_{std}'$ and $V_{rd}'$ are $pu$ stator and rotor per phase steady state voltages ; $X_{ls}, X_{lr}$ stator and rotor leakage reactance in $pu$ ; $R_s$ and $R_r$ are stator and rotor resistance per
phase in \( pu \); \( s^{\text{slip}} \) is slip factor, \( \psi_s^{\text{flux}} \) and \( \psi_r^{\text{flux}} \) are \( pu \) stator and rotor per phase flux linkages.

The electromagnetic torque in an induction machine is the sum of air gap power and rotor fed power given by Equation (4.2) as \([11],[12],[46],[47]\):

\[
T_{e_{-\text{std}}} = \left( I_{\text{std}}^r \left( \frac{R_r}{s^{\text{slip}}} \right) + P_R \right)
\]

(4.2)

where, \( T_{e_{-\text{std}}} \) is the \( pu \) electromechanical torque from stator side, \( P_R \) is the rotor fed active power, \( L_m \) is the \( pu \) mutual inductance from Stator side, \( \omega_{\text{syn}} \) is the synchronous or angular speed at supply frequency \( pu \) and \( \phi_p \) power factor angle. The rotor fed active power is given by:

\[
P_R = \frac{V_r}{s^{\text{slip}}} I_{\text{std}}^r \cos \phi_p
\]

(4.3)

The magnetizing current \( I_{\text{std}}^m \) is given as:

\[
I_{\text{std}}^m = \frac{V_{\text{std}}^s}{X_m}
\]

(4.4)

The total input stator current per/phase is as:

\[
I_{\text{std}}^s = I_{\text{std}}^m + I_{\text{std}}^r
\]

(4.5)

Stator flux linkages are given by the relation as:

\[
\psi_{\text{std}}^s = L_{\text{std}} I_{\text{std}}^s + L_m \left( I_{\text{std}}^s - I_{\text{std}}^r \right)
\]

(4.6)

The stator’s active power as:

\[
P_{\text{std}}^s = V_{\text{std}}^s I_{\text{std}}^s \cos \phi_p
\]

(4.7)

whereas, the Stator’s reactive power is given by:

\[
Q_{\text{std}}^s = V_{\text{std}}^s I_{\text{std}}^s \sin \phi_p
\]

(4.8)
$w_m$ being the angular velocity of the rotor in mechanical rad/s and is given by:

$$w_m = w_{syn} \frac{2}{P}$$

(4.9)

Alternatively, the electromagnetic torque is given by [46] the following equation:

$$T_{em} = \frac{3}{2} \frac{PR}{s_{slip}} \frac{I_r^2}{w_{syn}}$$

(4.10)

The steady state response of DFIAM is given by Equations (4.1)-(4.10), which are simulated and results are obtained for different values of slip and voltage magnitude. To obtain simulation results, the pu values of parameters used for 1.5MW DFIAM are given in Table 4.1. The Figures 4.2(a),(b),(c),(d) show the steady state response of the induction machine for the Equations (4.1)-(4.10).
Figure 4.2 shows the steady state response of electromagnetic torque corresponding to different rotor voltages and slip factors. Operating region of the doubly fed asynchronous machine lies between the slip factors 0.2 and -0.2. Figure 4.3(a) shows the rotor current variations for different pu voltage magnitudes and slip values. The rotor current follows the Equation (4.1). The variations of rotor active and reactive power as per rotor voltage magnitudes for slip values are also shown in the Figure 4.2. Figure 4.3(b) shows that magnetizing current remains constant over slip and rotor voltage variations.
The magnetizing reactance considered to be constant i.e. unsaturated 2.9 pu. The angular speed is considered to be 1 pu. The stator’s magnetizing current corresponds to different rotor fed voltages and slip values are shown in the Figure 4.3.

4.2 Dynamic model of DFIG/DFIAM with various reference frames.

The per unit dynamic model of the three phase doubly fed induction 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 [7],[12],[38],[51],[54].

i) 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}
\]  

\[(4.11)\]
Figure 4.4 Stator phase voltages along \( dq \) and \( a\beta \)-axis.

ii) \( a\beta o \) (stationary) to \( d\alpha o \) reference:

\[
\begin{bmatrix}
    v_d \\
    v_q \\
    v_0
\end{bmatrix} =
\begin{bmatrix}
    \cos wt & \sin wt & 0 \\
    -\sin wt & \cos wt & 0 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    v_\alpha \\
    v_\beta \\
    v_o
\end{bmatrix}
\]

(4.12)

iii) \( d\alpha o \) to \( abc \) reference:

\[
\begin{bmatrix}
    v_a \\
    v_b \\
    v_c
\end{bmatrix} =
\begin{bmatrix}
    \cos\left(wt - \frac{2\pi}{3}\right) & -\sin\left(wt - \frac{2\pi}{3}\right) & 1 \\
    \cos\left(wt + \frac{2\pi}{3}\right) & -\sin\left(wt + \frac{2\pi}{3}\right) & 1
\end{bmatrix}
\begin{bmatrix}
    v_d \\
    v_q
\end{bmatrix}
\]

(4.13)

Assumptions for the Dynamic Model:

- No magnetic flux saturation so the mutual inductance is constant i.e unsaturated.

- Machine windings are connected in star configuration on stator and rotor side hence no zero component.

- \( V_a = V_{ph\max}\sin wt \), \( V_b = V_{ph\max}\sin\left(wt - 120^\circ\right) \) and \( V_c = V_{ph\max}\sin\left(wt + 120^\circ\right) \) are balanced three phase stator voltages.

As per park’s transformation the three phase stator and rotor voltages transformed to a \( d\alpha o \) rotating frame is given the following equations[7],[38],[51]:

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\[
\begin{bmatrix}
V_{qs} \\
V_{ds} \\
V_{bs}
\end{bmatrix} =
\begin{bmatrix}
-sin\theta_s & cos\theta_s & 1 \\
-sin\left(\theta_s - \frac{2\pi}{3}\right) & cos\left(\theta_s - \frac{2\pi}{3}\right) & 1 \\
-sin\left(\theta_s + \frac{2\pi}{3}\right) & cos\left(\theta_s + \frac{2\pi}{3}\right) & 1
\end{bmatrix}
\begin{bmatrix}
V_{as} \\
V_{bs} \\
V_{cs}
\end{bmatrix}
\tag{4.14}
\]

\(dq\) –axis components of stator voltages in terms of stator line voltages are given as:

\[
\begin{bmatrix}
V_{ds} \\
V_{qs}
\end{bmatrix} = \left(\frac{1}{3}\right)\begin{bmatrix}
\sqrt{3}\sin\theta_s + \cos\theta_s & V_{abs} & 2\cos\theta_s V_{bcr} \\
-\sqrt{3}\cos\theta_s + \sin\theta_s & V_{abs} & 2\sin\theta_s V_{bcr}
\end{bmatrix}
\tag{4.15}
\]

\(dq\) –axis components of rotor voltages in terms of rotor line voltages are given as:

\[
\begin{bmatrix}
V_{dr} \\
V_{qr}
\end{bmatrix} = \left(\frac{1}{3}\right)\begin{bmatrix}
\sqrt{3}\sin\Gamma + \cos\Gamma & V_{abr} & 2\cos\Gamma V_{bcr} \\
-\sqrt{3}\cos\Gamma + \sin\Gamma & V_{abr} & 2\sin\Gamma V_{bcr}
\end{bmatrix}
\tag{4.16}
\]

\[
\Gamma = \theta_s - \theta_r
\tag{4.17}
\]

\(\theta_s\) is the angle of reference frame and \(\Gamma\) is the angle between reference frame and position of rotor. \(w_s\) 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 \(W\) pu speed matrix for stator and rotor circuit is given by

\[
W = \begin{bmatrix}
0 & -w_s & 0 & 0 \\
w_s & 0 & 0 & 0 \\
0 & 0 & 0 & -(w_s - w_r) \\
0 & 0 & (w_s - w_r) & 0
\end{bmatrix}
\tag{4.18}
\]
4.2.1 Dynamic model of DFIG under 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 Equations (4.19) and (4.20). $\theta_r$ = the position of phase ‘a’ of rotor abc frame in electrical degree with respect to phase ‘a’ of stator abc reference frame as shown in Figure 4.5.

![Figure 4.5 Stator and rotor phase voltages along dq-axis for rotor reference frame.](image)

Stator voltage equations in $dq$-frame with respect to stator line voltages as:

\[
\begin{bmatrix}
V_{ds} \\
V_{qs}
\end{bmatrix} = \left(\frac{1}{3}\right) \begin{bmatrix}
(\sqrt{3}\sin \theta_r + \cos \theta_r)V_{abs} \\
(-\sqrt{3}\cos \theta_r + \sin \theta_r)V_{abs}
\end{bmatrix}
\begin{bmatrix}
2\cos \theta_r V_{hcr} \\
2\sin \theta_r V_{hcr}
\end{bmatrix}
\]

(4.19)

Rotor voltage equations in $dq$-frame with respect to the rotor line voltages as:

\[
\begin{bmatrix}
V_{dr} \\
V_{qr}
\end{bmatrix} = \left(\frac{1}{3}\right) \begin{bmatrix}
V_{abr} \\
V_{hcr}
\end{bmatrix}
\begin{bmatrix}
2V_{hcr} \\
(-\sqrt{3})V_{abr}
\end{bmatrix}
\]

(4.20)

For rotor reference frame $w_s = w_r$ for pu system $w_s = 1$ pu
\[
W = \begin{bmatrix}
0 & -w_r & 0 & 0 \\
w_r & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 
\end{bmatrix}
\] (4.21)

In general stator voltage \(dqo\) components in terms of voltage drops are as follows:

\[
\begin{align*}
V_{ds} &= \frac{d\varphi_{ds}}{dt} - w_r\varphi_{qs} + R_s i_{ds} \\
V_{qs} &= \frac{d\varphi_{qs}}{dt} + w_r\varphi_{ds} + R_s i_{qs} \\
V_{0s} &= \frac{d\varphi_{0s}}{dt} + R_s i_{0s}
\end{align*}
\] (4.22)

Also, the rotor voltages \(dqo\) components in terms of voltage drops are as follows:

\[
\begin{align*}
V_{dr} &= \frac{d\varphi_{dr}}{dt} - (w_r - w_r')\varphi_{qr} + R_r i_{dr} \\
V_{qr} &= \frac{d\varphi_{qr}}{dt} + (w_r - w_r')\varphi_{dr} + R_r i_{qr} \\
V_{0r} &= \frac{d\varphi_{0r}}{dt} + R_r i_{0r}
\end{align*}
\] (4.23)

From Equations (4.21), (4.22) and (4.23), the stator and rotor voltages for rotor reference frame are as:

Stator and rotor \(dqo\) voltages are given as:

\[
\begin{align*}
V_{ds} &= \frac{d\varphi_{ds}}{dt} - w_r\varphi_{qs} + R_s i_{ds} \\
V_{qs} &= \frac{d\varphi_{qs}}{dt} + w_r\varphi_{ds} + R_s i_{qs} \\
V_{0s} &= \frac{d\varphi_{0s}}{dt} + R_s i_{0s}
\end{align*}
\] (4.24)

\[
\begin{align*}
V_{dr} &= \frac{d\varphi_{dr}}{dt} + R_r i_{dr} \\
V_{qr} &= \frac{d\varphi_{qr}}{dt} + R_r i_{qr} \\
V_{0r} &= \frac{d\varphi_{0r}}{dt} + R_r i_{0r}
\end{align*}
\] (4.25)
By using the above Equations (4.24) and (4.25), the stator and rotor fluxes are described by the following relation as:

\[
\dot{\varphi}_{dq,s,r}(t) = \begin{bmatrix} V_{dq,s,r} \end{bmatrix} + \begin{bmatrix} -W \end{bmatrix} \begin{bmatrix} L^{\dagger} \end{bmatrix} \varphi_{dq,s,r}(t)
\]

\[
\varphi_{dq,s,r}(t) = \int \left( \begin{bmatrix} V_{dq,s,r} \end{bmatrix} + \begin{bmatrix} -W \end{bmatrix} \begin{bmatrix} L^{\dagger} \end{bmatrix} \varphi_{dq,s,r}(t) \right) dt
\]  

(4.26)

The above relation gives the stator and rotor flux vectors \( \varphi_{dq,s,r} \) in matrix form. Hence, the electromagnetic torque developed can be expressed as:

Electromagnetic torque:

\[
T_e = (\varphi_{ds,i_qs} - \varphi_{qs,i_qs})
\]  

(4.27)

From the mechanical model, the shaft generator speed is given as:

\[
\frac{d}{dt} w_m = \frac{1}{2H} (T_e - Fw_m - T_m)
\]  

(4.28)

\[
w_r(pu) = w_m = \int \frac{1}{2H} (T_e - Fw_m - T_m) dt
\]  

(4.29)

Since, \( \theta_e = \int w_r w_e dt \), therefore \( \theta_e = \theta_m / p \)

### 4.2.2 Dynamic model of DFIG/DFIAM under stator or stationary reference frame

For stationary reference frame phase ‘a’ of the stator voltage is in phase with the \( d \)-axis, thus \( \theta_r = 0 \), \( \Gamma = -\theta_r \) and stator and rotor voltages to \( dq \) component are given by Equation (4.30) and Equation (4.31) respectively. Here, \( \theta_r \) is the position of phase ‘a’ of rotor abc frame in electrical degree with respect to phase ‘a’ of stator abc reference frame as shown in Figure 4.6. Stator voltage equations in \( dq \)-frame are given in terms of line voltages as [7],[11], [12],[38], [51]:

\[
\begin{bmatrix} V_{ds} \\
V_{qs} \end{bmatrix} = \begin{bmatrix} \frac{1}{3} & V_{abs} & 2V_{bcs} \\
0 & (-\sqrt{\frac{3}{3}}) & V_{abs} \end{bmatrix}
\]  

(4.30)

Rotor \( dq \)-voltages are given by Equation (4.31) as:
where \( w_s \) 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 circuit is given by Equation (4.32). For stationary reference frame, \( w_s = 0 \) for pu system.

\[
W = \begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & w_r & 0 \\
0 & 0 & -w_r & 0 \\
\end{bmatrix}
\]  

(4.32)

The stator \( dqo \) voltages:

\[
\begin{align*}
V_{ds} &= \frac{d\phi_{ds}}{dt} + R_i i_{ds} \\
V_{qs} &= \frac{d\phi_{qs}}{dt} + R_i i_{qs} \\
V_{0s} &= \frac{d\phi_{0s}}{dt} + R_i i_{0s}
\end{align*}
\]  

(4.33)

![Figure 4.6 Stator and rotor phase voltages along \( dq \)-axis for a stationary reference frame.](image)

Rotor \( dqo \) voltages:

\[
\begin{align*}
V_{dr} &= \frac{d\phi_{dr}}{dt} + w_r \varphi_{dr} + R_i i_{dr} \\
V_{qr} &= \frac{d\phi_{qr}}{dt} + (-w_r)\varphi_{dr} + R_i i_{qr} \\
V_{0r} &= \frac{d\phi_{0r}}{dt} + R_i i_{0r}
\end{align*}
\]  

(4.34)
Stator and rotor flux vectors, electromagnetic torque and angular speed can be derived from the Equation (4.26)-(4.29).

4.3 Grid connected 1.5 MW DFIAM based wind turbine

To analyze the transient behavior of the doubly fed asynchronous machine, a Simulink® test model is constructed in MATLAB/Simulink® environment. A 1.5MW doubly fed asynchronous induction generator is connected to nominal line to line 575 V grid [11], [22],[51]. 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 the Figure 4.7.

![Figure 4.7 Test model for grid connected standalone DFIAM](image)

The single line diagram of the grid is shown in the Figure 4.7.

The test model shown above is used to test DFIAM’s performance pertaining to different operating conditions applied as below:

Case1. When DFIAM is at standstill i.e. \( s = 1 \). The external mechanical torque (\( T_m \)) and rotor voltage is also, set to zero.

Case2. DFIAM is started from standstill condition with some mechanical torque of \( T_m = -0.1 \text{pu} \).

Case3. When DFIAM is operated above synchronous speed with \( s = -0.2 \), and step voltage drop of 0.3 \( \text{pu} \) in stator voltage is applied. The rotor voltage \( V_r = 0 \). DFIAM is working in generating mode.
Table 4.1 1.5MW DFIG Generator Data [22],[51]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{nom}$</td>
<td>1.667e6 MVA</td>
<td>$L_{ss}$</td>
<td>0.18 pu</td>
</tr>
<tr>
<td>$V_{nom}$</td>
<td>575V</td>
<td>$i_{b}$</td>
<td>1673/1.414 A</td>
</tr>
<tr>
<td>$H$</td>
<td>0.68 s</td>
<td>$L_{sw}$</td>
<td>0.16 pu</td>
</tr>
<tr>
<td>$F$</td>
<td>0.01 pu</td>
<td>$P$</td>
<td>3</td>
</tr>
<tr>
<td>$R_{s}$</td>
<td>0.016 pu</td>
<td>$R_{r}$</td>
<td>0.023 pu</td>
</tr>
<tr>
<td>$f_{nom}$</td>
<td>60 Hz</td>
<td>$w_{p}$</td>
<td>2pi $f_{nom}$</td>
</tr>
</tbody>
</table>

4.3.1 Wind turbine model

The mechanical power is produced by the wind sweeping the turbine with swept area $S$ of the air disk due to the rotation of the turbine blades. The power coefficient of performance $C_p$ is dually dependent upon the blade pitch angle $\beta$ as well as the tip to speed ratio $\lambda$. The expression for power extracted from wind is as expressed in terms of the Equations (3.2)-(3.4) discussed in previous chapter. In this work, the Wind turbine is coupled to the shaft of DFIAM and the performance of the DFIAM is tested with slip $s = 1$ and $s = -0.2$. The results show the performance of wind turbine based DFIAM connected to grid. Further, a simple proportional gain of discrete PID controller is used which actuates pitch angle control for an error signal generated by reference $pu$ speed and generator’s $pu$ speed [7],[11],[22].

4.3.2 Performance study of doubly fed induction machine

In this section, the results of different case studies performed on the DFIAM are used to examine the behavior of DFIAM machine as motoring and generating mode as follows:

**Case 1 When slip** $s = 1, T_m = 0, V_r = 0$.

In this case, the slip is set to one i.e. DFIAM is in standstill condition. The DFIAM machine is operating as squirrel cage induction motor as the rotor voltage $V_r = 0$. 
The DFIAM is set to work as squirrel cage induction machine with 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 4.8(a) shows the dynamic response of stator
and rotor currents with magnitude of $5 \, pu$ at $t = 0$. At $t = 4s$ rotor current attain minimum value 0.01 $pu$ and stator current attains steady state value of 0.4 $pu$. Figure 4.8(b) shows the transient response of electromagnetic torque $T_e$ and generator shaft speed $w_r$ in $pu$.

**Case 2.** When $s = 1$, $T_m = -0.1pu$ and $V_r = 0 pu$

The response of DFIAM under this case is shown in Figure 4.9(a) and 4.9(b). Here DFIAM is working as squirrel rotor induction motor as well as generator both. The initial speed of the generator shaft is 0.

![Figure 4.9 (a) Stator currents, rotor currents and stator voltages (pu)](image)

For slip as 1 with supply voltage applied to the stator’s terminals at $t = 0s$, the stator and rotor current transients are shown in the Figure 4.9(a).
The dynamic response of $T_e$ and $w_r$ are shown in the Figure 4.9(b). The motoring mode with $t_s = 1.2s$ is shifted to generator mode as the electrical torque is $-1pu$, and hence this mode shows the performance of the machine as motor and an induction generator.

**Case 3.** With $s = -0.2$, grid voltage changes to $0.3pu$, wind speed $= 12m/s$ and $V_r = 0 pu$

In this mode, the rotor voltage is set to zero and the stator voltage dip of $0.3pu$ is applied at $t = 0.3s$ to $t = 0.6s$. The shaft of the DFIG is coupled with the 1.5MW wind turbine and a simple PID controller for pitch control actuates on the error signal of generator speed and reference speed. Initial slip $s = -0.2$ refers to the initial speed DFIAM as $1.2 pu$. 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 as shown in the Figure 4.10(a).
Figure 4.10 (a) Stator currents, rotor currents and stator voltages (pu)

Figure 4.10 (b) Transient response of $T_e$ (pu), theta (rad) and shaft speed (pu).

Also, the dynamic response of $T_e$ and $w_r$ is shown in the Figure 4.10(b). At $t=1.4$, the generating mode reaches steady state condition.
4.4 Model for DFIG as inertial contribution to stabilize system frequency

Figure 4.11 shows the overall transfer-function block diagram of a power system comprising a conventional generator providing frequency regulation as well as a non-conventional DFIG-based wind turbine generator contributing to frequency regulation. The incremental active power demand $\Delta P_D$ subtracted from the incremental values of conventional generation $\Delta P_g$ and wind generation $\Delta P_{NC}$ equals the power transferred from the neighboring area, $\Delta P_{12}$ as given in (3.28).

![Diagram](image)

**Figure 4.11 Power system dynamic model with mixed generation [29]**

From Figure 4.11 and Equations (3.27), (3.28) and (3.32)

$$2H = fD^*T_p$$

$$D = \frac{1}{K_p}$$

$$\frac{2H}{f} \frac{d\Delta f}{dt} = \Delta P_f - D\Delta f = \Delta P_g + \Delta P_{NC} - \Delta P_{12} - \Delta PD - D\Delta f$$

$$\left(\frac{2H}{f} + K_{df}\right) \frac{d\Delta f}{dt} = P_g - \Delta P_{12} - \left(\frac{K_pf + D}{b^*}\right)\Delta f$$

Here $H$ is inertia constant of the power system and $D$ is the damping constant of the power system. Figure 3.3 shows the dynamic model adopted for the study of frequency
regulation [29] with DFIG-based wind turbine generator. This model is in essence taken from the DFIG inertia emulation model presented in Figure 4.12.

![Figure 4.12 DFIG-based wind turbine control based on frequency change [174], [179]](image)

The contribution of the DFIG towards system inertia can be seen in Equation (4.37). The differences between the models described in Figure 3.13 and that in Figure 4.12 [29] is the additional reference power setting which is build based on the change in frequency using a washout filter with time constant $T_w$ and relies on a conventional primary regulation performance in a transient.

$$\Delta P_f = \frac{1}{R} \Delta X$$

(4.39)

$R$ is the droop constant as used conventionally and $\Delta X$ is the frequency change measured at point of common coupling.

### 4.5 Conclusion

In this chapter, a fourth ordered continuous dynamic model of DFIAM is constructed using first order differential equations. The steady state and dynamic performance of the machine is tested in Simulink/ Matlab® environment. The various state space models of
DFIAM (continuous type) based on rotor reference frame and stationary reference frames has been made. The simulation results show the performance of DFIAM under various conditions as squirrel cage motor and generator. Lastly, the inertial response of DFIG was obtained to study system frequency stability issues.