

## Chapter 4

### Space-Vector Controlled Doubly-Fed Induction Generator

#### 4.1 Introduction

Using six pulse inverter to feed the rotor of the DFIG, produces high low order harmonics in the rotor excitation current. These harmonics distorted the stator voltage waveform. In order to improve this waveform, i.e. to minimize the stator voltage total harmonic distortion, space vector plus width modulation technique will be introduced to control the inverter [22].

#### 4.2 Space-Vector Controlled DFIG

Figure 4.1 shows the space-vector controlled DFIG using an uncontrolled rectifier and space-vector pulse-width modulation (SVPWM) controlled inverter. The rotor voltage and frequency can be controlled in order to maintain constant stator voltage of 380-V and frequency of 50-Hz [22].

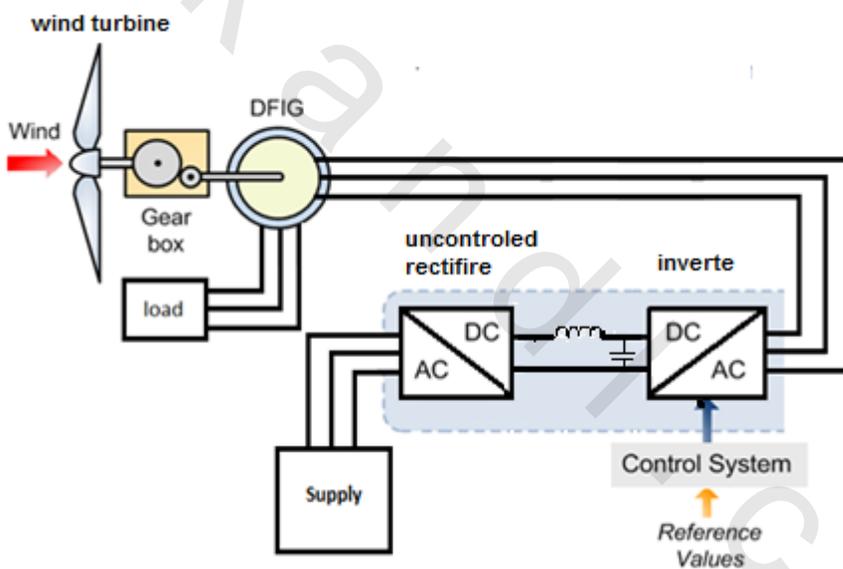


Figure 4.1 Space-Vector Controlled DFIG

##### 4.2.1 Principle of the SVPWM

Space-vector modulation is well-known for its convenient digital implementation. In SVPWM the inverter is controlled through the concept of inverter states. Each inverter state corresponds to a certain combination of switches. There are two switches in each leg of a two-level inverter. As the switches in one leg cannot be both ON or OFF at the same time, and there are three converter legs in a three-phase system, the total number of converter states is 8, as shown in Figure 4.2. States are numbered in binary format from 000 to 111 (0 for OFF state of the upper switch and 1 for its ON state) [23-24].

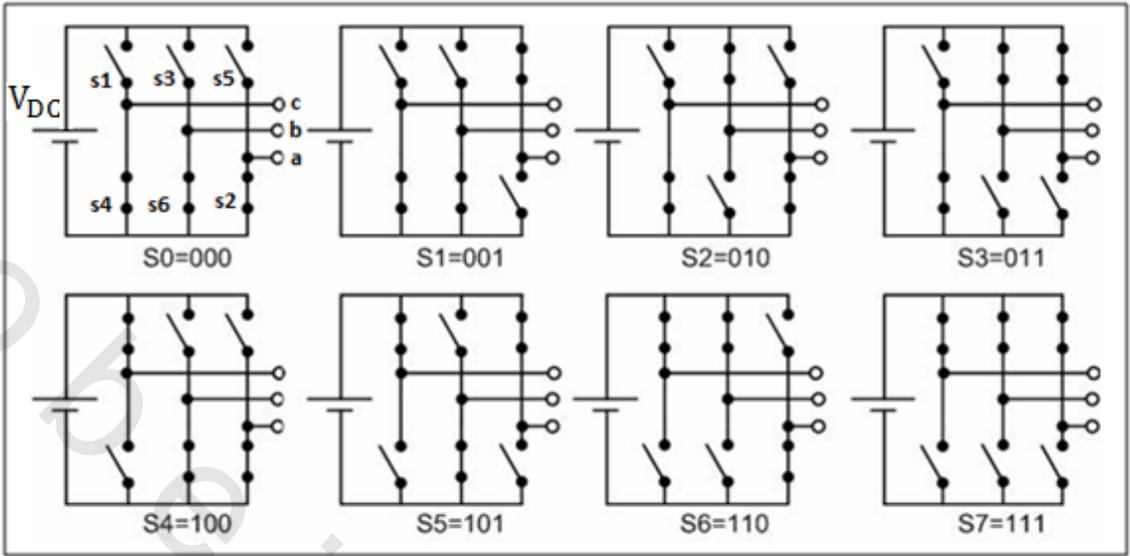


Figure 4.2 Possible switching configurations of a 3-phase inverter

Mapping the phase voltages corresponding to the eight combinations onto the d-q plane by performing a d-q transformation, shown in equation (4.1), results in six non-zero vectors and two zero vectors. The nonzero vectors form the axes of a hexagonal and the line voltages as shown in Figure 4.3. The angle between any two adjacent non-zero vectors is  $60^\circ$ . The two zero vectors are at the origin and apply zero voltage to the motor. The eight vectors are called the basic space vectors and are denoted by  $V_0, V_1, V_2, V_3, V_4, V_5, V_6$  and  $V_7$ . The same transformation is applied to the desired output voltage vector to get the desired voltage vector in the d-q form.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 1 & -0.5 & -0.5 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \times \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} \tag{4.1}$$

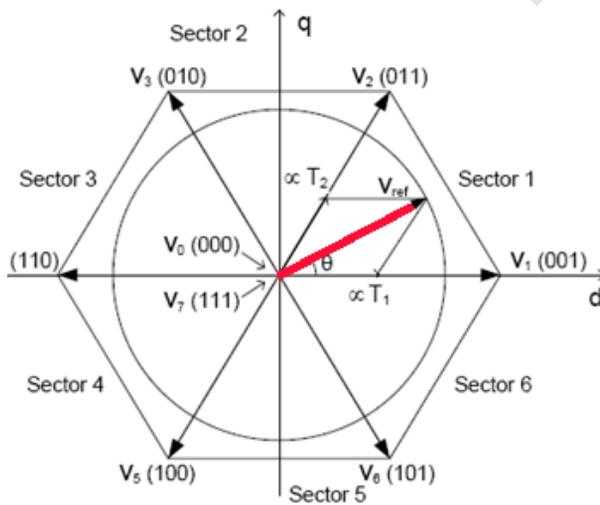


Figure 4.3 Representation of the eight possible switching configurations

Table 4.1 shows the line-to-line voltages as well as the d-q axis stator voltage in each of the inverter eight possible configurations.

Table 4.1 Space Vector Modulation Inverter States

C	B	A	V <sub>ab</sub>	V <sub>bc</sub>	V <sub>ca</sub>	V <sub>ds</sub>	V <sub>qs</sub>	Vector
0	0	0	0	0	0	0	0	U(000)
0	0	1	V <sub>DC</sub>	0	-V <sub>DC</sub>	2/3V <sub>DC</sub>	0	U <sub>0</sub>
0	1	1	0	V <sub>DC</sub>	-V <sub>DC</sub>	V <sub>DC</sub> /3	V <sub>DC</sub> /3	U <sub>60</sub>
0	1	0	-V <sub>DC</sub>	V <sub>DC</sub>	0	-V <sub>DC</sub> /3	V <sub>DC</sub> /3	U <sub>120</sub>
1	1	0	-V <sub>DC</sub>	0	V <sub>DC</sub>	-2V <sub>DC</sub> /3	0	U <sub>180</sub>
1	0	0	0	-V <sub>DC</sub>	V <sub>DC</sub>	-V <sub>DC</sub> /3	-V <sub>DC</sub> /3	U <sub>240</sub>
1	0	1	V <sub>DC</sub>	-V <sub>DC</sub>	0	V <sub>DC</sub> /3	-V <sub>DC</sub> /3	U <sub>300</sub>
1	1	1	0	0	0	0	0	U(111)

The objective of space vector PWM technique is to approximate the output voltage vector  $V_{ref}$  by a combination of the eight switching patterns [25]. Equation (4.2) says that for every PWM half period  $T_z$  in sector 1, the desired reference voltage can be approximated by having the power inverter in switching pattern  $V_1$  and  $V_2$  for  $T_1$  and  $T_2$  duration of time respectively. Since the sum of  $T_1$  and  $T_2$  is less than or equal to  $T_z$  the power inverter need to be put in 0 pattern for the rest of the period. Therefore Equation (4.2) becomes Equation (4.3) and the time duration  $T_1$  and  $T_2$  can be written as a function of the modulation index shown in equations (4.4), (4.5) & (4.6), also the reference voltage in time domain can be written as a function of the modulation index shown in equation (4.7).

$$\int_0^{T_z} \overline{V}_{ref} dt = T_1 \overline{V}_1 + T_2 \overline{V}_2 \quad (4.2)$$

$$T_z * V_{ref} \begin{bmatrix} \cos \theta \\ \sin \theta \end{bmatrix} = T_1 * V_{DC} \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 * V_{DC} \begin{bmatrix} \cos 60^\circ \\ \sin 60^\circ \end{bmatrix} \quad (4.3)$$

Where  $T_1 + T_2 + T_0 = T_z$

$$\text{Let } M = \frac{V_{ref}}{V_{DC}}$$

Therefore,

$$T_1 = T_z * M * \sin(60^\circ - \theta) \quad (4.4)$$

$$T_2 = T_z * M * \sin \theta \quad (4.5)$$

$$T_0 = T_z - T_1 - T_2 \quad (4.6)$$

From equations (4.3) and (4.5), therefore

$$V_{ref} = \frac{\sqrt{3}}{2} * M * V_{DC} \quad (4.7)$$

Where

$$T_z = \frac{T_s}{2}$$

$T_s$ : Sample time

M: Modulation index

The switching time table for each sector is shown in Table (4.2).

Table 4.2 Switching Time Table for Each Sector

Sector	Upper switches duty time ( $S_1, S_3, S_5$ )	Switching pattern ( $S_1$ to $S_6$ )
<b>1</b>	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_2 + T_0/2$ $S_5 = T_0/2$	
<b>2</b>	$S_1 = T_1 + T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_0/2$	
<b>3</b>	$S_1 = T_0/2$ $S_3 = T_1 + T_2 + T_0/2$ $S_5 = T_2 + T_0/2$	

<p><b>4</b></p>	$S_1 = T_0/2$ $S_3 = T_1 + T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	
<p><b>5</b></p>	$S_1 = T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_2 + T_0/2$	
<p><b>6</b></p>	$S_1 = T_1 + T_2 + T_0/2$ $S_3 = T_0/2$ $S_5 = T_1 + T_0/2$	

### 4.2.2 Simulation

Detailed system simulations were performed to evaluate the performance of the space-vector plus width modulation DFIG. Controlled DFIG simulation using Simulink toolbox is shown in Figure 4.4. The system consists of an uncontrolled rectifier and a dc filter linked with a controlled inverter, the supply of the rectifier voltage is 380-V at 50-Hz frequency and the DC filter component values are  $L= 3.2\text{-mH}$ ,  $C= 500\text{-}\mu\text{F}$ .

The controlled inverter is controlled by space vector plus width modulation to control the voltage and frequency with constant ratio and also to minimize the total harmonic distortion factor. The following subsections will explain each block.

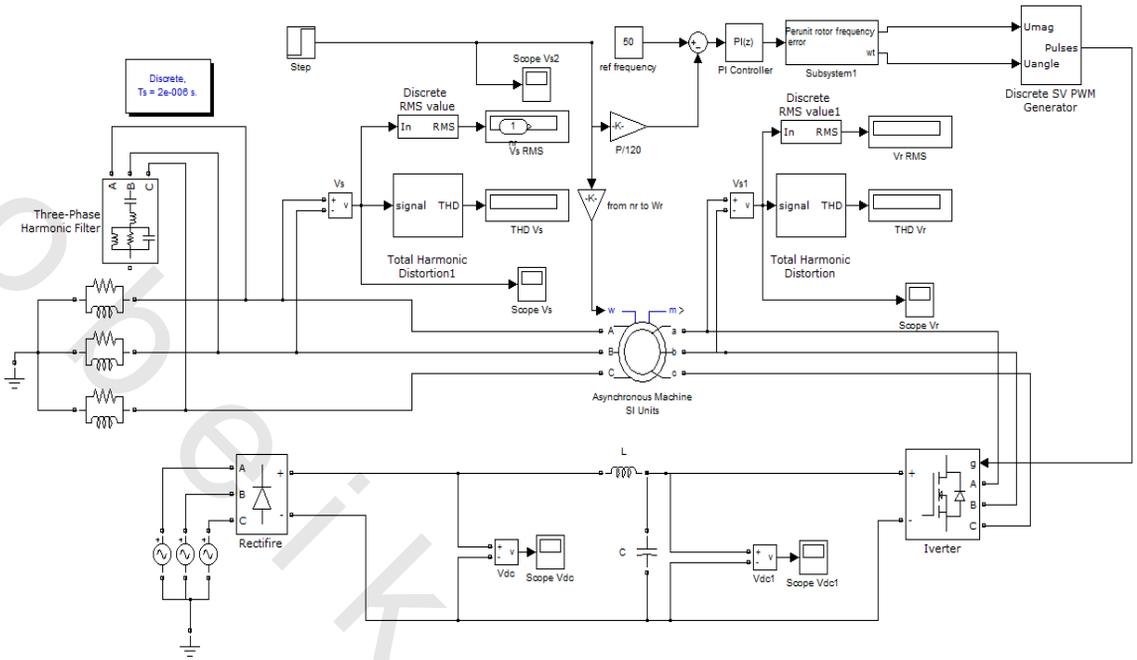


Figure 4.4 Closed loop Simulink simulation

**4.2.2.1 Discrete SVPWM Generator**

This block is a MATLAB built-in block utilizes the space vector pulse width modulation (SVPWM) technique to generate firing pulses to the 6 switching inverter transistors. The modulation index  $M$  (magnitude of the reference vector  $U$ ) must be a value between 0 and 1; the block maintains the values of  $(V/f)$  in the rotor constant. The input sample frequency is taken 500-kHz as in the DSP Microcontroller [13].

**4.2.2.2 Subsystem 1**

Subsystem 1 shown in Figure 4.5 is used to convert the stator frequency error to pulses signal connected to PI controller with  $K_p = 2.5$  and  $K_i = 1.8\text{-sec}^{-1}$ , also to build  $(\omega_s t)$  for the SVPWM inputs. This is achieved by comparing the stator (load) frequency (50-Hz) with the variation in rotor speed as given by equation (3.4):

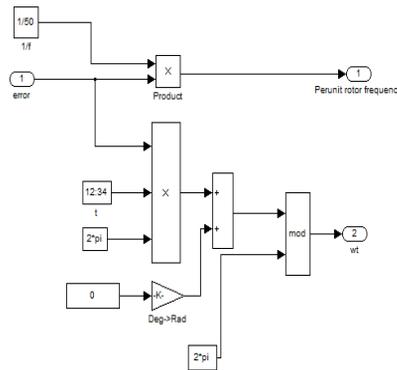


Figure 4.5 Subsystem1

### 4.2.3 Simulation Results

#### 4.2.3.1 Without Harmonic Elimination

The simulation rotor speeds are selected  $\pm 20\%$  of 1000-rpm as mentioned in chapter 3. Figure 4.6 shows the stator and rotor voltages at different speeds.

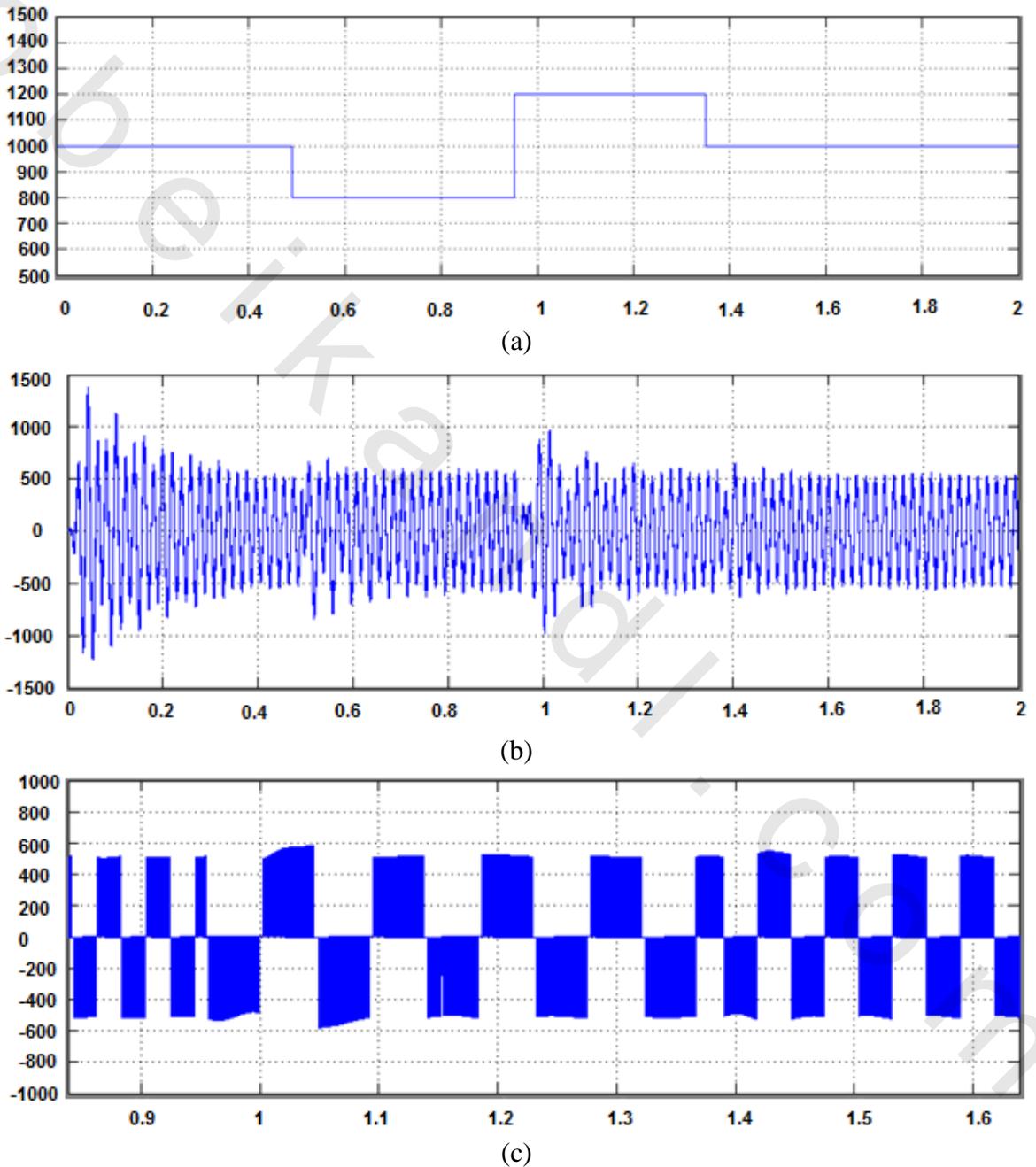
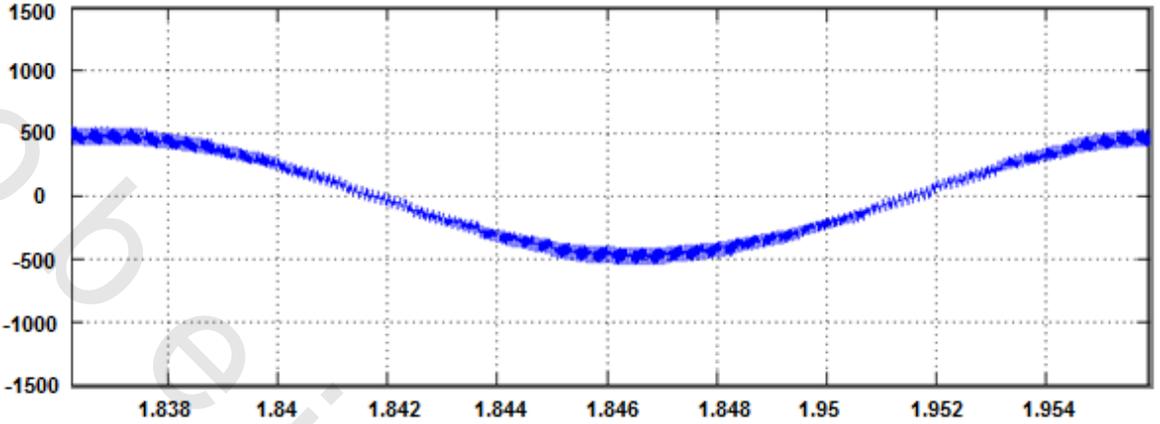
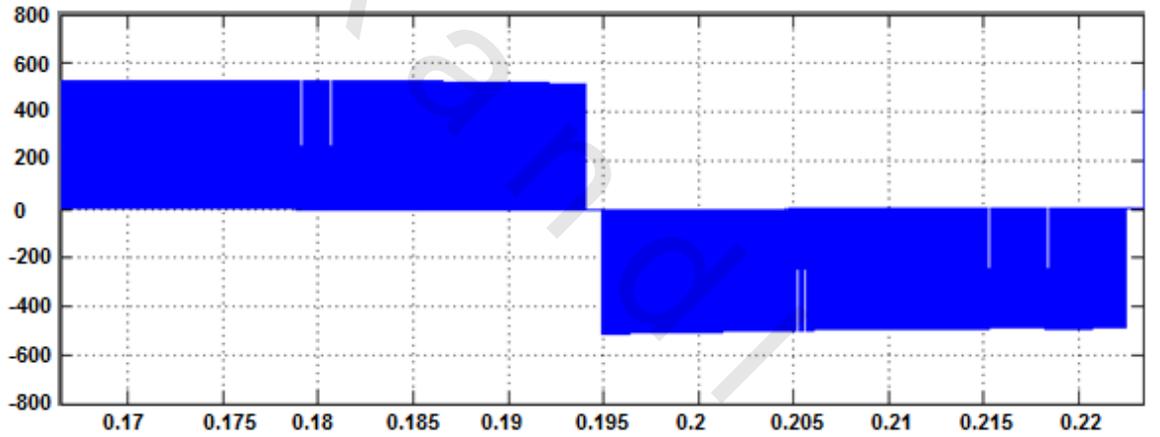


Figure 4.6 Stator and rotor voltages at different speeds: (a) Speed variation pattern, (b) Stator voltage, (c) Rotor voltage

Figure 4.7 shows the stator and rotor voltages for one cycle at steady state speed (1000-rpm) the measurement of the stator voltage total harmonic distortion is 8%.



(a)



(b)

Figure 4.7 One cycle of the stator and rotor voltages at steady state: (a) Stator voltage, (b) Rotor voltage

#### 4.2.3.2 With 3rd Harmonic Elimination

A filter is connected in parallel with the load; the filter is build up from passive RLC components and adjusted to eliminate the third harmonic. This block is a MATLAB built-in block and the inputs to the block are nominal voltage and frequency, nominal reactive power, frequency to be eliminated and the quality factor. Those values are referred to equivalent series RLC circuit as given by equations (4.8), (4.9) and (4.10):

$$2\pi n f = \sqrt{\frac{1}{LC}} \quad (4.8)$$

$$Q = \frac{1}{2\pi n f C R} = \frac{R}{2\pi n f L} \quad (4.9)$$

$$Q_C = 2\pi f C V^2 * \frac{n^2}{(n^2-1)} \quad (4.10)$$

Where

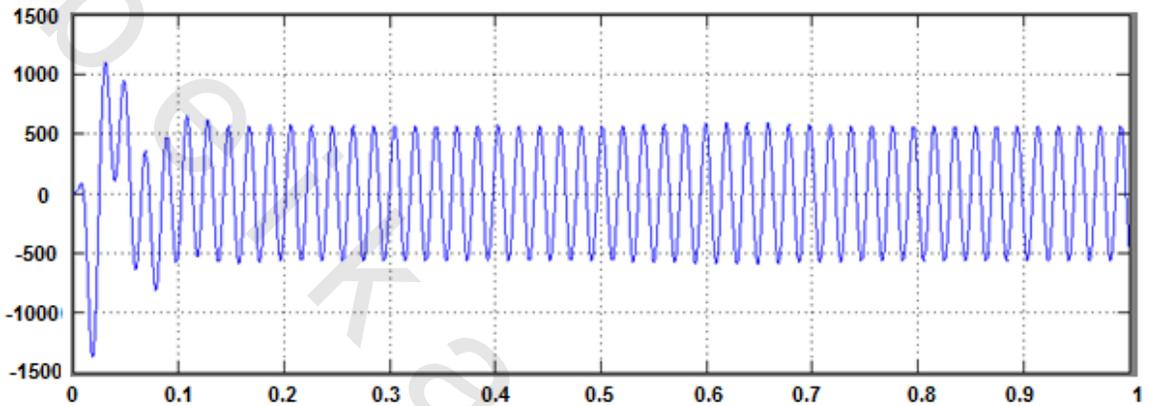
$n$ : Order of eliminated harmonic, chosen to be the third

$Q$ : Quality factor

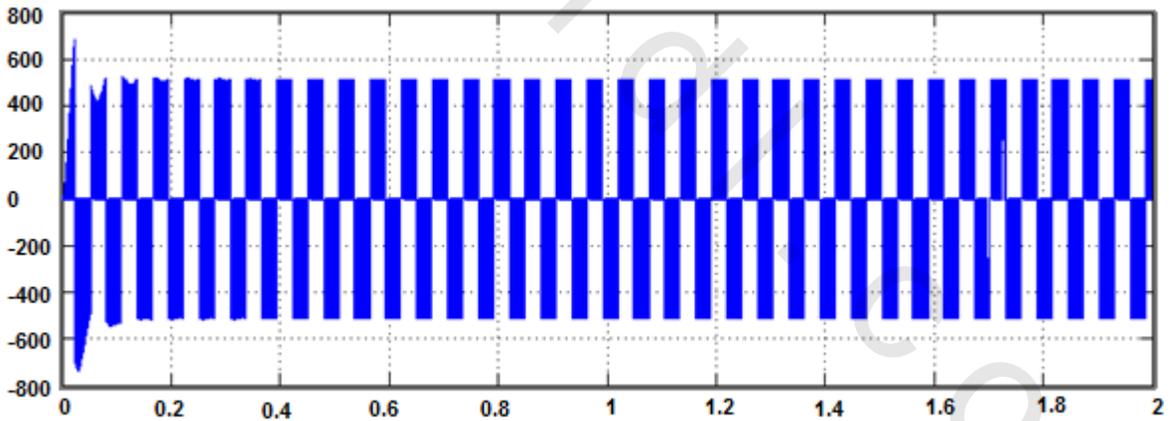
$Q_C$ : Reactive power

By Choosing an inductor having  $L=1.0\text{-mH}$ , then  $C=1120\text{-}\mu\text{F}$  &  $R=1.0\text{-}\Omega$ . The quality factor, and reactive power are  $Q = 1.0$  &  $Q_C = 57.5\text{-Kvar}$ .

Figure 4.8 shows the stator and rotor voltages at steady state speed (1000-rpm).



(a)



(b)

Figure 4.8 Stator and rotor voltages at steady state: (a) Stator voltage & (b) Rotor voltage

Figure 4.9 Shows stator and rotor voltages for one cycle at steady state with the specified filter at speed (1000 rpm), the measurement of the stator voltage total harmonic distortion is 2.2%.

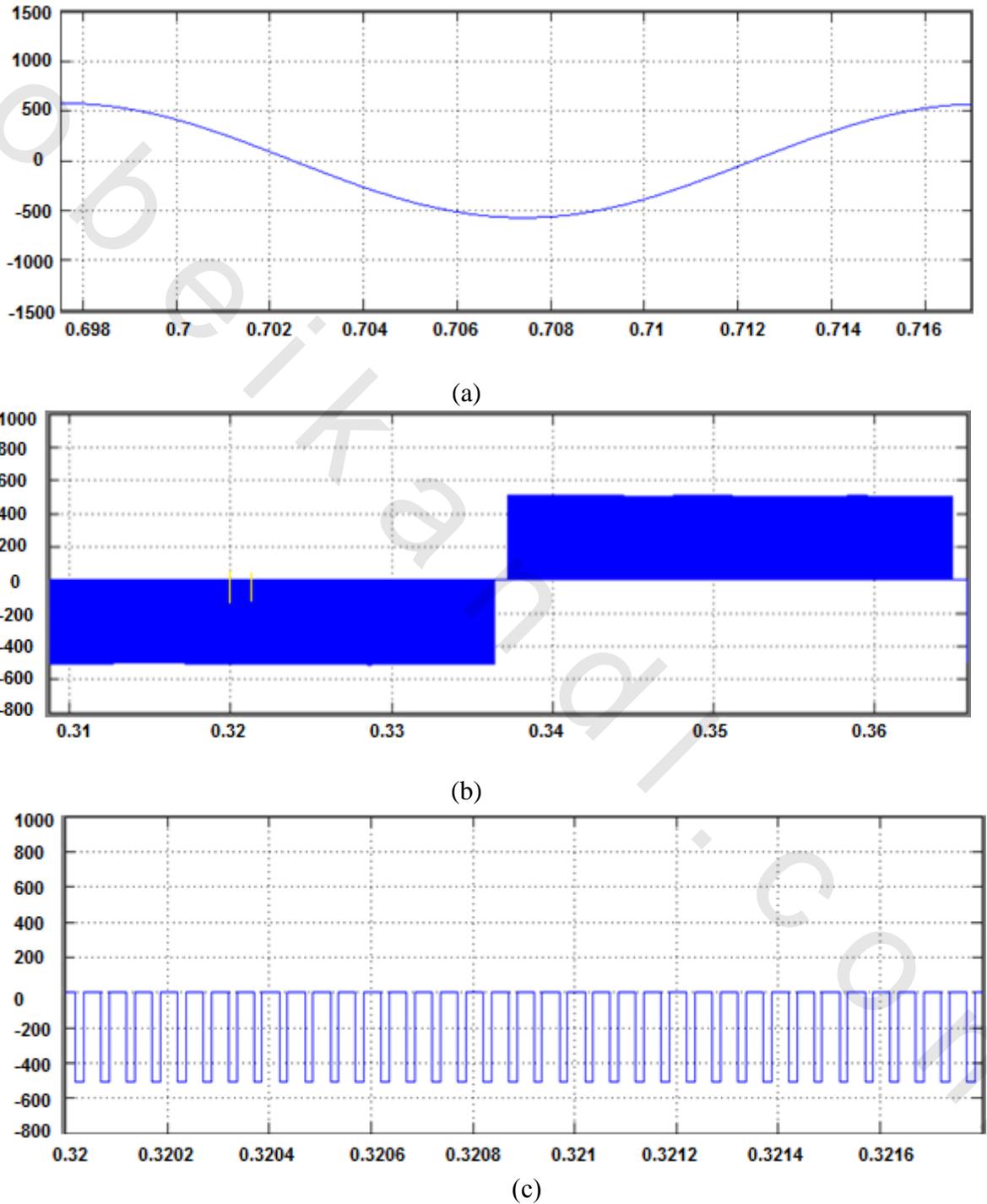


Figure 4.9 Stator and rotor voltages at steady state with filter: (a) Stator voltage, (b) & (c) Rotor voltage

#### 4.2.4 Comment

Using SVPWM to control the inverter improves the voltage waveform by reducing its total harmonic distortion from 19.6 % when using the six-pulse inverter to 8%. More reduction in the stator voltage total harmonic distortion can be achieved by eliminating the third harmonic using a passive RLC filter.

#### 4.3 Space-Vector Controlled DFIG Self-excited

In a places that the ac source is not available there are two method to do the previous control one method is to replace the rectifier and the dc filter with a dc battery and in this case the output is the same as the previous simulation. If there is no dc battery source or ac source the charged capacitor can solve the problem of the initial machine excitation figure 4.10 shows the connection [17-20].

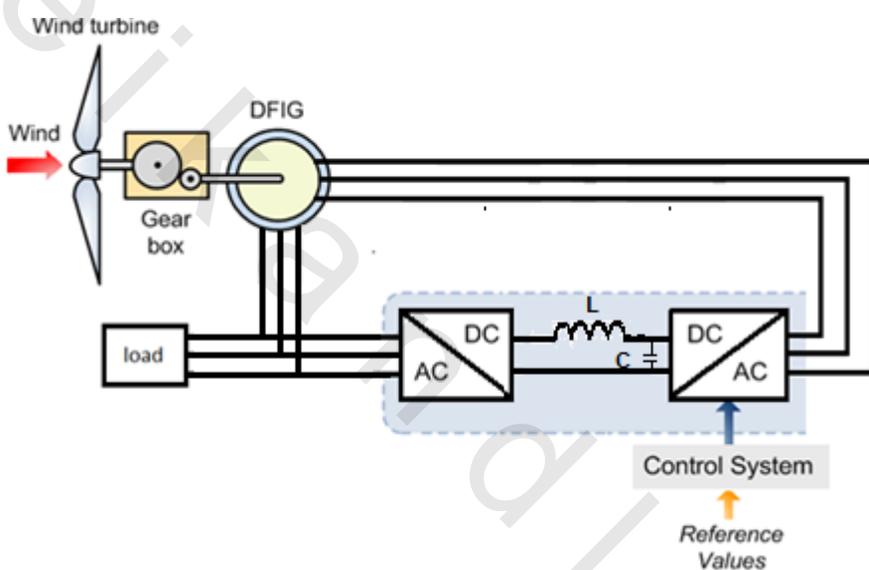


Figure 4.10 Space-Vector Controlled DFIG Self-Excited

#### 4.3.1 Simulation

Controlled DFIG simulation using Simulink toolbox is shown in Figure 4.11 The system consists of an uncontrolled rectifier and a dc filter with a capacitor of 1000-  $\mu$ F and the capacitor is initial charged by 500-V ,  $L= 3.2$ -mH linked with a controlled inverter, The controlled inverter is controlled by space vector pulse width modulation to control the voltage and frequency with constant ratio and a filter is connected in parallel with the load as in the previous section to minimize the total harmonic distortion factor[27-29].

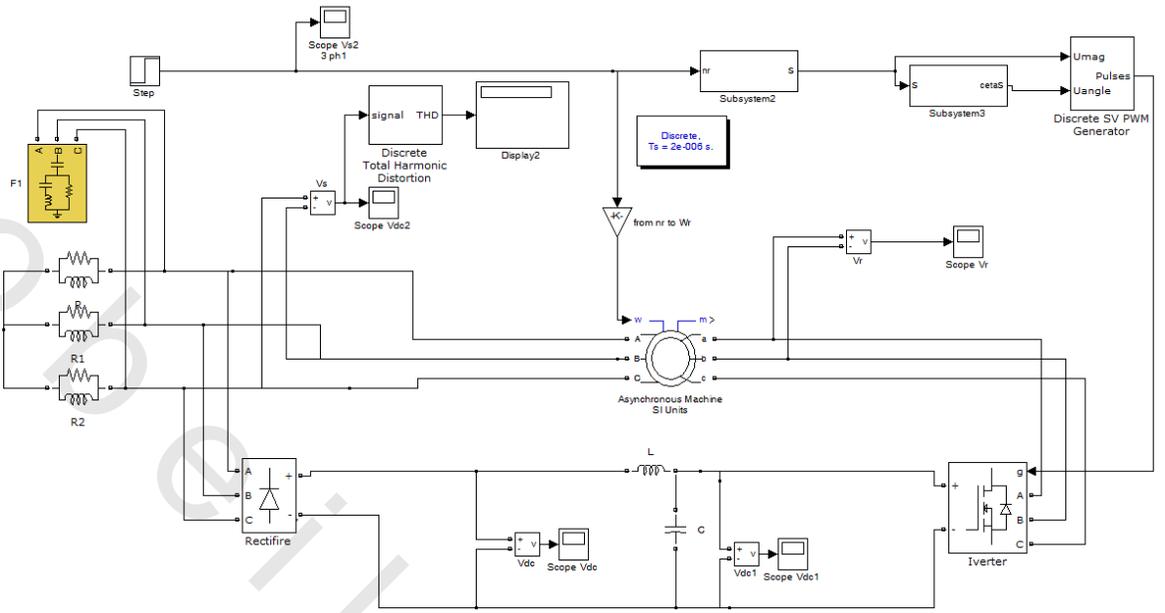
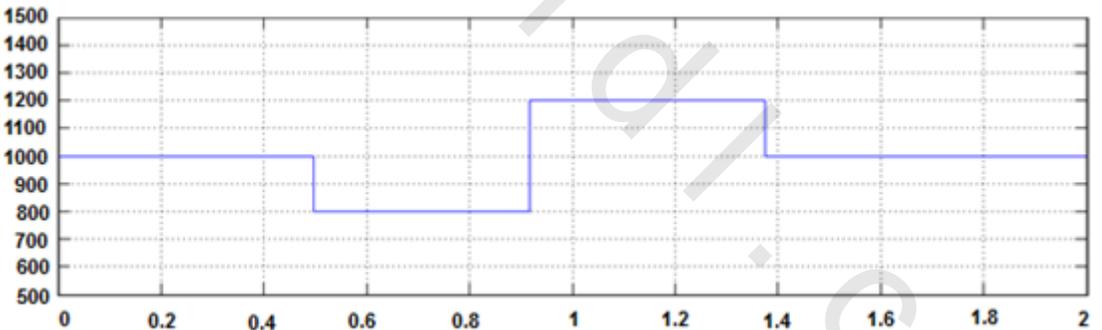


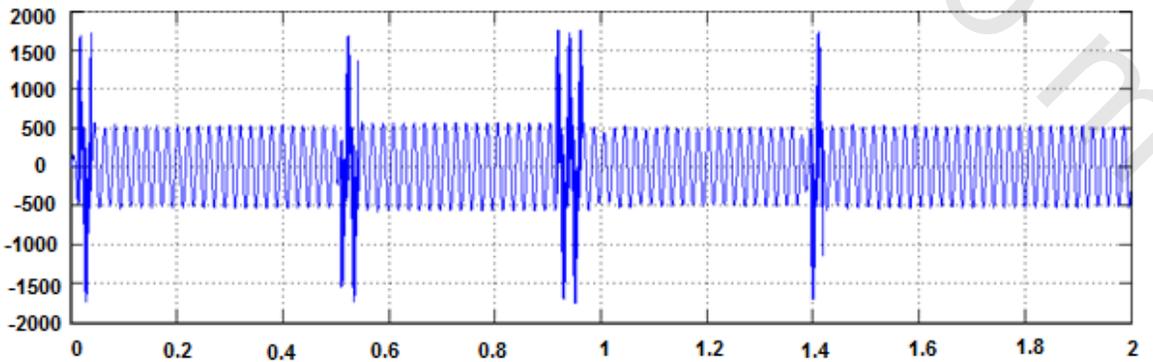
Figure 4.11 Closed loop Simulink simulation

### 4.3.2 Simulation Results

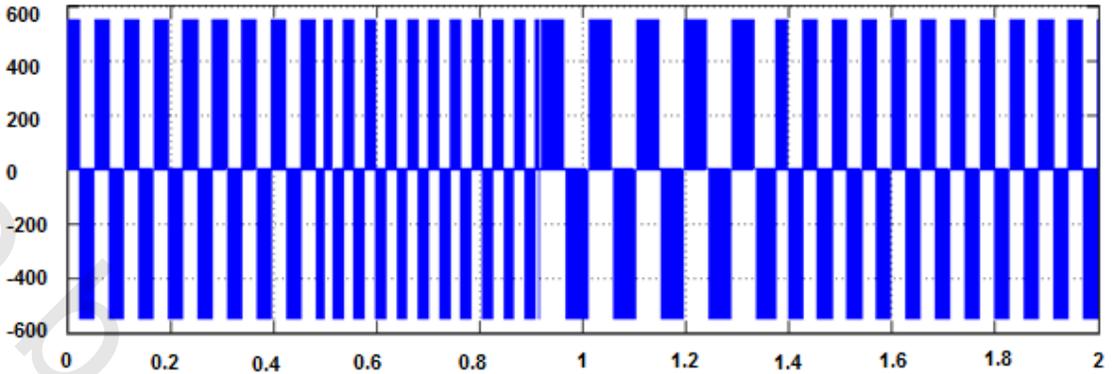
Figure 4.12 shows the stator and rotor voltages at different speeds.



(a)



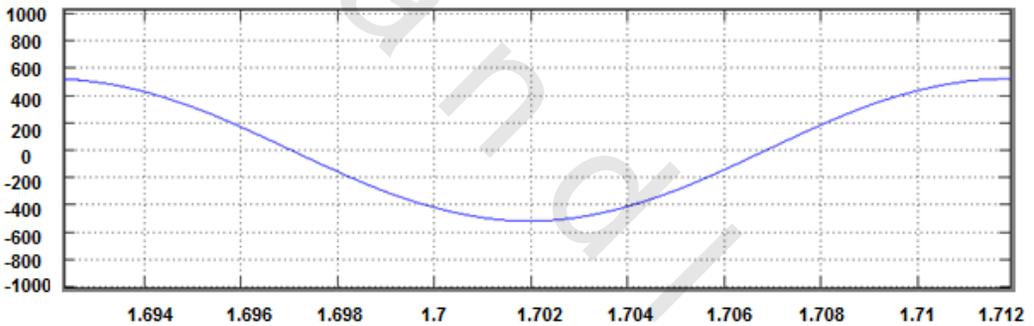
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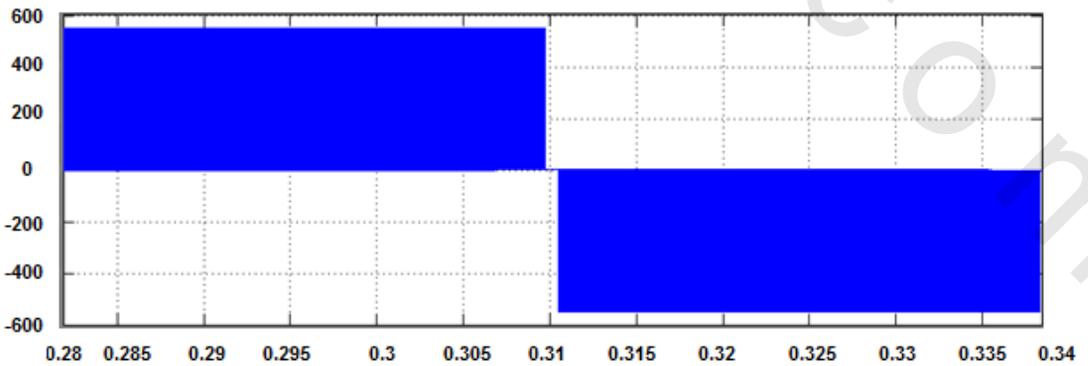
(c)

Figure 4.12 Stator and rotor voltages at different speeds: (a) Speed variation pattern, (b) Stator voltage, (c) Rotor voltage

Figure 4.13 Shows stator and rotor voltages for one cycle at steady state with the specified filter at speed (1000 rpm), the measurement of the stator voltage total harmonic distortion is 2.2%.



(a)



(b)

Figure 4.13 One cycle of the stator and rotor voltages at steady state: (a) Stator voltage, (b) Rotor voltage