Chapter 3

Stand-Alone Doubly-Fed Induction Generator

3.1 Introduction

For stand-alone or autonomous operation, mostly single doubly fed induction generator or parallel operated generators are focused according to available analysis references. These induction generators driven by the individual prime movers (wind speed) employed excitation supply to build up desired voltage via self-excited phenomena. Hence the value of the excitation supply voltage and frequency and the rotor speed determine the magnitude of the generated voltage and its frequency [16].
Taking into account the principles of operation of doubly-fed induction generators that the magnetic field at the rotor can rotates in the same direction as the rotor speed or in the opposite direction, in this machine the rotor field rotates in the same direction as the rotor speed, in this case the slip S is represented in equation (3.1) [17].

$$S = \frac{n_s + n_r}{n_s} \tag{3.1}$$

Where

n_s : Synchronous rotating field speed (rpm)

3.2 Machine parameters

The machine parameters are the same as mentioned in Chapter 2, taking into account the influence of magnetizing flux linkage saturation the mutual inductance can be chosen from the look-up Table 3.1. Those values are calculated from no-load test at different stator voltages.

Table 3.1 Mutual inductance look-up table

V_{stator}(V)	150	170	200	215	250	300	325	350	380
L_m (H)	0.42	0.42	0.42	0.42	0.35	0.3	0.26	0.2	0.1722

3.3 Uncontrolled DFIG

A doubly fed induction generator (DFIG) is shown in Figure 3.1. The stator terminals are connected to the load without any control and the rotor terminals are connected to a three-phase supply to produce the necessary air gap flux.

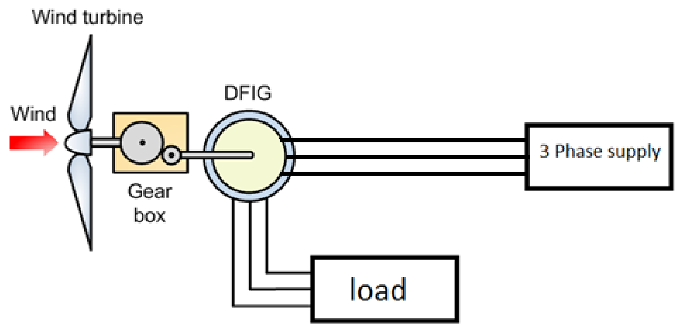


Figure 3.1 Uncontrolled DFIG

3.3.1 Simulation

Detailed system simulations were performed to evaluate the performance of the DFIG. Uncontrolled DFIG simulation using Simulink toolbox is shown in Figure 3.2. The stator terminals are connected to an inductive load. The rotor terminals are connected to a three phase supply to produce the required flux. The simulation with a fixed rotor voltage and frequency of 380-V and 50-Hz frequency will be performed with variation in the wind speed[18-19].

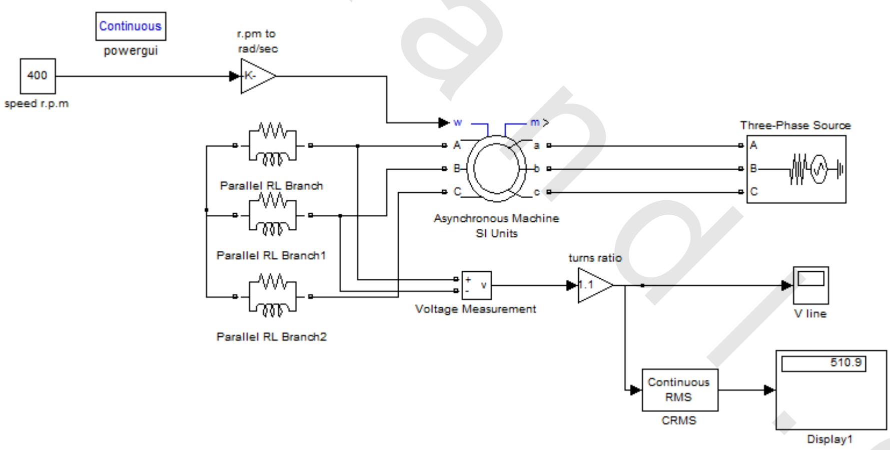


Figure 3.2 Stand-alone uncontrolled DFIG Simulink simulations

3.3.2 Scopes

The output voltage and frequency of the stator will change with the change of the wind speed. To show the effect of wind speed, the simulation will be performed for three different speeds. The output frequency was calculated as follows:

$$f = \frac{1}{T}$$

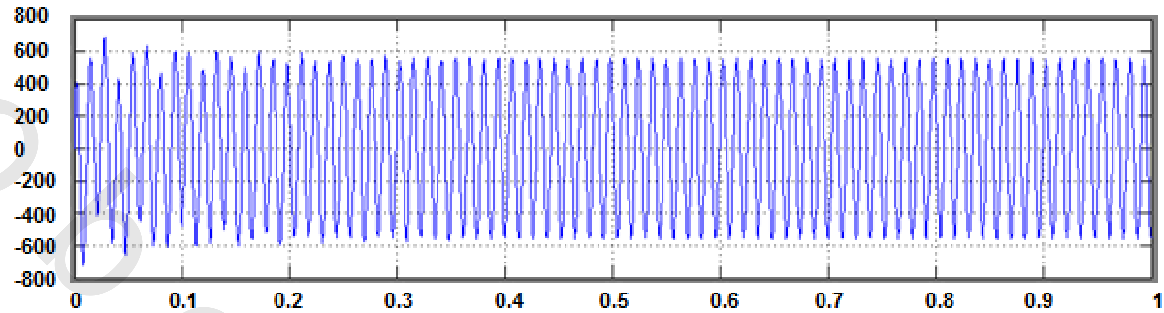
Where

f : frequency in hertz

T: Time period in second

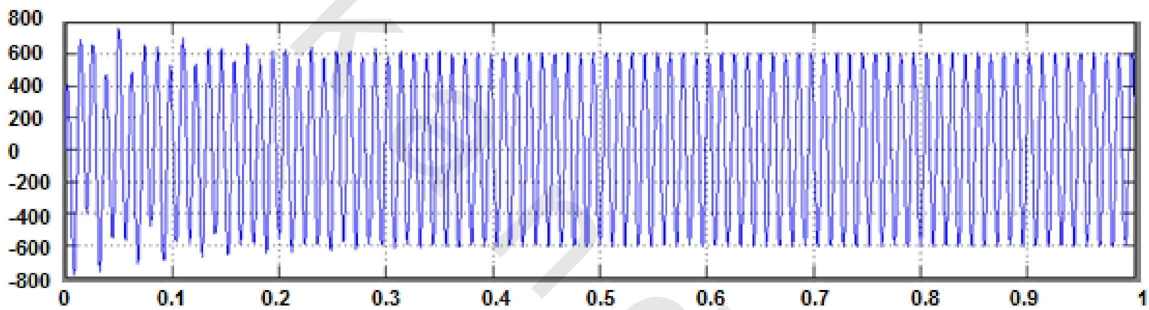
Figure 3.3 shows stator voltage at different rotor speeds.

$V = 398 - V$ $f = 76.67 - Hz$



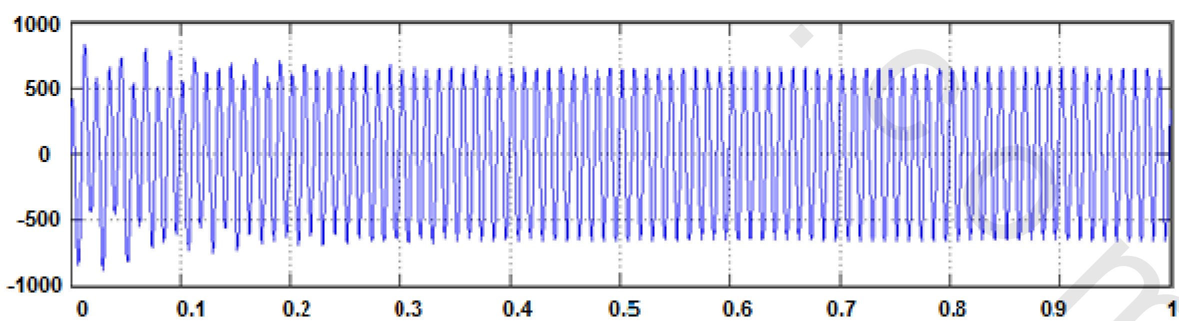
(a)

$V = 433.2 - V$ $f = 83.33 - Hz$



(b)

$V = 467.9 - V$ $f = 90 - Hz$

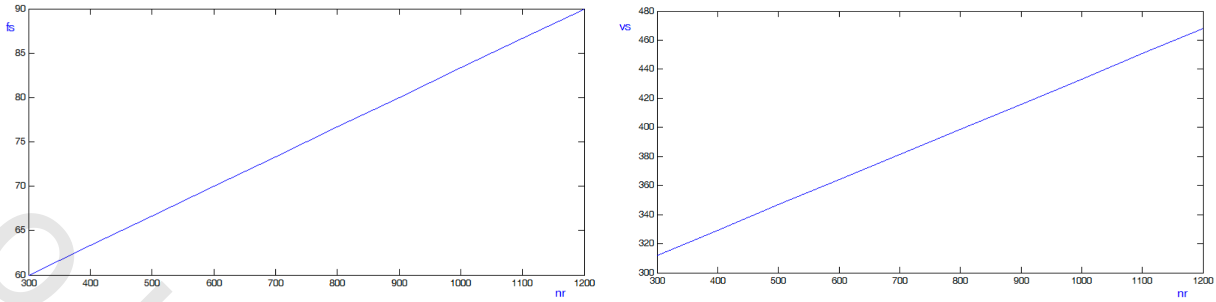


(c)

Figure 3.3 Stator voltage at different speeds: (a) 800-rpm, (b) 1000-rpm & (c) 1200-rpm

3.3.3 Comment

The uncontrolled system cannot achieve a fixed stator voltage and/or frequency as shown in Figure 3.4.



(a) (b)

Figure 3.4 Effect of speed variation at (a) the stator frequency (b) the stator voltage

3.4 Controlled DFIG

The change in the wind speed changes both stator voltage and frequency as indicated before, by using a rectifier and inverter the rotor voltage and frequency can be controlled in order to maintain constant stator voltage of 380-V and frequency of 50-Hz [20-21] . Figure 3.5 shows the controlled DFIG using a controlled AC/DC rectifier and a DC/AC six pulse (180°) inverter. Both rectifier and inverter are controlled to achieve constant V/f. The basic idea is to keep the load frequency and load voltage constant at 50-Hz and 380-V respectively. This is achieved by comparing the stator (load) frequency (50-Hz) with the variation in rotor speed. If, f_r is the rotor (inverter) frequency and f_s is the stator frequency, then:

$$f_r = \frac{f_s}{S} \qquad (3.2)$$

$$n_s = \frac{120 * f_s}{P} \qquad (3.3)$$

From equations (3.1), (3.2) and (3.3), therefore

$$f_r = f_s - \frac{P * n_r}{120} \qquad (3.4)$$

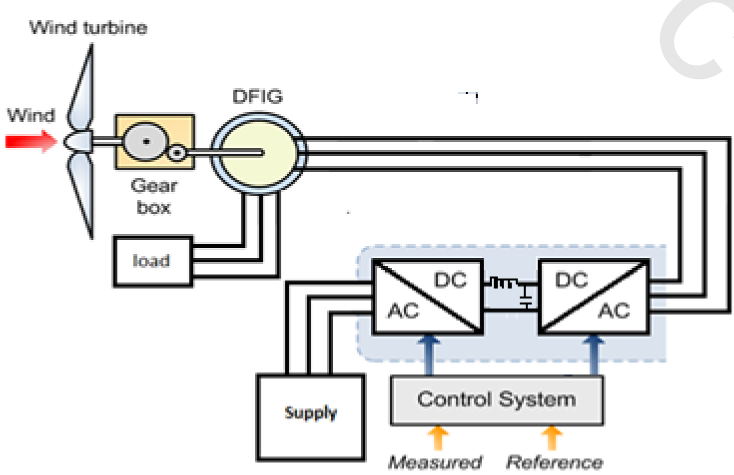


Figure 3.5 Controlled DFIG

3.4.1 Simulation

The system is consisting of a controlled rectifier and a dc filter linked with a six pulse (180°) inverter, the supply of the rectifier voltage 380-V and 50-Hz frequency and the DC filter component values are L= 3.2-mH, C= 500-µF. The following subsections will explain each block.

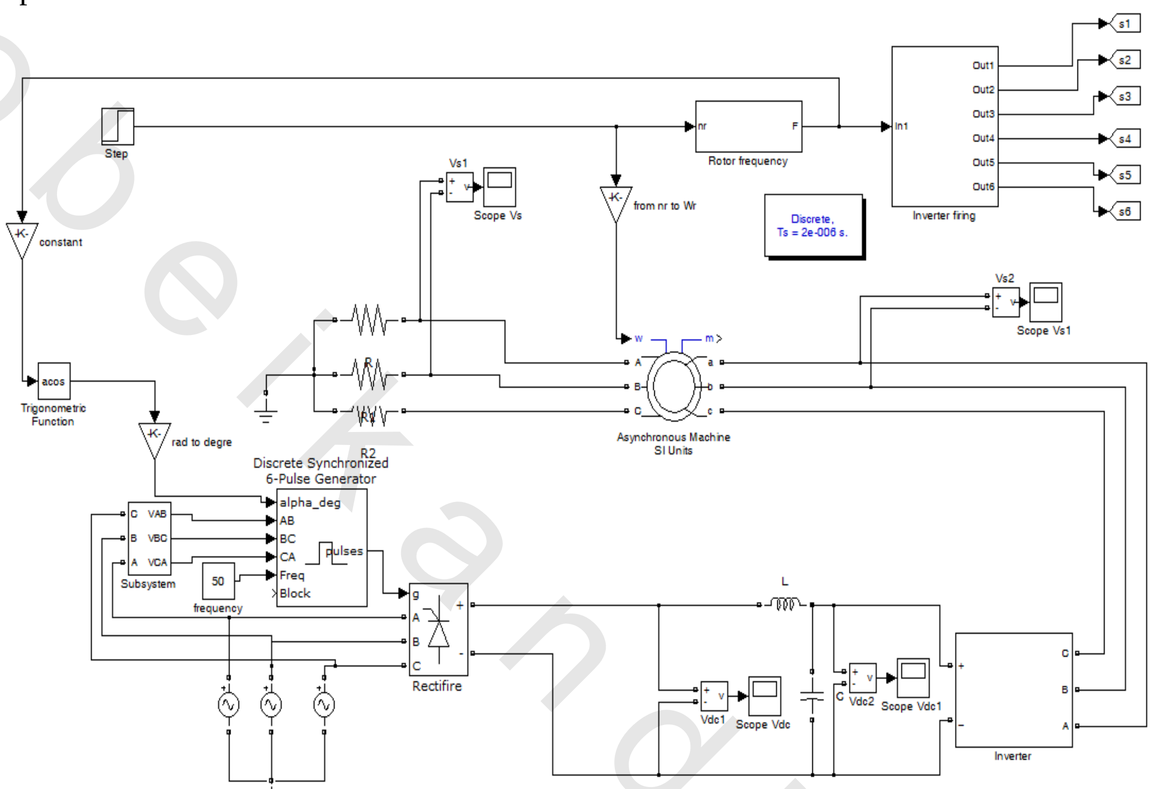


Figure 3.6 Closed loop Simulink simulation

3.4.1.1 Inverter frequency

The block shown in Figure 3.7 was built to get inverter frequency at different wind speed as given by equation 3.4:

$$f_s = f_L - \frac{P * n_r}{120} \quad , \qquad f_L = 50 - Hz$$

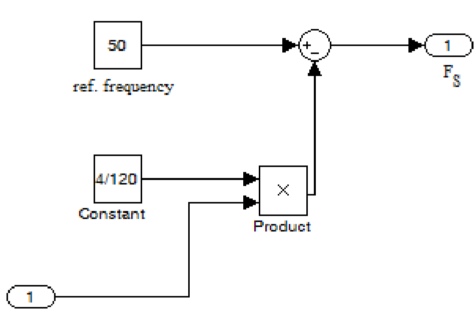


Figure 3.7 Inverter frequency block

3.4.1.2 Inverter firing

The block shown in Figure 3.8 was built to determine the inverter firing signals for the six transistors according to the required inverter frequency based on 180° firing technique.

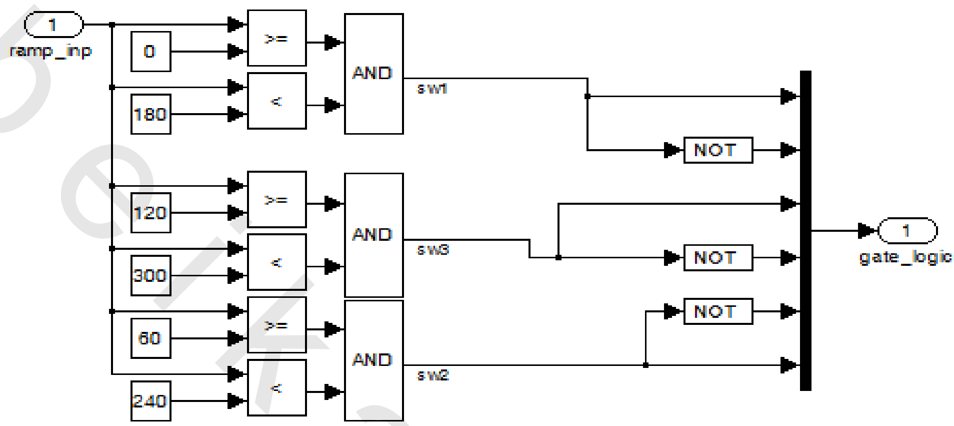


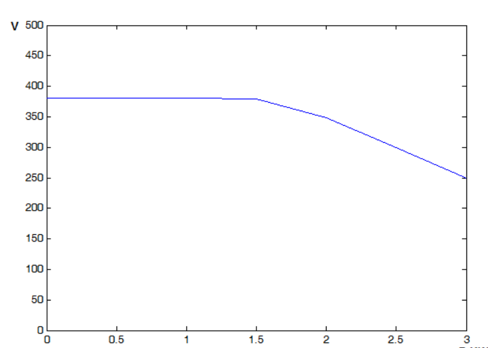
Figure 3.8 Inverter firing block

3.4.1.3 Discrete Synchronized 6-Pulse Generator

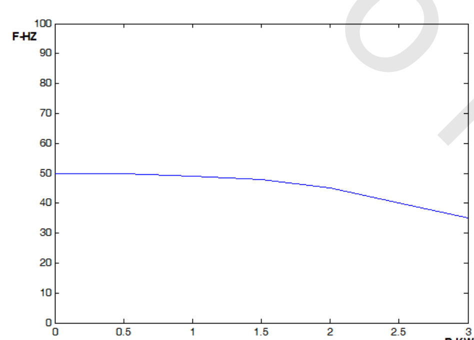
This is a MATLAB built-in block; it can be used to generate the firing signals for the six thyristors of the controlled rectifier. The output of the block is a vector of six pulses individually synchronized on the six thyristors. The pulses are generated α degree after the increasing zero crossings of the thyristor commutation voltages.

3.4.2 Generator loading characteristic

Figure 3.9 show the voltage and frequency of the generator output at different loading conditions.



(a)



(b)

Figure 3.9 Stator voltages and frequency at different loading: (a) voltage and power, (b) Frequency and power

3.4.3 Simulation Results

Typical generators after the gear box in the wind system is operating with a rotation speed of 800-rpm to 3600-rpm. For this reason the simulation speeds are selected ±20% of 1000-rpm [15]. Figure 3.10 shows the stator and rotor voltages at different speeds. It can be seen that both stator voltages and frequency are constant at 380-V and 50-Hz respectively.

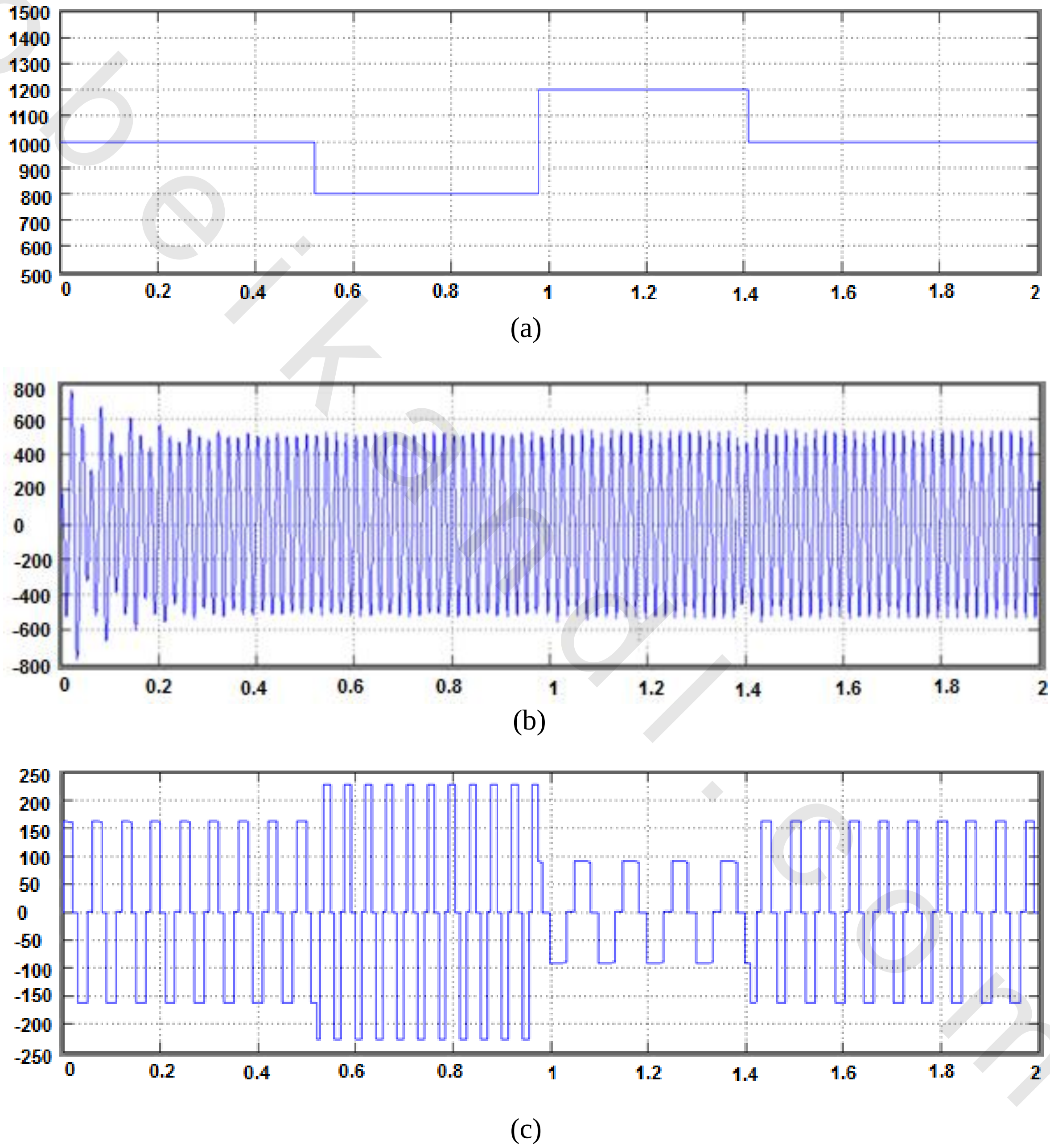


Figure 3.10 Stator and rotor voltages at different speeds: (a) Speed variation pattern, (b) Stator voltage, (c) Rotor voltage

3.4.3 Experimental Verification

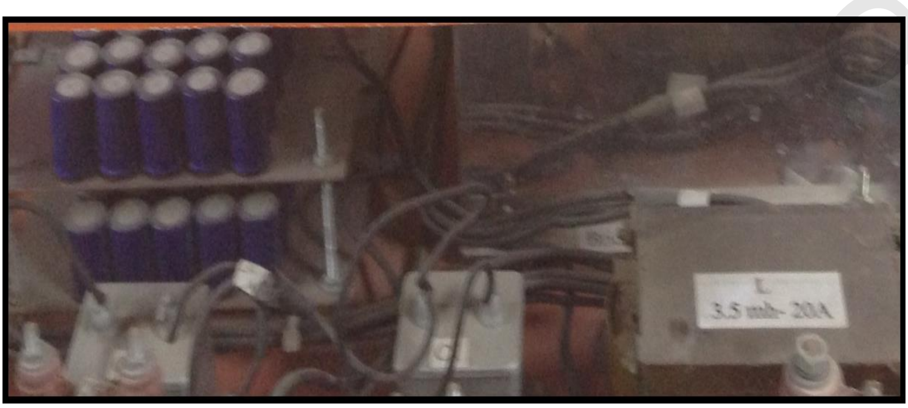
To verify the simulation results a controlled DFIG was set up in the laboratory. The following subsections illustrate the experimental setup, the experimental results and a comparison between simulation and experimental results.

3.4.3.1 Experimental Setup

The hardware components were built using a six pulse (180°) inverter and a controlled rectifier connected with each other through a dc filter as shown if Figure 3.11.

(a)

(b)



(c)

(d)

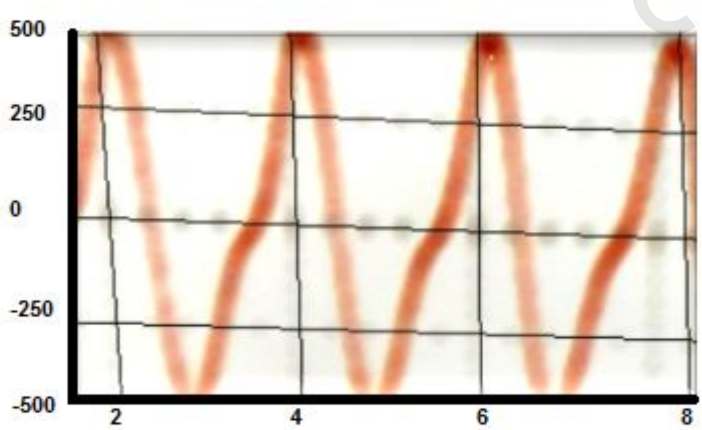
Figure 3.11 Hardware components: (a) Inverter, (b) Rectifier, (c) DC filter, (d) Overall circuit

3.4.3.2 Experimental Results

In this experiment the DFIG was driven at constant speeds using a separately excited dc motor (representing the wind turbine). The rotor of the DFIG was fed from the output of a six pulse inverter while its stator is connected to a three-phase balanced load.

Figure 3.12 shows the stator and rotor voltage at rotor speed of 800-rpm. The stator voltage oscilloscope scales are 250-V/division and 2-ms/division respectively, therefore:

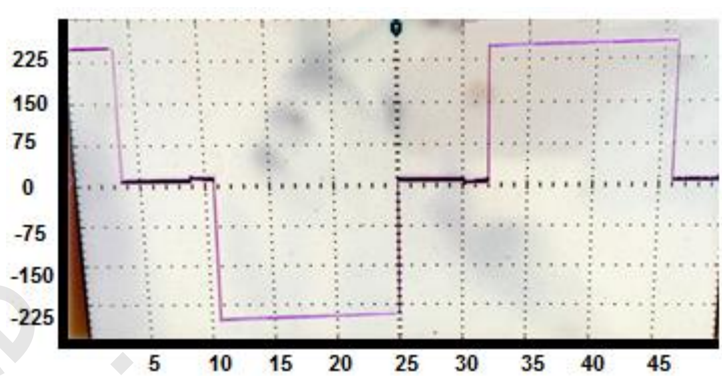
$V = 380 - V$ $\quad\quad$ $f = 50 - Hz$



(a)

The rotor voltage oscilloscope scales are 75-V/division and 5-ms/division respectively, therefore:

$V = 240 - V$ $f = 23.52 - Hz$

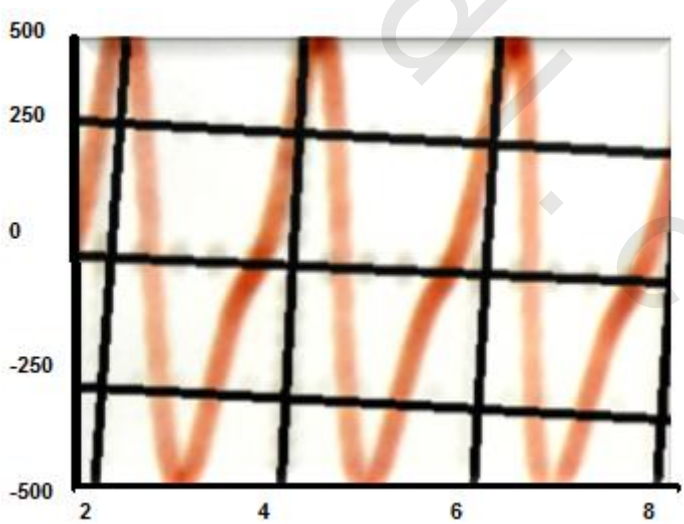


(b)

Figure 3.12 Stator and rotor voltage at 800-rpm: (a) Stator voltage, (b) Rotor voltage

Figure 3.13 shows the stator and rotor voltage at rotor speed of 1000-rpm. The stator voltage oscilloscope scales are 250-V/division and 2-ms/division respectively, therefore:

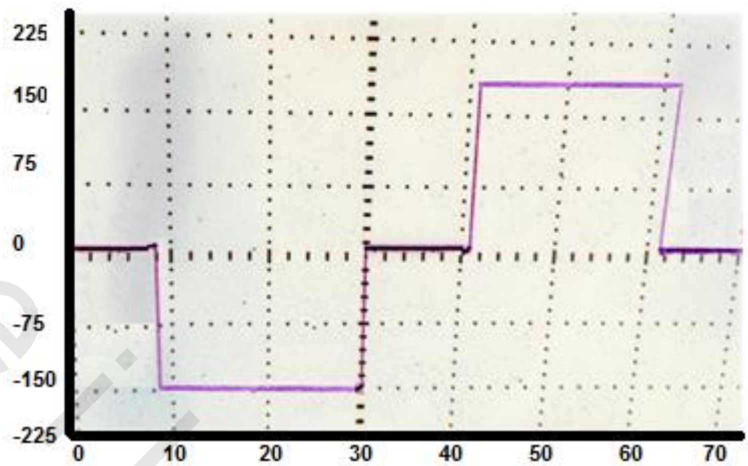
$V = 380 - V$ $f = 50 - Hz$



(a)

The rotor voltage oscilloscope scales are 75-V/division and 10-ms/division respectively, therefore:

$V = 165 - V$ $f = 16.66 - Hz$

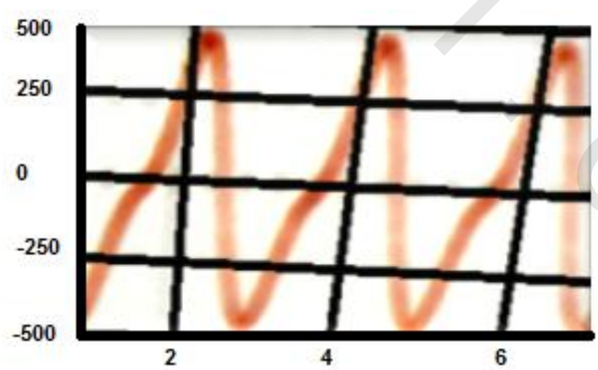


(b)

Figure 3.13 Stator and rotor voltage at 1000-rpm: (a) Stator voltage, (b) Rotor voltage

Figure 3.14 shows the stator and rotor voltage at rotor speed of 1200-rpm. The stator voltage oscilloscope scales are 250-V/division and 2-ms/division respectively, therefore:

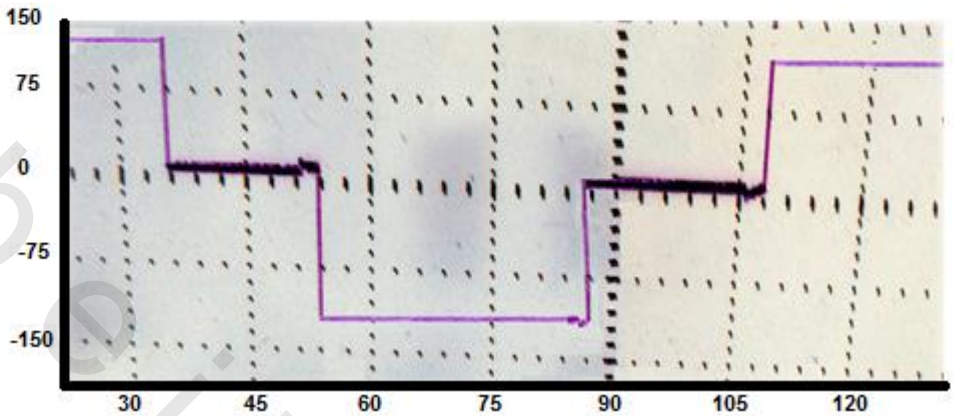
$V = 380 - V$ $f = 50 - Hz$



(a)

The rotor voltage oscilloscope scales are 75-V/division and 15-ms/division respectively, therefore:

$V = 102 - V$ $f = 9.5 - Hz$



(b)

Figure 3.14 Stator and rotor voltage at 1200-rpm: (a) Stator voltage, (b) Rotor voltage

From the previous measurements, it is obvious that both stator voltage and frequency are constant at 380-V and 50-Hz respectively. On the other hand the rotor voltage and inverter frequency are reduced from 240-V, 23.52-Hz when the rotor speed is 800-rpm to 102-V, 9.5-Hz when the rotor speed is 1200-rpm.

3.4.3.3 Comparison between Simulation and Experimental Results

Comparing simulation and experimental results shows a good agreement between them. Both stator voltages and frequency are constant at 380-V and 50-Hz respectively. The maximum errors in the rotor voltage and inverter frequency are 5.2% and 5% respectively, which are acceptable values.

From these results it can be seen that although the stator voltage is kept constant at 380-V, its waveform is not a pure sinusoidal. The stator voltage total harmonic distortion is found to be 19.6 %. To improve the stator voltage waveform an inverter controlled by space vector pulse width modulation technique will be presented in the next chapter.