Chapter 5

Grid-Connected Doubly-Fed Induction Generator

5.1 Introduction

Grid-controlled DFIG have been used extensively for wind turbine systems due to its variable speed capability, adjustable stator power factor, increased output power, and relatively small size converter compared to squirrel cage induction generators [27].
For grid-connected DFIG, the stator winding is directly connected to the power grid while its rotor winding is connected to a two back to back AC/DC converters as shown in Figure 5.1.
Since the stator of the DFIG is connected to a grid it has constant voltage and constant frequency and the objective is to control both active and reactive power under variable speed operation. This objective can be achieved by controlling rotor voltage magnitude, rotor voltage angle (δ), rotor frequency and rotor voltage sequence.

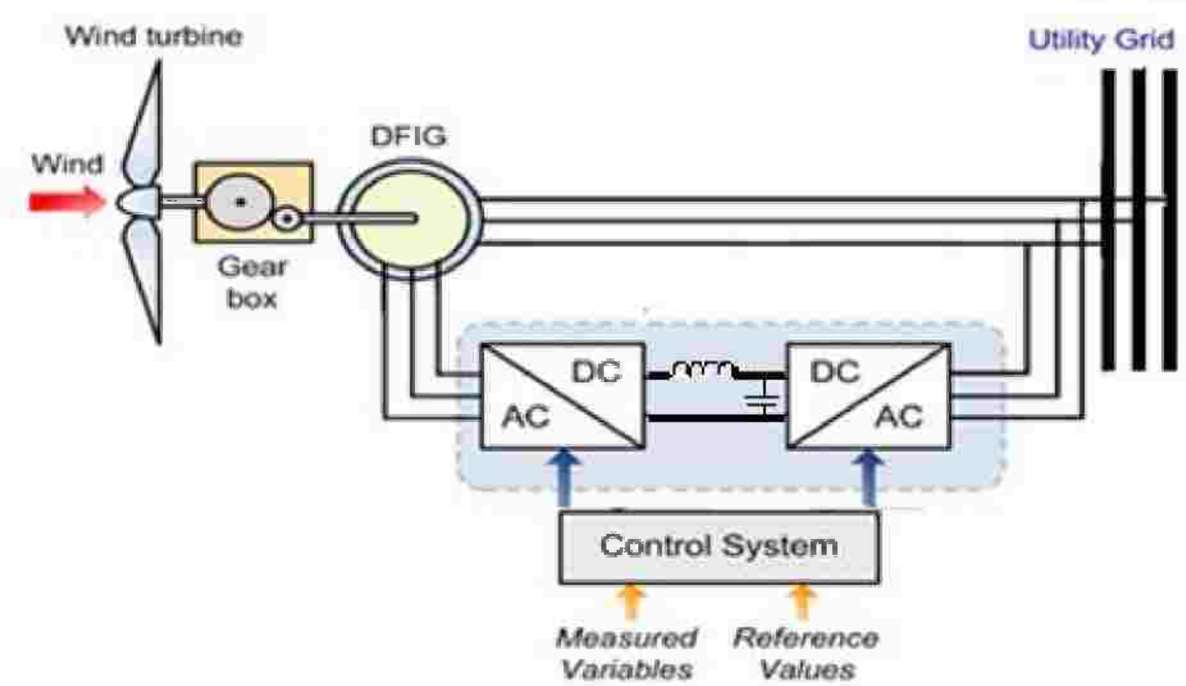


Figure 5.1 Grid connected DFIG

A schematic power flow diagram of grid-connected DFIG is shown in Figure 5.2. The positive direction for measurements are as indicated. It is obvious that, when the system works in the generating mode $P_s < 0$, i.e. negative. When the machine in variable speed operates below synchronous speed (sub-synchronous), slip power $P_r > 0$; when the machine operates above synchronous speed (super-synchronous), $P_r < 0$ [28].

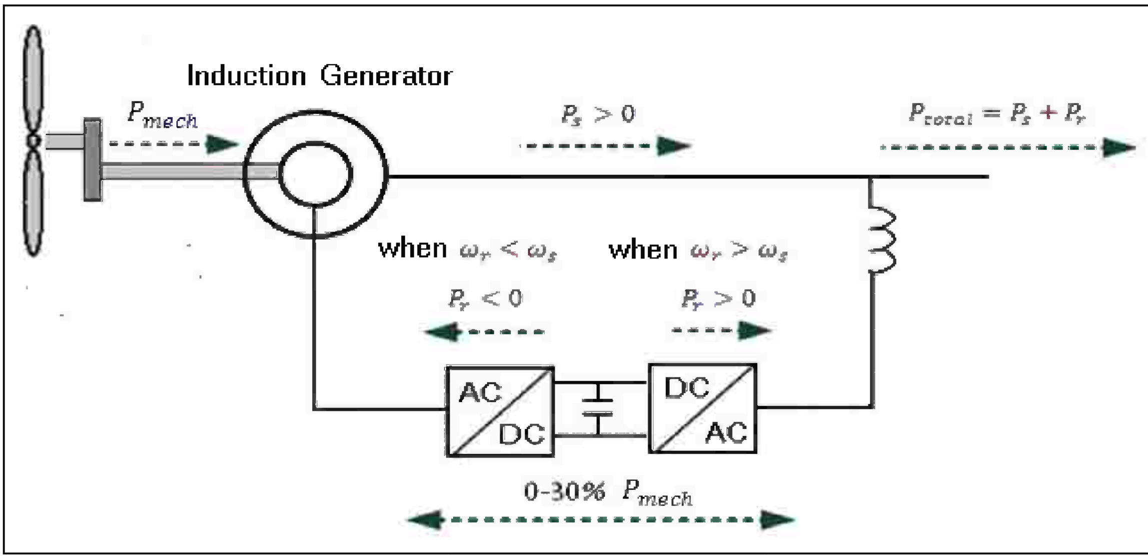


Figure 5.2 Power flow of grid-connected DFIG

5.2 Control strategy

From the well-known steady-state induction machine IEEE recommended equivalent circuit shown in Figure 5.3, the rotor voltage magnitude and angle during steady-state can be deduced as follows:

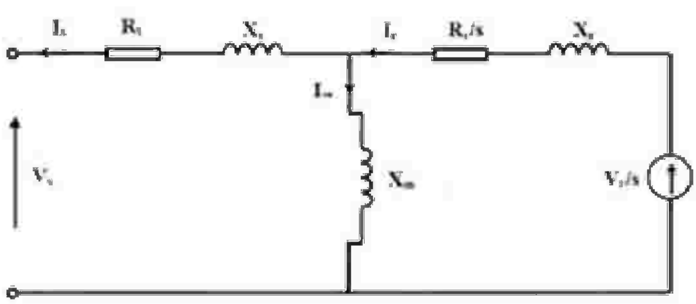


Figure 5.3 Induction machine IEEE recommended equivalent circuit

For a given stator active and reactive power, it follows that:

$$P_s = 3 * V_s * I_s * \cos \emptyset \qquad (5.1)$$

$$Q_s = 3 * V_s * I_s * \sin \emptyset \qquad (5.2)$$

Using equations (5.1) and (5.2), the stator current $\overline{I_s}$can be calculated. Then:

$$\overline{V_m} = \overline{V_s} + \overline{I_s} \, (R_s + j \, X_s) \qquad (5.3)$$

$$\overline{I_r} = \overline{I_m} + \overline{I_s} \qquad (5.4)$$

$$\overline{I_m} = \frac{\overline{V_m}}{j \, X_m} \qquad (5.5)$$

$$\overline{V_r} = S\,(\overline{V_m} + \overline{I_r}\,(\frac{R_r}{S} + j\,X_r)) \quad (5.6)$$

And the rotor voltage frequency is:

$$f_r = S\, f_s \quad (5.7)$$

Where:

P_s: Stator active power –W
Q_s: Stator reactive power –VAR
V_s : Stator voltage –V
I_s: Stator current –A
$\emptyset$: Angle between stator voltage and current
V_m: Magnetization branch voltage –V
I_m : Magnetization branch current –V
V_r : Rotor voltage –V
I_r : Rotor current –A
S : Slip

It should be noted that S is positive for sub-synchronous speed and S is negative for super-synchronous speed. These quantities will be introduced as inputs to the open-loop controller to drive the system of equations representing the machine performance during transient given in Chapter 2.

5.3 Simulation

Detailed system simulations were performed to evaluate the performance of the grid-connected DFIG using Simulink toolbox is shown in Figure 5.4. This system has MATLAB function blocks that can calculate the magnitude, angle, frequency and sequence of a rotor voltage. In practice this can be done using a DSP controller.
The system consists of a grid-side controlled converter (CON1) to achieve the required voltage magnitude and a rotor-side controlled converter (CON2) that controls the frequency, sequence and the phase shift of the rotor voltage. The following subsections will explain each block.

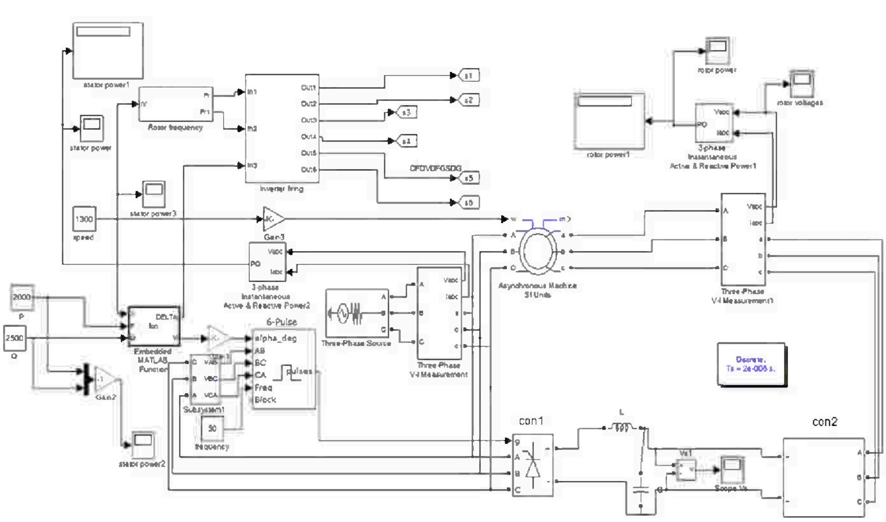


Figure 5.4 Grid-connected DFIG simulation

5.3.1 Embedded MATLAB function block

This block calculates the required rotor voltage magnitude and angle for the desired stator active and reactive power using the set of equations (5.1)-(5.6). The calculations were done using the machine parameters mentioned in Chapter 2. The stator voltage (grid voltage) is set to 380-V, 50-Hz.

5.3.2 Grid-side converter firing angle

The relation between the firing angle and the rotor voltage is as follows equation (5.8)

$$V_{o/p}=\frac{3\sqrt{3}}{\pi}*V_{phase}*\cos(\alpha) \qquad (5.8)$$

Where:

$V_{o/p}$: Grid-side converter (CON1) average output voltage (V)

V_{phase}: Grid-side converter (CON1) input peak phase voltage (V)

α: Grid-side converter (CON1) firing angle

For V_{phase}= 310-V the firing angle for grid-side converter is calculated from the calculated rotor voltage in Embedded MATLAB function as follows:

$$\alpha=\cos^{-1}\frac{V_{o/p}}{513.2} \qquad (5.9)$$

5.3.3 Rotor-side converter firing block

This block is shown in Figure 5.5. It generates CON2 firing signal based on the required frequency and the voltage sequence. For the sub-synchronous speed the sequence is positive and for the super–synchronous speed the sequence is negative. Also this block controls the required voltage angle phase shift.

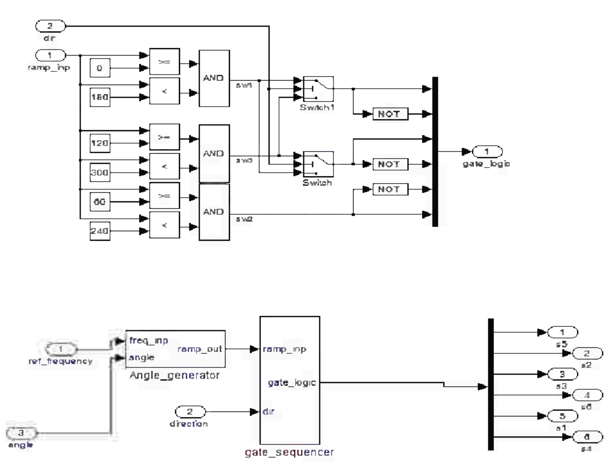


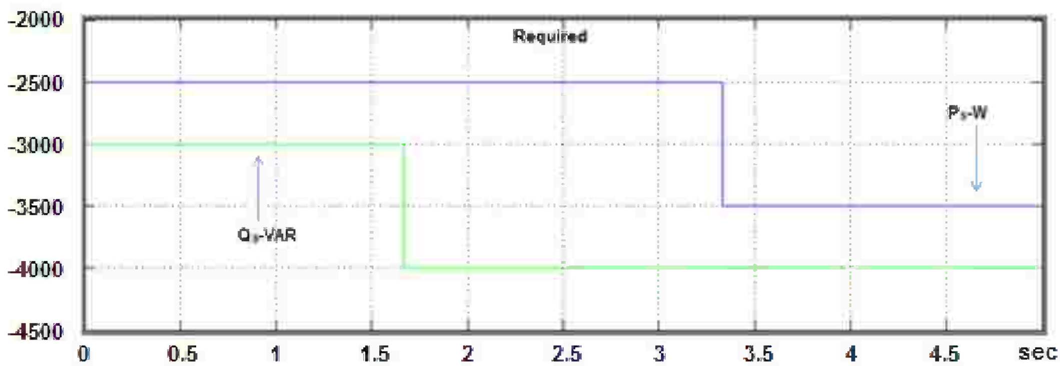
Figure 5.5 Inverter firing signal

5.4 Simulation results

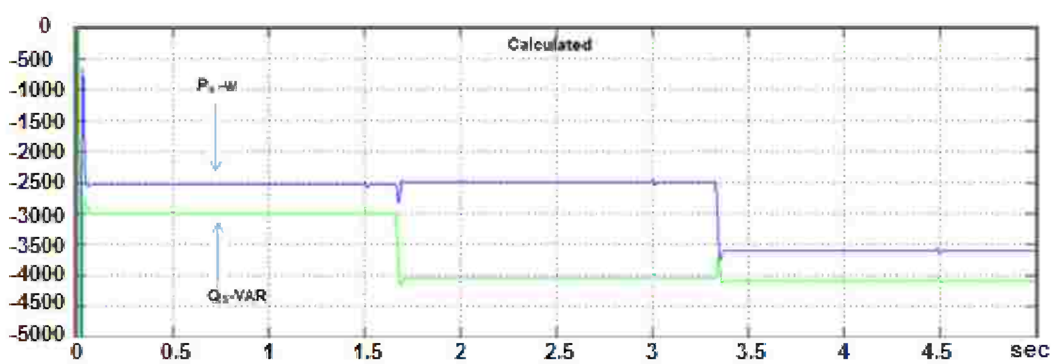
A digital simulation for grid-connected DFIG was carried out at two different rotor speeds 1300-rpm (sub-synchronous speed) and 1700-rpm (super-synchronous speed).

5.4.1 Sub-synchronous speed results

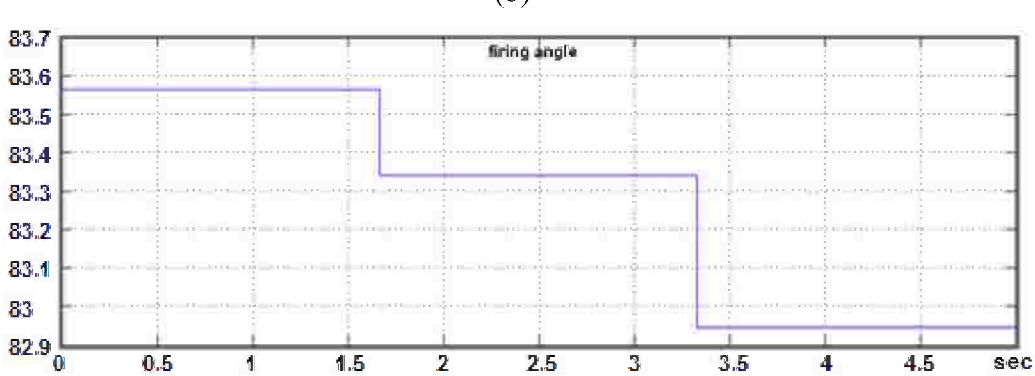
The required active and reactive powers supplied from the DFIG stator to the grid are as shown in Figure 5.6 (a). The active power was increased from 2500 to 3500-W at time =3.34-s, while the reactive power was increased from 3000 to 4000-VAR at time = 1.67-s. Figure 5.6 (b), (c), and (d) shows the corresponding stator, rotor active and reactive power and the rotor voltage.

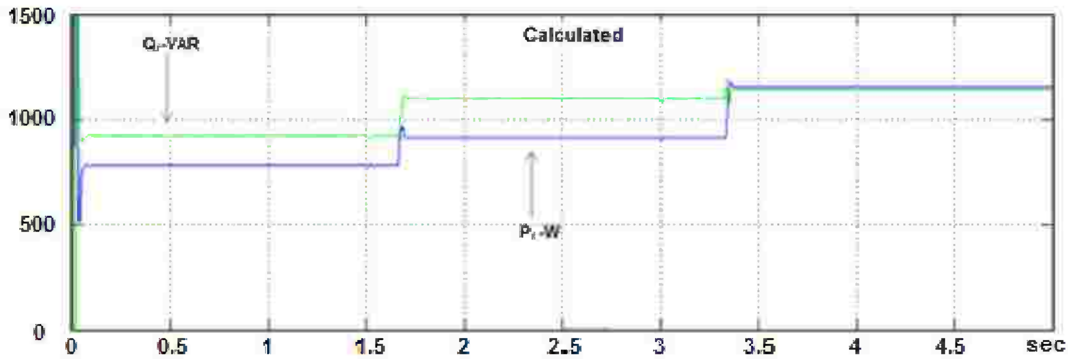


(a)

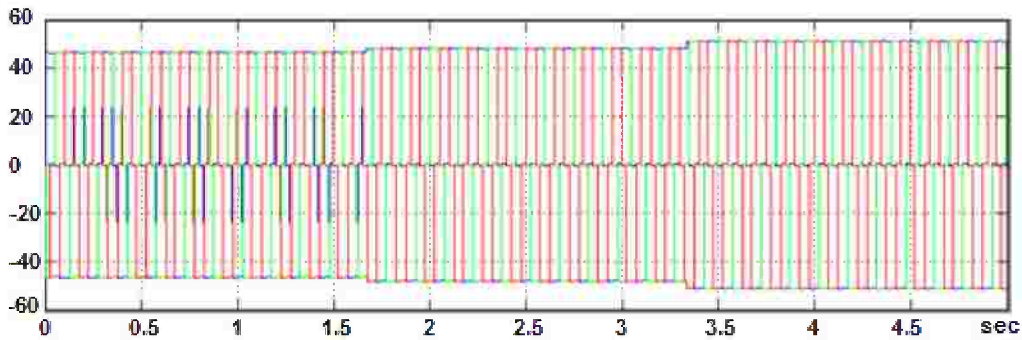


(b)





(c)



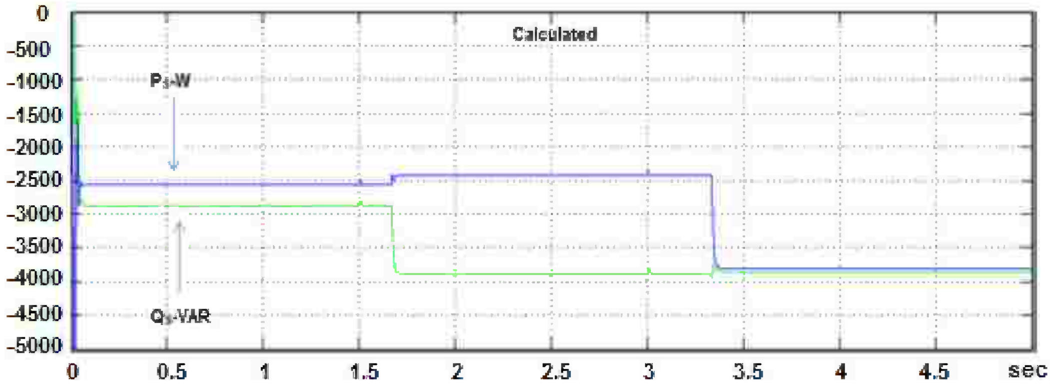
(d)

Figure 5.6 Stator and rotor power and voltages at 1300-rpm
(a) Required stator active and reactive power, (b) Calculated stator active and reactive power, (c) Grid-side converter firing angle, and calculated rotor active and reactive power, and (d) Three-phase rotor voltages

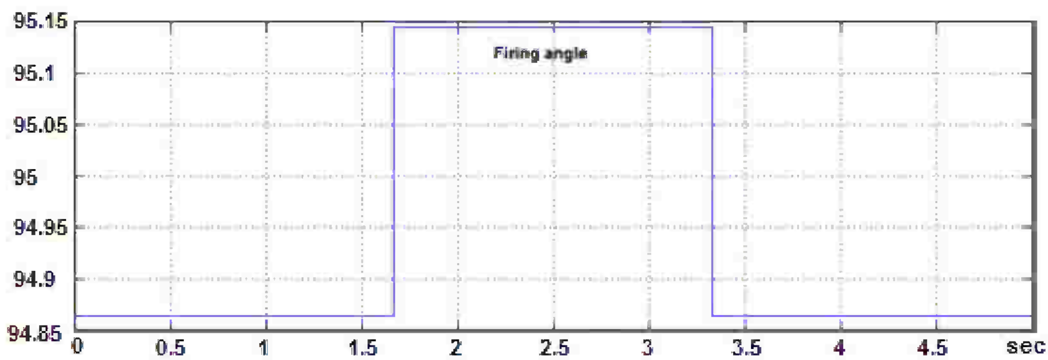
5.4.2 Super-synchronous speed results

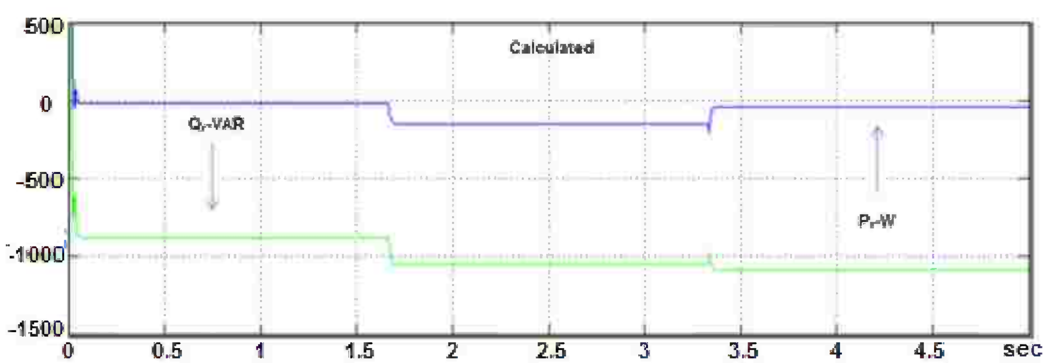
The required active and reactive powers supplied from the DFIG stator to the grid are as shown in Figure 5.7 (a). The active power was increased from 2500 to 3500-W at time =3.34-s, while the reactive power was increased from3000 to 4000-VAR at time = 1.67-s. Figure 5.7 (b), (c), and (d) shows the corresponding stator, rotor active and reactive power and the rotor voltage.
A comparison between figures 5.6(d) and 5.7(d) shows that the voltage sequence reverses for super-synchronous speed.

(a)

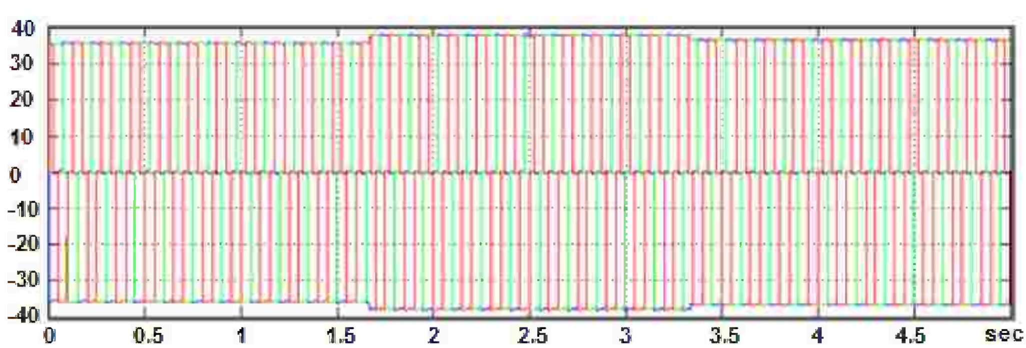


(b)





(c)



(d)

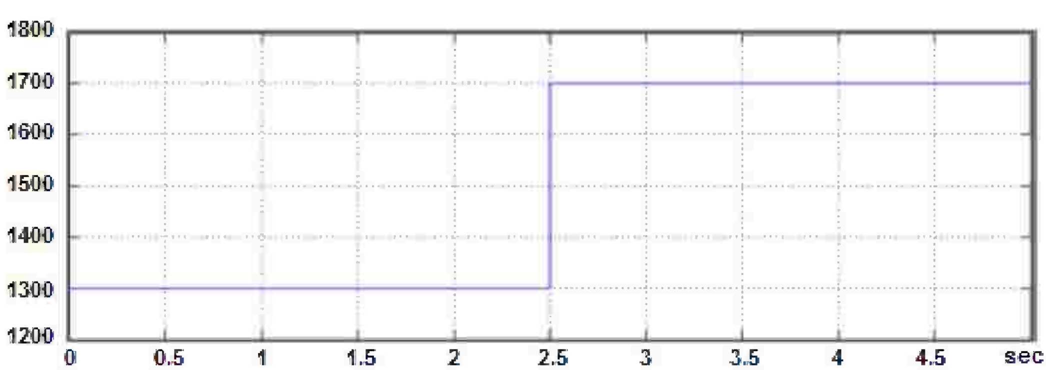
Figure 5.7 Stator and rotor power and voltages at 1700-rpm

(a) Required stator active and reactive power, (b) Calculated stator active and reactive power, (c) Grid-side converter firing angle, and calculated rotor active and reactive power, and (d) Three-phase rotor voltages

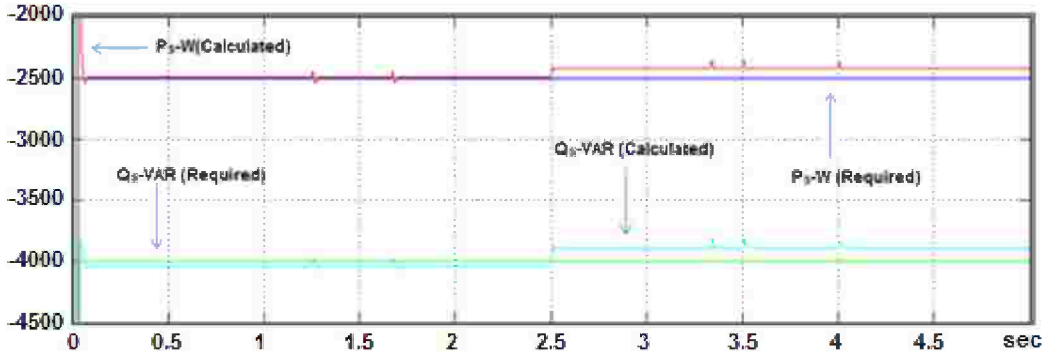
Figure 5.6 and Figure 5.7 indicate that the stator calculated active and reactive power follows the required ones. The maximum percentage error between required and calculated power is less than 7%. This error is acceptable since it is an open loop system and the rotor voltage magnitude and angle were calculated from an approximate equivalent circuit without considering the magnetic circuit saturation effect. The developed controller achieves the objective of controlling both active and reactive power under different speed pattern operation. It is also clear from firing angle figures for grid-side converter that this converter follows the change of rotor power direction, from working in the rectifying mode in Figure 5.6 ($\alpha < 90^o$) to work in the inverting mode in Figure 5.7 ($\alpha > 90^o$).

5.4.3 Speed variation results

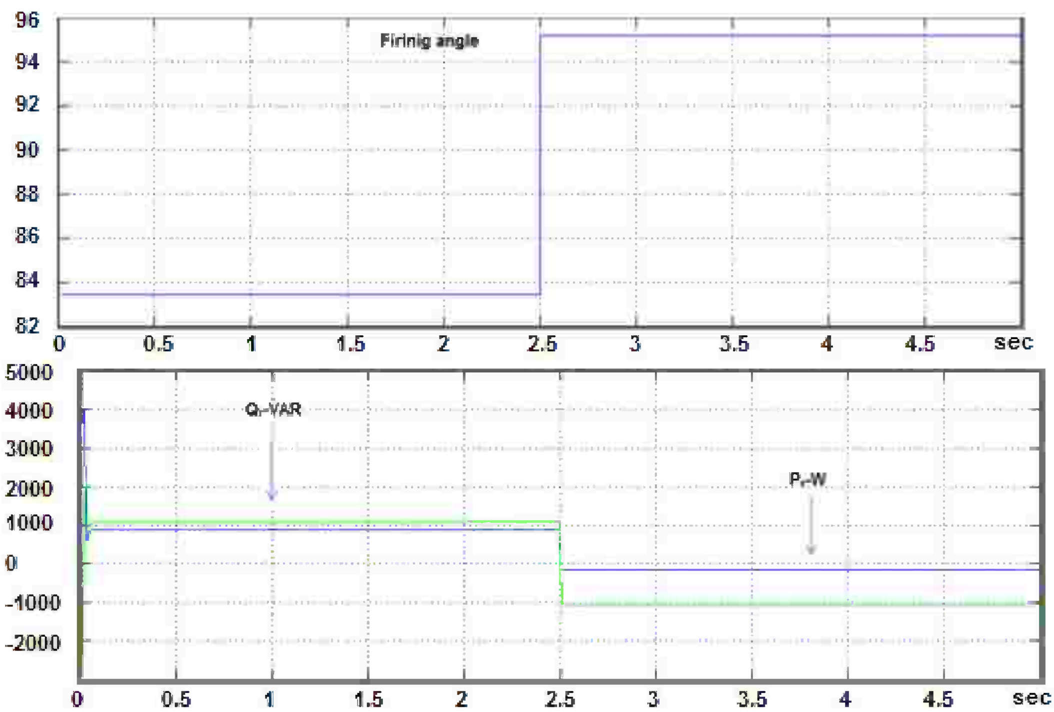
To study the effect of wind speed variation on both active and reactive output power supplied from the DFIG to the grid, it is assumed that an active power of 2500-W and a reactive power of 4000–VAR is required when a sudden change in the wind speed occurs. Figure 5.8(a) shows a variation of wind speed from 1300-rpm (sub-synchronous) to 1700-rpm (super-synchronous) at time= 2.5-s. Figure 5.8 (b), (c), and (d) shows the corresponding stator, rotor active and reactive power and the rotor voltage.
It should be noted that, the change in wind speed from sub-synchronous speed to super-synchronous speed changes the magnitude, the angle and the sequence of the rotor voltage, Figure 5.8(d), to keep the active and reactive power constant. The maximum percentage error between required and actual power is less than 5%. Again, it is clear from firing angle for grid-side converter that this converter follows the change of rotor power direction, from working in the rectifying mode for wind speed 1300-rpm ($\alpha < 90^o$) to work in the inverting mode for wind speed 1700-rpm ($\alpha > 90^o$).



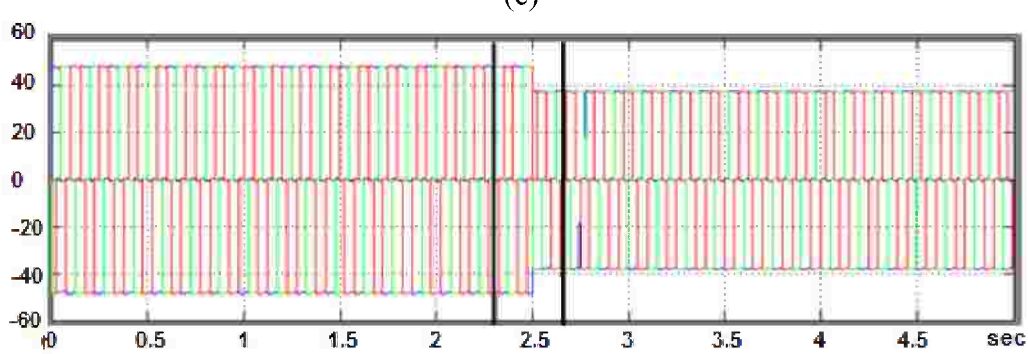
(a)

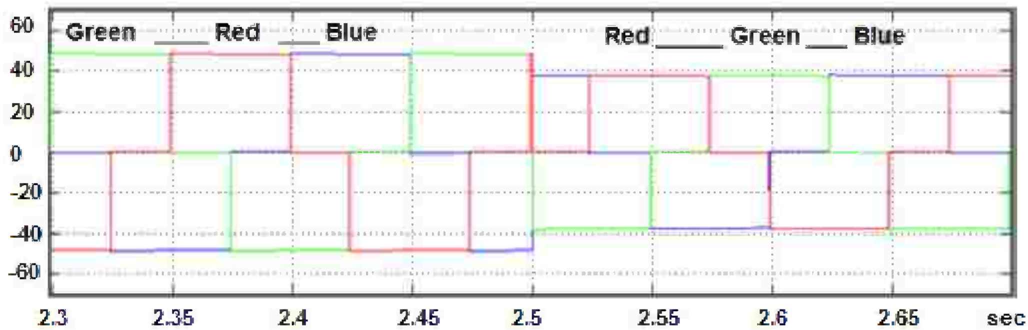

Ps-W(Calculated)
Qs-VAR (Required)
Qs-VAR (Calculated)
Ps-W (Required)
sec

(b)


Firinig angle
sec
Qr-VAR
Pr-W
sec

(c)


sec



(d)

Figure 5.8 Stator and rotor power and voltages

(a) Change in wind speed pattern, (b) Stator active and reactive power (required and calculated), (c) Grid-side converter firing angle, and calculated rotor active and reactive power, and (d) Three-phase rotor voltages