CHAPTER 6

ANALYSIS OF MATRIX CONVERTERS

6.1 INTRODUCTION

New technical challenges emerge due to increased wind power penetration, dynamic stability and power quality, implying research of more realistic physical models for wind energy systems. Power electronic interfaces have been developed for integrating wind turbine generator with the grid or to the load. The use of power electronic converters in variable speed wind energy conversion scheme yields enhanced power extraction. In variable speed operation, a control method designed to extract maximum power from the turbine and provide constant grid voltage and frequency is required (Baroudi et al 2007).

Recently there has been considerable interest in the potential benefits of matrix converter technology, especially for variable speed induction machine applications (Ghedamsi et al 2006 and Wheeler et al 2002). The matrix converter is an advanced circuit topology capable of converting AC to AC. As stated by Venturini (1980), many benefits are encompassed by this topology such as, the matrix converter fulfills the requirements to provide a sinusoidal voltage at the load side and on the other hand, it is also possible to adjust the unity power factor on the mains side under certain conditions. Since there is no DC link as in common converters, the matrix converter can be built as a full-silicon structure. Using a
sufficiently high pulse frequency, the output voltage and input current both are shaped sinusoidally.

The matrix converter is an alternative to an inverter drive for three-phase frequency control. This chapter deals with the implementation and analysis of single phase and three phase matrix converters employing different control algorithms applicable for variable speed wind energy conversion systems supplying isolated loads.

6.2 SINGLE PHASE MATRIX CONVERTER

Single phase AC–AC converter has a number of potential applications. Several approaches to control the output of single-phase AC-AC converter are available in the literature (Jacobina et al 2006, Perez et al 2006, Sunter and Aydogmus 2008). The proposed work deals with a design, simulation and implementation of single-phase induction motor drive fed by a Sinusoidal PWM (SPWM) based matrix converter used in variable speed applications. The characteristics of a single phase AC-AC converter feeding an induction motor load with particular emphasis on the harmonic content is presented with the aid of simulation study and hardware implementation.

6.1.1 Converter Topology

Figure 6.1 shows the block diagram of single phase matrix converter fed induction motor drive. The matrix converter converts fixed frequency fixed voltage to variable frequency variable voltage and is fed to the single phase induction motor. The actual speed as sensed by the sensor and the reference speed are compared by the comparator and error in the speed is obtained. The current and voltage controllers are used to generate pulses to the matrix converter. SPWM is used as the control strategy to regulate the speed of single phase induction motor.
The main circuit of a matrix converter is composed of an input filter bidirectional switches also known as bilateral switches. Mostly two anti-parallel reverse blocking IGBT’s are used as bidirectional switches. In addition to bidirectional operation with the same set of switches, an optimized power factor, reduced harmonic content of input currents and voltage stress are also achieved (Sunter and Aydogmus 2008).

6.1.2 Modulation Strategy

To obtain an output voltage of desired magnitude and frequency, the matrix converter chops the high frequency input AC voltage. SPWM
technique is used to generate switching signals for the switches $S_2$ and $S_4$ respectively while the switches $S_1$ and $S_3$ are operated at modulation frequency, $f_m$. The fundamental component of the output voltage is given by Equation (6.1)

$$f_o = f_m - f_i$$  (6.1)

where $f_m$ is the modulation frequency and $f_i$ is the input frequency. The output voltage is proportional to the modulation ratio. The input voltage is given by Equation (6.2)

$$V_i(t) = V_{in} \cos \omega_i t$$  (6.2)

The output voltage will be Equation (6.3)

$$V_o(t) = V_{om} \cos \omega_o t$$  (6.3)

To control the power switches $S_1$, $S_2$, $S_3$ and $S_4$, the following four switching states are used. The other possible states are not applied (Sunter and Aydogmus 2008).

- The first state being the ‘ON’ state for $S_1$ and $S_4$ will be during the positive cycle with the output voltage as the input voltage.

- The negative cycle of input voltage will be the second state keeping the switches $S_2$ and $S_3$ in 'ON' state.

- The remaining two states will have zero output with switches $S_1$ and $S_2$, $S_3$ and $S_4$ are in ‘ON’ state respectively.
6.1.3 System Modeling

The simulation model of closed loop control of the proposed system driving a single phase induction motor with the reference speed and the applied voltage is given by Figure 6.4.

Figure 6.3 MATLAB / SIMULINK Model of the proposed system without feedback

Figure 6.4 MATLAB / SIMULINK Model of the proposed system with feedback
6.1.4 Simulation Results and Discussion

An input voltage of magnitude 150 V and frequency 50 Hz is applied to the SPWM based single phase matrix converter and the results are analyzed. The various simulation results are displayed in Figures 6.5 to 6.8.

Figure 6.5 Input voltage Vs Time

![Input Voltage Vs Time Graph]

Figure 6.6 SPWM signals

The modulation scheme and switching signals of the proposed system is shown in Figure 6.6. When a carrier signal with a frequency of 1.25 kHz and reference sinusoidal voltage of frequency 50 Hz are compared with the relational operator and logical operator, SPWM pulses with variable pulse width are generated. These pulses are used to control the output voltage and
output current of the matrix converter. The output voltage of 150 V and a current of 0.15 A obtained are shown in Figures 6.7 and 6.8 respectively. Further study of harmonic spectrum in the output voltage signal using FFT analysis yields a Total Harmonic Distortion (THD) of 15.95% as given by the Figure 6.9.

![Figure 6.7 Output voltage Vs Time](image1)
![Figure 6.8 Load current Vs Time](image2)

**Figure 6.7 Output voltage Vs Time**  **Figure 6.8 Load current Vs Time**

![Figure 6.9 Harmonic spectrum of output voltage](image3)

**Figure 6.9 Harmonic spectrum of output voltage**

To drive a ½ HP, 230 V, 50 Hz, 1.4 A, single phase induction motor fed by SPWM based matrix converter, a closed loop control to regulate the speed of the motor using PID controller is employed. The simulation
results are shown in Figures 6.10 to 6.12. The input voltage of magnitude 230 V and frequency 50 Hz is given as input. The matrix converter converts fixed frequency fixed voltage to variable frequency variable voltage to obtain the required speed for the motor. An output voltage of 225 peak to peak is obtained for a modulation depth of 0.75.

![Input Voltage Vs Time](image)

**Figure 6.10 Input voltage Vs Time**

![Output Voltage Vs Time](image)

**Figure 6.11 Output voltage Vs Time**

![Speed Vs Time](image)

**Figure 6.12 Speed Vs Time**

Figure 6.12 shows the rotor speed of single phase induction motor. The speed gradually increases from zero reaches 1480 rpm in 2 sec. The transient state exists till 2.3 sec and it reaches its steady state value of 1400 rpm. The total harmonic distortion in output voltage waveform is found to be 19.75 % from the Figure 6.13.
6.1.5 Model Validation

For experimental studies, a laboratory model of single phase matrix converter has been designed to feed various types of loads such as R-load, R-L load or a single phase induction motor. Square wave PWM pulses have been generated using a dsPIC 30F3011 microcontroller. The switching frequency was taken as 10 kHz, and the modulation frequency was varied in steps from 0 to 50 Hz. The modulation depth was varied between 0.01 and 1. The output pulses from the microcontroller are given to gate driver circuit of the converter switches.

The matrix converter is capable of blocking voltage and conducting current in both directions. As the bidirectional switches are not available in the market today, additional construction of the same with some power semiconductor devices is needed. Supertex GN2470 is a 700 V, 3.5 A Insulated Gate Bipolar Transistor (IGBT) that combines the positive aspects
of both Bipolar Junction Transistors (BJT) and Metal Oxide Field Effect Transistors (MOSFET) is used. This device possesses lower on-state voltage drop with high blocking voltage capabilities and low conduction voltage drop at high currents. It is not possible to simply turn off all the switches as this will open circuit the inductive motor load causing a very high voltage transients. Hence a small capacitor is used for this clamp and it is rated to take the energy stored in the inductance of the load without exceeding the maximum voltage rating of the devices.

![Block diagram of hardware model](image)

**Figure 6.14 Block diagram of hardware model**

The block diagram of the hardware model of single phase AC-AC converter fed induction motor drive is shown in Figure 6.14. Gate driver circuit is designed in such a way to detect collector-to-emitter voltage ($V_{ce}$) of a turned-on IGBT, short circuits etc. In square wave PWM, the gating signals are generated by comparing a square wave reference signal of frequency $f_r$ with a triangular carrier wave of frequency $f_c$. The reference frequency determines the output frequency $f_o$ and its peak amplitude controls the modulation index and in turn the RMS output voltage. A 40 pin dsPIC 30F3011 microcontroller is used as pulse generator. To obtain four different constant voltages (+5V, +10V, +12V, -5V), switched mode power supply is used. The circuit diagram of SMPS is shown in Figure 6.15. It consists of
pulse generator, MOSFET (2SK2848) and high frequency pulse transformer, chopper, opto-coupler (PC923) and filter.

Figure 6.15 Circuit diagram of SMPS

The hardware of matrix converter as shown in Figure 6.16 was fabricated and the output is fed to the drive. An R-L Load of \( R = 10 \, \Omega \), \( L = 0.1 \, H \) is connected across the matrix converter. As shown in Figure 6.17 (a), a single phase AC voltage of 115 V and frequency 50 Hz is given as input to the converter. The microcontroller is used to produce control signals based on square wave pulse width modulation technique for the gates of the IGBT. The hardware results are analyzed under various Voltage / Frequency ratios. The output waveforms and the harmonic spectra are measured using Power Quality Analyzer and presented in the following figures. From Figure 6.17 (b), the input current is about 1 A.
The output voltage shown in Figure 6.18 (a) is of pulsed sinusoidal waveform. The peak to peak voltage is 114 V and frequency is 50 Hz. Figure 6.18 (b) depicts the output current waveform at 50 Hz frequency.

Figure 6.17(a, b) Input voltage and current waveforms
Figure 6.18(a, b) Output voltage and current for $f_0 = 50$ Hz with R-L load

Now a fan load of capacity ½ HP, 220 V, 1.4 A is connected across the matrix converter. The output voltage shown in Figure 6.19 (a) is of pulsed sinusoidal waveform. The peak to peak voltage is 91 V and frequency is 45 Hz. The output current is approximately 1 A at 45 Hz.

Figure 6.19(a, b) Induction motor voltage and current for $f_0 = 45$ Hz

Figure 6.20 Harmonic spectrum of output voltage for $f_0 = 45$ Hz
The THD level of output voltage at frequency $f_0 = 45$ Hz is 59.8 % of the fundamental frequency as given by the Figure 6.20. Form the harmonics table it is observed that harmonics present in output voltage waveform of third order is 33.0 %, fifth order is 4.4 %, seventh order is 2.5 %, ninth order is 0.7 %, eleventh order is 2.4 %, thirteenth order is 2.4 % and fifteenth order is 5.5 % of fundamental frequency respectively. For various frequencies, the results are obtained and shown in Figures 6.21 – 6.22. It is observed, that the rms voltage and peak voltage of matrix converter are 101.7 V and 167.2 V respectively for 48 Hz. The peak current of matrix converter is 1A.

Figure 6.21(a, b, c) Output voltage, current and harmonic spectrum for $f_0 = 48$ Hz

Figure 6.22(a, b, c) Output voltage, current and harmonic spectrum for $f_0 = 50$ Hz
For 90 V / 45 Hz, the total harmonic distortion is 60% and for 115 V / 50 Hz the total harmonic distortion is 36%. When the output frequency is equal to supply frequency, the total harmonic distortion is low. As the output voltage increases the harmonics also increases.

![Graph showing speed response of the induction motor.](image)

**Figure 6.23 Speed response of the induction motor**

Figure 6.23 shows the speed characteristics of the single phase induction motor without feedback. For the set value of frequency, the V/f ratio of the drive is automatically maintained and it runs at its nearest synchronous speed. The motor takes 6.3 sec to reach its steady state value of 1410 rpm, when compared to the steady state speed of 1400 rpm in the simulation study. Thus the model is validated.

**6.3 THREE PHASE MATRIX CONVERTER**

In literature, several methods of incorporating conventional AC-DC-AC conversion system for wind power applications have been discussed. Usually the generator side converter will be a controlled / uncontrolled rectifier or a voltage source converter (VSC). The utility side converter is often a VSC unit. The main drawbacks of this type of conversion are increased size and weight, low reliability of DC link capacitor; poor line power factor and significant harmonic distortion in line and machine currents (Vinod Kumar et al 2009). The IEEE Standard 519 (1991) severely restricts
line harmonic injection. Matrix converters will avoid the conventional AC-DC-AC conversion, so the steps involved in the conversion is reduced. Due to the lack of DC link capacitor for energy storage, the total size of the system is reduced. The following sections deal with the three phase matrix converters applied for wind turbine generators.

6.4 CONVERTER TOPOLOGIES

The different converter topologies are discussed below.

6.4.1 Indirect Matrix Converter

The indirect matrix converter topology consists of 18 IGBT switches with an extra leg as shown in Figure 6.24. So this converter has 3^4 switching states. The switching combinations are same as that of any matrix converter except some extra switching combinations. This topology is more complex but easy to control. The modulation can be divided into two, input side modulation and the load side modulation. In order to have better control, input modulation method is developed. The switch used is IGBT because of high power handling capability.

Figure 6.24 Schematic representation of indirect matrix converter
6.4.2 Nine Switched Matrix Converter

As mentioned by Ebubekir Erdem et al (2005), conventional way of matrix converter concept is nine switch topology using bi-directional switches. They are arranged as three sets of three, so that any of the three input phases can be connected to any of the three output lines, as shown in Figure 6.25. The matrix components $S_{11}, S_{12}, \ldots, S_{33}$ represent nine bi-directional switches which are capable of blocking voltage in both directions and of switching without any delays (Alberto Alesina and Marco Venturini, 1989). The matrix converter connects the three given inputs, with constant amplitude, $V_i$ and frequency, $f_i$ through the nine switches to the output terminals in accordance with pre calculated switching angles. The three-phase output voltages obtained have controllable amplitudes, $V_o$ and frequency, $f_o$. The number of switching states in the matrix converter is 27 ($3^3$) and the switching states can be achieved by changing sequence of the signal given to the switches. The switch used is IGBT because of high power handling capability.

![IGBT Switch](image)

Figure 6.25 Schematic representation of nine switched matrix converter
6.5 MODELING OF VENTURINI ALGORITHM BASED
MATRIX CONVERTER

A Venturini’s modulation algorithm is used for matrix converter
and is defined in terms of the three phase input and output voltages at each
sampling instant and can be easily implemented for closed loop operations
(Altun and Sunter, 2003). This algorithm also provides unity fundamental
displacement factor at the input regardless of the load displacement factor. In
this method, a set of three-phase input voltages with constant amplitude and
frequency is considered, for calculating the duty cycle of each of the nine
bidirectional switches. The result thus obtained and when implemented allows
the generation of a set of three-phase output voltages by sequential piecewise
sampling of the input waveforms (Zhang et al 1998).

A simplified version of the Venturini algorithm as discussed by
Sunter (1995) is used here to simulate and analyze the performance of the
matrix converter. For the real-time implementation of the proposed
modulation algorithm, it is required to measure any two of three input line-to-
line voltages. Then, input peak voltage $V_{im}$ and and input position $\omega_{it}$ are
calculated as shown in Equations (6.4) and (6.5). Similarly the target output
peak voltage and the output position can be calculated as Equations (6.6) and
(6.7), where $V_{AB}, V_{BC}$ are the instantaneous input line voltages and $v_a, v_b, v_c$
are the target phase output voltages.

$$V_{im}^2 = \frac{4}{9} \left( V_{AB}^2 + V_{BC}^2 + V_{AB}V_{BC} \right)$$  \hspace{1cm} (6.4)

$$\omega_{it} = \arctan \left[ \frac{V_{BC}}{\sqrt{3} \left( \frac{2}{3} V_{AB} + \frac{1}{3} V_{BC} \right)} \right]$$  \hspace{1cm} (6.5)

$$V_{om} = \frac{4}{9} \left| v_a + v_b + v_c \right|$$  \hspace{1cm} (6.6)
\[
\omega_{oa} = \arctan \left[ \frac{v_b - v_c}{\sqrt{3}(v_a)} \right]
\] (6.7)

Alternatively, in a closed loop system the voltage magnitude and angle may be the direct outputs of the control loop. Then, the voltage ratio is calculated from Equation (6.8).

\[
q = \frac{V_{om}}{V_{im}}
\] (6.8)

where \( q \) is the desired voltage ratio, and \( V_{im} \) is the peak input voltage.

Triple harmonic terms are found as Equations (6.9) – (6.11)

\[
k_{31} = \frac{\sqrt{3}}{2} \times \frac{q}{q_m} \sin(\omega_{it}) \sin(3\omega_{it})
\] (6.9)

\[
k_{32} = \frac{\sqrt{3}}{2} \times \frac{q}{q_m} \sin(\omega_{it} - \frac{2\pi}{3}) \sin(3\omega_{it})
\] (6.10)

\[
k_{33} = \sqrt{V_{om}} \left[ \frac{\sqrt{3}}{2} \cos(3\omega_{it}) - \frac{\sqrt{3}}{6} \times \frac{q}{q_m} \cos(3\omega_{it}) \right]
\] (6.11)

where \( q_m \) is the maximum voltage ratio (0.866).

Then, the three modulation functions for output of phase ‘a’ are given as Equations (6.12) – (6.14).

\[
M_{Aa} = \frac{\sqrt{3}}{2} + k_{31} + \frac{2}{3} V_{im} (v_a + k_{33} \left( \frac{2}{3} V_{AB} \right)
\] (6.12)

\[
M_{Ba} = \frac{\sqrt{3}}{3} + k_{32} + \frac{2}{3} V_{im} (v_a + k_{33} \left( \frac{2}{3} V_{BC} \right)
\] (6.13)

\[
M_{Ca} = 1 - (M_{Aa} + M_{Ba})
\] (6.14)
The modulation functions for the other two output phases, b and c are obtained by replacing \( v_b \) and \( v_c \) with \( v_a \), respectively in Equation (6.12) and Equation (6.13). The modulation functions have third harmonic components at the input and output frequencies added to them to produce output voltage, \( v_o \). This is a requirement to get the maximum possible voltage ratio. It is noted that in Equation (6.6) that there is no requirement for the target outputs to be sinusoidal. In general, three phase output voltages and input currents can be defined in terms of the modulation functions in matrix form as given by Equation (6.15) and Equation (6.16).

Output voltage per phase = M function*Input voltage per phase

\[
\begin{bmatrix}
  v_a \\
v_b \\
v_c
\end{bmatrix} =
\begin{bmatrix}
  M_{Aa} & M_{Ba} & M_{Ca} \\
  M_{Ab} & M_{Bb} & M_{Cb} \\
  M_{Ac} & M_{Bc} & M_{Cc}
\end{bmatrix}
\begin{bmatrix}
  v_A \\
v_B \\
v_C
\end{bmatrix}
\] (6.15)

Input current per phase = Transpose of M function*Output current per phase

\[
\begin{bmatrix}
  i_A \\
i_B \\
i_C
\end{bmatrix} =
\begin{bmatrix}
  M_{Aa} & M_{Ab} & M_{Ac} \\
  M_{Ba} & M_{Bb} & M_{Bc} \\
  M_{Ca} & M_{Cb} & M_{Cc}
\end{bmatrix}
\begin{bmatrix}
  i_A \\
i_B \\
i_C
\end{bmatrix}
\] (6.16)

where \( M \) is the instantaneous input-phase to output-phase transfer matrix of the three-phase matrix converter. \( v_{iph} \) and \( v_{oph} \) are the input and output phase voltage vectors and \( i_{iph} \) and \( i_{oph} \) represent the input and output phase current vectors. Alternatively, from Equation (6.15) and Equation (6.16), the output line voltages and input line currents can be expressed as Equation (6.17) and Equation (6.18) respectively.

Output line voltage = m-function*Input line voltage
\[
\begin{bmatrix}
    v_{ab} \\
    v_{bc} \\
    v_{ca}
\end{bmatrix} =
\begin{bmatrix}
    m_{Ab} & m_{Bb} & m_{Cb} \\
    m_{Ac} & m_{Bc} & m_{Cc} \\
    m_{Aa} & m_{Ba} & m_{Ca}
\end{bmatrix}
\begin{bmatrix}
    V_{AB} \\
    V_{BC} \\
    V_{CA}
\end{bmatrix}
\]  

(6.17)

\[
\begin{bmatrix}
    i_{AB} \\
    i_{BC} \\
    i_{CA}
\end{bmatrix} =
\begin{bmatrix}
    m_{Ab} & m_{Ac} & m_{Aa} \\
    m_{Bb} & m_{Bc} & m_{Ba} \\
    m_{Cb} & m_{Cc} & m_{Ca}
\end{bmatrix}
\begin{bmatrix}
    i_{ab} \\
    i_{bc} \\
    i_{ca}
\end{bmatrix}
\]  

(6.18)

where \( m_{Aa}, m_{ab} \) and \( m_{ac} \) are calculated displaced vectors of \( M_{Aa}, M_{ab} \) and \( M_{ac} \) respectively. Similarly modulation values of other two phases are also calculated as given in Equation (6.19):

\[
\begin{align*}
    m_{Ab} &= \frac{1}{3} (M_{Ba} - M_{Ab}) - \frac{1}{3} (M_{Bb} - M_{Bb}) \\
    m_{Bb} &= \frac{1}{3} (M_{Ba} - M_{Bb}) - \frac{1}{3} (M_{Cb} - M_{Cb}) \\
    m_{Cb} &= \frac{1}{3} (M_{Ca} - M_{Cb}) - \frac{1}{3} (M_{Ba} - M_{Ba}) \\
    m_{Ac} &= \frac{1}{3} (M_{Ab} - M_{Ac}) - \frac{1}{3} (M_{Bb} - M_{Bb}) \\
    m_{Bc} &= \frac{1}{3} (M_{Bb} - M_{Bb}) - \frac{1}{3} (M_{Cb} - M_{Cb}) \\
    m_{Cc} &= \frac{1}{3} (M_{Cb} - M_{Cb}) - \frac{1}{3} (M_{Ba} - M_{Ba}) \\
    m_{Aa} &= \frac{1}{3} (M_{Ac} - M_{Aa}) - \frac{1}{3} (M_{Ba} - M_{Ba}) \\
    m_{Bb} &= \frac{1}{3} (M_{Ba} - M_{Bb}) - \frac{1}{3} (M_{Cc} - M_{Cc}) \\
    m_{Ba} &= \frac{1}{3} (M_{Cc} - M_{Cc}) - \frac{1}{3} (M_{Ac} - M_{Ac}) \\
\end{align*}
\]

(6.19)

Figure 6.26 shows the model of the matrix converter in blocks. Ideal switches have been assumed in the simulation of the matrix converter power circuit. The input variables to the matrix converter are the clock, input voltages \((V_i)\) and target output voltages \((V_o)\) obtained from a controller. The target voltage is given as second input \((V_o)\). The input voltage block represents Equations (6.4) and (6.5). The target output block represents Equations (6.6) and (6.7). The M function block, represents Equations (6.12) -
(6.14) for single phase and similar three phase calculations are performed. Modulation functions are taken out for calculating the output voltages and input currents using Equation (6.17) and Equation (6.18) respectively. The switching frequency of the matrix converter is determined by the signal generator block, where $f_s = 2$ kHz.

The block “Duty cycle generator” consist of logic gates and simple mathematical algorithms. Here the modulation functions are compared with the signal generator waveform, probably square or saw tooth at the input and arranged to have logic levels. Logic gates are used at the output to get three gate signals proportional to the duty cycle of the power switches for one output phase. The “switch” option is a SIMULINK building block. It has three inputs, in(1), in(2) and in(3) and one output. It operates in accordance with the following logic:

if \( \text{in}(2) > 0 \) then output=$\text{in}(1)$

else output=$\text{in}(3)$

Similarly nine switches are used to have three phase output voltages.

![Figure 6.26 Block schematic of matrix converter model](image_url)
6.6 MODELING OF SPACE VECTOR MODULATED MATRIX CONVERTER

Space Vector Modulation (SVM) is an algorithm similar to the rotating flux of the induction machine. This is based on the representation of the three phase input currents and three phase output line voltages on the space vector plane. SVM completely exploit the possibility of matrix converters to

- control the input power factor regardless the output power factor
- fully utilize the input voltages
- reduce the number of switch commutations in each cycle period

Since the matrix converter is supplied by the wind turbine driven self-excited induction generator, the input phases must never be short-circuited and as the loads are inductive in nature, the output phases must not be left open-circuited.

Based on the above two conditions, only 27 \((3^3)\) switching combinations are possible out of 512 \((2^9)\). These can be classified into three groups with 6, 18 and 3 different switching combinations respectively. In the first group of 6 combinations, each output phase is connected to a different input phase. The second group of 18 combinations has two output phases short-circuited. These are the active configurations that determine an output voltage vector and an input current vector, having fixed directions. The third group includes 3 combinations with all the three output phases short-circuited. They are the zero configurations that determine zero input current and zero output voltage vectors (Eubekir Erdem et al 2005 and Casadei et al 1993).

The three phase waveforms are converted to d-q co-ordinates using Park’s transformation method (Alexandru, 2007) as given by Equation (6.20).
For $\theta = 0$, Clarke’s transformation matrix is obtained. The Concordia matrix of abc-$\alpha\beta$ transformation is given by Equation (6.21).

$$[C_c] = \sqrt{2/3} \begin{bmatrix} 1 & -\frac{1}{2} & \frac{1}{2} \\ 0 & \sqrt{3/2} & -\sqrt{3} - 2 \\ \frac{1}{\sqrt{2}} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

The multiplication of $V_a, V_b, V_c$ with $[C_c]$ gives the values $V_\alpha$ and $V_\beta$ as Equations (6.22) and (6.23):

$$V_\alpha = 0.816 \left( V_a - \frac{1}{2} V_b - \frac{1}{2} V_c \right)$$

$$V_\beta = 0.816 (-0.866 V_b - 0.866 V_c)$$
The rotating vector is divided into 6 sectors in which each sector has a phase difference of 60°. The sectors are divided as 1, 2, 3, 4, 5 and 6 in the way 0° - 60°, 60° - 120°, 120° - 180°, 180° - 240°, 240° - 300°, 300° - 360° respectively. Based on the sectors, the d-q coordinates are determined.

The switching function for each switch is,

\[ S_{kj} = \begin{cases} 
1, & \text{Switch } S_{kj} \text{ closed} \\
0, & \text{Switch } S_{kj} \text{ opened}
\end{cases} \]

where \( K = \{A,B,C\}, j = \{a,b,c\} \)

\[ S_{Ka} + S_{Kb} + S_{Kc} = 1 \]

The mathematical relationship between input and output instantaneous phase voltages is given by Equation (6.24),

\[
\begin{bmatrix}
v_A \\
v_B \\
v_C
\end{bmatrix} =
\begin{bmatrix}
S_{Aa} & S_{Ab} & S_{Ac} \\
S_{Ba} & S_{Bb} & S_{Bc} \\
S_{Ca} & S_{Cb} & S_{Cc}
\end{bmatrix}
\begin{bmatrix}
v_u \\
v_b \\
v_c
\end{bmatrix}
\tag{6.24}
\]

where \( v_A, v_B, v_C \) and \( v_u, v_b, v_c \) represent input and output phase voltages. Based on the above equation, line-line voltages and phase currents at the output and input terminals are given by Equation (6.25) and Equation (6.26).

\[
\begin{bmatrix}
v_{AB} \\
v_{BC} \\
v_{CA}
\end{bmatrix} =
\begin{bmatrix}
S_{Aa} - S_{Ba} & S_{Ab} - S_{Bb} & S_{Ac} - S_{Bc} \\
S_{Ba} - S_{Ca} & S_{Bb} - S_{Cb} & S_{Bc} - S_{Cc} \\
S_{Ca} - S_{Aa} & S_{Cb} - S_{Ab} & S_{Cc} - S_{Ac}
\end{bmatrix}
\begin{bmatrix}
v_A \\
v_B \\
v_C
\end{bmatrix}
\tag{6.25}
\]

\[
\begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix} =
\begin{bmatrix}
S_{Aa} & S_{Ba} & S_{Cc} \\
S_{Ba} & S_{Bb} & S_{Cb} \\
SAc & S_{Bc} & S_{Cc}
\end{bmatrix}
\begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix}
\tag{6.26}
\]

where \( v_{AB}, v_{BC}, v_{CA} \) and \( i_A, i_B, i_C \) are output voltages and currents respectively.
The instantaneous input source voltages are given by Equations (6.27) – (6.29)

\[ v_A = v_{in} \sin \omega_A t \]  \hspace{1cm} (6.27)

\[ v_B = v_{in} \sin (\omega_A t - 2\pi/3) \]  \hspace{1cm} (6.28)

\[ v_C = v_{in} \sin (\omega_A t + 2\pi/3) \]  \hspace{1cm} (6.29)

Figure 6.27 shows the sector representing output voltages, each vector representing the output line voltages. The sectors are such that they are at a phase difference of 60°. The space vector representation of input current is illustrated in Figure 6.28. The input phase voltages to the matrix converter as expressed in Equation (6.30) are at a phase difference of 120° electrical.

\[ \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = V_{in} \begin{bmatrix} \cos(\omega t) \\ \cos(\omega t - \frac{2\pi}{3}) \\ \cos(\omega t + \frac{2\pi}{3}) \end{bmatrix} \]  \hspace{1cm} (6.30)

The reference phase voltages are given by Equation (6.31)

\[ \begin{bmatrix} v_{AB} \\ v_{BC} \\ v_{CA} \end{bmatrix} = \sqrt{3}V_{in} \begin{bmatrix} \cos(\omega_A t - \varphi_A + \frac{\pi}{6}) \\ \cos(\omega_A t - \varphi_A + \frac{\pi}{6} - \frac{2\pi}{3}) \\ \cos(\omega_A t - \varphi_A + \frac{\pi}{6} + \frac{2\pi}{3}) \end{bmatrix} \]  \hspace{1cm} (6.31)

The output voltages are based on the reference phase voltages Equation (6.31), given to the converter.
The output currents are given by Equation (6.32)

\[
\begin{bmatrix}
i_A \\
i_B \\
i_C
\end{bmatrix} = I_{om} \begin{bmatrix}
\cos(\omega o t - \varphi_o - \varphi_L) \\
\cos(\omega o t - \varphi_o - \varphi_L - \frac{2\pi}{3}) \\
\cos(\omega o t - \varphi_o - \varphi_L + \frac{2\pi}{3})
\end{bmatrix}
\]  

(6.32)

The reference input currents are given by Equation (6.33)

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} = I_{im} \begin{bmatrix}
\cos(\omega t - \varphi_i) \\
\cos(\omega t - \varphi_i - \frac{2\pi}{3}) \\
\cos(\omega t - \varphi_i + \frac{2\pi}{3})
\end{bmatrix}
\]  

(6.33)

The reference input currents determine the output waveforms. The switching of matrix converter depends upon the amplitude and the frequency of the reference input. The switching combinations are determined by the order of selected sequence. The frequency of reference voltage and frequency of carrier wave determines the switching pulse of the SVM. The switching sequence is defined by the order which is selected from the total number of switching combinations, 27.

The detailed switching combinations in six sectors with respect to input voltage and input current are tabulated in Table 6.1. So there will be 36 (6 x 6) sectors considering all the switching combinations. Here only one sequence of switching combination is switching is used. For example, in combination 1, +1 means forward switch of first group (out of nine groups) and -3 means reverse switch of third group and so on (Eubekir Erdem et al 2005).
Table 6.1 Switching combinations in six sectors for matrix converter

<table>
<thead>
<tr>
<th>$V_o$ \ $I_i$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1-3</td>
<td>+2-3</td>
<td>-1+2</td>
<td>-1+3</td>
<td>-2+3</td>
<td>+1-2</td>
</tr>
<tr>
<td></td>
<td>-4+6</td>
<td>-5+6</td>
<td>+4-5</td>
<td>+4-6</td>
<td>+5-6</td>
<td>-4+5</td>
</tr>
<tr>
<td>2</td>
<td>-7+9</td>
<td>-8+9</td>
<td>+7-8</td>
<td>+7-9</td>
<td>+8-9</td>
<td>-7+8</td>
</tr>
<tr>
<td></td>
<td>+1-3</td>
<td>+2-3</td>
<td>-1+2</td>
<td>-1+3</td>
<td>-2+3</td>
<td>+1-2</td>
</tr>
<tr>
<td>3</td>
<td>+4-6</td>
<td>-8+9</td>
<td>-4+5</td>
<td>-4+6</td>
<td>-5+6</td>
<td>+4-5</td>
</tr>
<tr>
<td></td>
<td>-7+9</td>
<td>+5-6</td>
<td>+7-8</td>
<td>+7-9</td>
<td>+8-9</td>
<td>-7+8</td>
</tr>
<tr>
<td>4</td>
<td>+4-6</td>
<td>5-6</td>
<td>-4+5</td>
<td>+1-3</td>
<td>+2-3</td>
<td>+4-5</td>
</tr>
<tr>
<td></td>
<td>+1-3</td>
<td>-2+3</td>
<td>-1-2</td>
<td>-4-5</td>
<td>-5-6</td>
<td>-1+2</td>
</tr>
<tr>
<td>5</td>
<td>-1+3</td>
<td>-2+3</td>
<td>+1+2</td>
<td>+1-3</td>
<td>+2-3</td>
<td>-1+2</td>
</tr>
<tr>
<td></td>
<td>+7-9</td>
<td>+8-9</td>
<td>+7-8</td>
<td>+7-9</td>
<td>+8-9</td>
<td>-7+8</td>
</tr>
<tr>
<td>6</td>
<td>+7-9</td>
<td>+8-9</td>
<td>-7-8</td>
<td>+4-6</td>
<td>+5-6</td>
<td>+7-8</td>
</tr>
<tr>
<td></td>
<td>-4+6</td>
<td>-5+6</td>
<td>+4-5</td>
<td>-7+9</td>
<td>-8+9</td>
<td>-4+5</td>
</tr>
</tbody>
</table>

Table 6.2 Switching configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>ABC</th>
<th>Configuration</th>
<th>ABC</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1</td>
<td>abb</td>
<td>1</td>
<td>aba</td>
</tr>
<tr>
<td>-3</td>
<td>acc</td>
<td>2</td>
<td>abb</td>
</tr>
<tr>
<td>-4</td>
<td>aba</td>
<td>3</td>
<td>acc</td>
</tr>
<tr>
<td>+6</td>
<td>aca</td>
<td>4</td>
<td>aca</td>
</tr>
<tr>
<td>0</td>
<td>aaa</td>
<td>5</td>
<td>aaa</td>
</tr>
<tr>
<td>0</td>
<td>bbb</td>
<td>1</td>
<td>aba</td>
</tr>
<tr>
<td>0</td>
<td>bbb</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Table 6.2 shows the switching configurations generally used in the matrix converter nine switched topology. Here A, B, C, and a, b, c represent the output phases and input phases respectively. To have three phase voltage
transfer, any of switches of all the three phases must be in ON position while the switches in the same leg must not be switched ON simultaneously to avoid short-circuit between the switches. Hence three switching combinations are invalid vectors (Eubekir Erdem et al 2005 and Casadei et al 1993).

6.7 SIMULATION RESULTS AND DISCUSSION

6.7.1 Matrix Converter employing Venturini Algorithm

The matrix converter described in section 6.5 is modeled and simulated using MATLAB / SIMULINK for both loaded and unloaded conditions. The simulation diagrams for both cases are depicted in Figures 6.29 and 6.30 respectively. The results obtained are analyzed as follows. The parameter inputs under unloaded and loaded conditions are tabulated in Table 6.3.

Figure 6.29 MATLAB / SIMULINK model of a three phase matrix converter under unloaded condition
Table 6.3 Operating conditions used for analysis

<table>
<thead>
<tr>
<th>Parameter inputs for 3-phase matrix converter under unloaded condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input specifications:</strong></td>
<td><strong>Output target specifications:</strong></td>
</tr>
<tr>
<td>Input voltage, ( V_i ) = 311.08 V</td>
<td>Output voltage, ( V_o ) = 155.54 V</td>
</tr>
<tr>
<td>Input frequency, ( f_i ) = 50 Hz</td>
<td>Output frequency, ( f_o ) = 100 Hz</td>
</tr>
<tr>
<td>( V_o/V_i ) = 50 %</td>
<td>Switching frequency, ( f_s ) = 2000 Hz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter inputs for 3-phase matrix converter under loaded condition</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input specifications:</strong></td>
<td><strong>Load specifications:</strong></td>
</tr>
<tr>
<td>Input voltage, ( V_i ) = 311.08 V</td>
<td>( R = 20 \Omega; \ L = 0.04 ) Henry</td>
</tr>
<tr>
<td>Input frequency, ( f_i ) = 50 Hz</td>
<td><strong>Output target specifications:</strong></td>
</tr>
<tr>
<td>( V_o/V_i ) = 50 %</td>
<td>Output voltage, ( V_o ) = 155.54 V</td>
</tr>
<tr>
<td></td>
<td>Output frequency, ( f_o ) = 100 Hz</td>
</tr>
<tr>
<td></td>
<td>Duty cycle frequency, ( f_s ) = 2000 Hz</td>
</tr>
</tbody>
</table>

Figure 6.30 MATLAB / SIMULINK model of a three phase matrix converter under loaded condition
Figure 6.31 Input voltage waveform of three phase matrix converter

Figure 6.32 Output voltages of phase a, b and c under unloaded condition

Figure 6.33 Waveforms of calculated M-functions for one phase
Figure 6.34 Waveforms of calculated M-functions for all the three phases

Figure 6.35 Load current for one phase
Figure 6.36 Load current for all the three phases

Figure 6.37 FFT Analysis of load current for one phase
The simulation results of unloaded matrix converter operated at the specified parameters in Table 6.3 are presented in Figures 6.31 – 6.37. Figure 6.31 represents the input voltage waveform with a magnitude of 311.08 V. The simulated results of the three output voltages are illustrated in Figure 6.32. Figure 6.33 represents the calculated M-function values for one phase, say “a”. Calculated M-values for all the three phases are given in Figure 6.34. At this stage one can summarize that the pre calculated M-values provide high quality switching pattern.

Now the three phase matrix converter is loaded with star connected three phase R-L load (20 Ω and 0.04 Henry) as shown in Figure 6.29. Here unity input power factor is considered, which means one phase input current is low passed compared with the respective input voltages. The simulation results of loaded matrix converter are presented in Figures 6.35-6.37. The results of load current for one phase and for all the three phases are presented in Figures 6.35 and 6.36 respectively. The load currents are nearly sinusoidal. It can be further improved by modulating the switching frequency.

Figure 6.37 shows their FFT analysis. The fundamental harmonics is at 50 Hz and the additional harmonics are around the switching frequency. The Total Harmonic Distortion (THD) is found to be 17.74 % of the fundamental frequency of 50 Hz.

### 6.7.2 Conventional AC-DC-AC Converter using Space Vector Modulation

Figure 6.38 shows MATLAB / SIMULINK model of conventional AC-DC-AC converter employed with SVM. It consists of 12 IGBT switches. The SVM pulses are given as the firing signals to the IGBTs. They are shown for six sectors in Figure 6.39. According to the given sequence the pulse is generated. The sequence is 0°-60°, 60°-120°, 120°-180°, 180°-240°, 240°-300°,
300°-360°. Each sequence represents single sector in the order \( s_1, s_2, s_3, s_4, s_5 \) and \( s_6 \) respectively. The simulation parameters are tabulated in Table 6.4.

Figure 6.38 Simulation model of conventional SVM based AC-DC-AC Converter

Figure 6.39 SVM pulses
Table 6.4 Simulation parameters of converters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage $V_{in}$</td>
<td>400 V (Line Voltage)</td>
</tr>
<tr>
<td>Input Frequency $f_{in}$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Switching Frequency $f_s$</td>
<td>5000 Hz</td>
</tr>
<tr>
<td>Switching Period $T_s$</td>
<td>20 $\mu$sec</td>
</tr>
<tr>
<td>R-Load</td>
<td>2000 $\Omega$</td>
</tr>
<tr>
<td>L ( R-L Load )</td>
<td>1.5 H</td>
</tr>
</tbody>
</table>

Figure 6.40 Input line voltages to the converter

Figures 6.40 to 6.42 show the simulation results of the conventional AC-DC-AC converter. Due to losses in the two conversion stages, the output line voltage is 350 V. FFT analysis of the output voltage and output current is done using MATLAB and the harmonic spectrum of both cases are presented in Figure 6.43.

Figure 6.41(a, b) Output line and phase voltages for R-Load
From the results, it is seen that THD level is 20.45 % and 20.46 % of the fundamental frequency of 50 Hz respectively. The harmonic injection is due to the DC link present in the model. The simulation results are summarized in Table 6.5.

![Figure 6.42(a, b) Output current for R-Load and R-L Load](image1)

(a)  
(b)

![Figure 6.43(a, b) Harmonic spectrum of output voltage and current](image2)

(a)  
(b)

Table 6.5 Simulation results of AC-DC-AC converter

<table>
<thead>
<tr>
<th>V_o (Output Voltage)</th>
<th>230 V (Phase Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>350 V (Line Value)</td>
</tr>
<tr>
<td>I_o (Output Current for R-Load)</td>
<td>0.125 A</td>
</tr>
<tr>
<td>I_o (Output Current for R-L Load)</td>
<td>0.099 A</td>
</tr>
<tr>
<td>THD (for Voltage)</td>
<td>20.45 %</td>
</tr>
<tr>
<td>THD (for Current)</td>
<td>20.46 %</td>
</tr>
</tbody>
</table>
6.7.3 Indirect Matrix Converter using Space Vector Modulation

The indirect Matrix Converter is an advanced version of AC-DC-AC converter. This model does not contain the DC link but it has two parts separated as input and output. The simulation model is illustrated in Figure 6.44. There are 18 switches and separate legs for input and output respectively. The switching is done using SVM pulses. Here the SVM pulses are given to the gates according to the switching order. The extra leg in the circuit gives more number of switching combinations.

![Simulation model of indirect matrix converter](image)

**Figure 6.44 Simulation model of indirect matrix converter**

![Output line and phase voltages for R-Load](image)

**(a) (b)**

**Figure 6.45(a, b) Output line and phase voltages for R-Load**
The simulation results are depicted in Figures 6.45 and 6.46. Figure 6.45 shows the output AC voltages for R-Load. There is an intermediate fictitious DC link and hence the harmonic distortion is reduced. The results obtained from FFT analysis is shown in Figure 6.47. Table 6.6 summarizes the results obtained for both R and R-L loads.

**Table 6.6 Simulation Results of Indirect Matrix Converter**

<table>
<thead>
<tr>
<th></th>
<th>230 V (Phase Value)</th>
<th>350 V (Line Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_o$ (Output Voltage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_o$ (Output Current for R-Load)</td>
<td>0.125 A</td>
<td></td>
</tr>
<tr>
<td>$I_{o,R-L}$ (Output Current for R-L Load)</td>
<td>0.099 A</td>
<td></td>
</tr>
<tr>
<td>THD (for Voltage)</td>
<td>20.38 %</td>
<td></td>
</tr>
<tr>
<td>THD (for Current)</td>
<td>20.38 %</td>
<td></td>
</tr>
</tbody>
</table>
6.7.4 Nine Switched Matrix Converter using Space Vector Modulation

Figure 6.48 illustrates the simulation model of the direct AC-AC converter with nice switch topology. There are 27 switching combinations. The avoidance of intermediate step causes reduction in losses. The switching is done using SVM pulses. The simulation results are shown in Figures 6.49 and 6.50.
Figure 6.50(a, b) Output current for R-Load and R-L Load

Figure 6.51(a, b) FFT Analysis of output voltage and current

The percentage of THD as shown by Figure 6.51 indicate that the performance of proposed model when compared to the conventional converter with 5.11 % and 5.12 % respectively. The entire results obtained are tabulated in Table 6.7. FFT analysis shows that the performance of improved matrix converter is better than the conventional converter but not impressive as matrix converter. The comparison between converters as summarized in Table 6.8 shows that matrix converter (nine switch topology) is more efficient in reducing harmonics and voltage transfer.
Table 6.7 Simulation results of nine switched matrix converter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_o ) (Output Voltage)</td>
<td>230 V (Phase Value)</td>
</tr>
<tr>
<td></td>
<td>400 V (Line Value)</td>
</tr>
<tr>
<td>( I_o ) (Output Current for R-Load)</td>
<td>0.125 A</td>
</tr>
<tr>
<td>( I_o ) (Output Current for R-L Load)</td>
<td>0.099 A</td>
</tr>
<tr>
<td>THD (for Voltage)</td>
<td>5.11 %</td>
</tr>
<tr>
<td>THD (for current)</td>
<td>5.12 %</td>
</tr>
</tbody>
</table>

Table 6.8 Comparison of power electronic converters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>AC-DC-AC Converter</th>
<th>Indirect matrix Converter</th>
<th>Nine Switched Matrix converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switching speed</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Voltage transfer ratio</td>
<td>400 V / 350 V</td>
<td>400 V / 350 V</td>
<td>400 V / 400 V</td>
</tr>
<tr>
<td>THD % (V/I)</td>
<td>20.46 / 20.45</td>
<td>20.38 / 20.38</td>
<td>5.11 / 5.12</td>
</tr>
<tr>
<td>Frequency regulation</td>
<td>Not possible</td>
<td>Possible</td>
<td>Possible</td>
</tr>
</tbody>
</table>

The simulation model of closed loop speed control of SVM based three phase matrix converter feeding a three phase induction motor is shown in Figure 6.52. The control consists of voltage control loop and current control loop. For continuous change in the reference speed, the output is controlled at the desired level. The control loops will sense the state of the system through a reference block and so the voltage level of the system is maintained. The simulation parameters along with the details of induction motor load are given in Table 6.9. The simulation results of closed loop system to control the speed of the induction motor are shown in Figures 6.53. For a set speed of 157 rad/sec, the electromagnetic torque, output currents and
the rotor speed are shown in Figure 6.53(c). Irrespective of the input voltage, the speed is maintained constant. This illustrates the effectiveness of the control.

Figure 6.52 Simulation model of closed loop control of matrix converter

Table 6.9 Simulation parameters of closed loop operation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Type</td>
<td>Induction Motor</td>
</tr>
<tr>
<td>Capacity</td>
<td>5 HP</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>400 V</td>
</tr>
<tr>
<td>Rated Current</td>
<td>7.5 A</td>
</tr>
<tr>
<td>R_s (Stator Resistance)</td>
<td>0.087 Ω</td>
</tr>
<tr>
<td>L_s (Stator Inductance)</td>
<td>0.8 mH</td>
</tr>
<tr>
<td>R_r (Rotor Resistance)</td>
<td>0.228 Ω</td>
</tr>
<tr>
<td>L_r (Stator Inductance)</td>
<td>0.8 mH</td>
</tr>
<tr>
<td>L_m</td>
<td>34.7 mH</td>
</tr>
<tr>
<td>Operating Frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Rated Speed</td>
<td>1500 rpm</td>
</tr>
</tbody>
</table>

Input Voltage $V_{in}$ 400 V (Line)
Input Frequency $f_{in}$ 50 Hz
Switching Frequency $f_s$ 5000 Hz
$T_s$ 20 μs
Figure 6.53(a, b, c) Simulation results of closed loop control
The block schematic of the hardware set-up of a three phase matrix converter is shown in Figure 6.54. It consists of power module, control module and required protection circuits. The specifications are given in Appendix.

Figure 6.53(d) Output voltage

Figure 6.54 Block schematic of hardware set-up
The design and implementation of matrix converter circuit along with the required modules is done by considering the current state of semiconductor technology and the power rating of the prototype model.

### 6.8.1 Power Module

The power module consists of nine bidirectional switches capable of blocking voltage and conducting current in both directions. These switches are made up of 9 bidirectional switches with NPT\(^3\) IGBT and fast diode bridge (FIO 50-12BD) for the reverse flow of current. The functional circuit diagram of the power switches is shown in Figure 6.55.

![Functional circuit diagram of matrix converter](image)

**Figure 6.55 Functional circuit diagram of matrix converter**

Input filter is used to reduce the switching frequency harmonics present in the input current. Simple LC filter is used for this purpose. The requirements of the LC filter are,

- Cut-off frequency lower than the switching frequency of matrix converter
- Minimal reactive power at grid frequency
- Minimal volume and weight
- Minimal filter inductance voltage drop at rated current in order to avoid reduction in voltage reduction ratio
The filter is designed in such a way that the input and output currents of the converter are not affected.

Isolated gate driver (HCPL-4506) circuits as given in Figure 6.56 are used to amplify the controller voltage of 5 V to the switching voltage of 15 V for the power switches. It contains a GaAsP LED which is optically coupled to an integrated high gain photo detector. Due to minimized propagation delay difference between the devices, these optocouplers improve the inverter efficiency through reduced switching dead time.

Figure 6.56 Driver circuit for IGBTs

6.8.2 Control Module

Controller is the heart of the whole module. Matrix converters require complex control algorithm and hence the programming is implemented using Field Programmable Gate Arrays (FPGA). FPGA are arrays of logic blocks, surrounded by programmable I/O blocks which can be linked together to form complex logic implementations. A typical FPGA
contains from 64 to tens of thousands of logic blocks and an even greater number of flip-flops. The individual cells are interconnected by a matrix of wires and programmable switches. The array of these logic cells and interconnections form a fabric of basic building blocks for logic circuits. Complex designs are created by combining these basic blocks to create the desired circuit. The FPGA technology offers a many more advantages as compared to other conventional technologies. The program can easily be changed to optimize and control the converter parameters like frequency and voltage. A very attractive high-level simulation tool is provided by FPGA, called XILINX. (Prawin Ange et al 2011).

Xilinx Spartan-3E XC3S100E FPGA is a 144-Thin Quad Flat Pack package which is used to generate gating signals. After initializing the control board, VHDL (Very High Speed Integrated Chip Hardware Description Language) code of PWM signal generation using Xilinx ISE 10.1 software is written as per the logic given below.

PWM is a technique to provide a logic “1” and logic “0” for a controlled period of time. Zero crossing detected three phase voltage is compared with the sinusoidal PWM signal generated from three phase reference voltages. Thus nine pulses to the matrix converter switches are generated. The pulse pattern for the bi-directional switches is shown in Table 6.10.

Table 6.10 Switching pulse pattern

<table>
<thead>
<tr>
<th>Supply Voltage</th>
<th>SPWM Voltage</th>
<th>PWM Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>R TOP</td>
<td>V a top</td>
<td>PWM1</td>
</tr>
<tr>
<td>Y TOP</td>
<td>V b top</td>
<td>PWM2</td>
</tr>
<tr>
<td>B TOP</td>
<td>V c top</td>
<td>PWM3</td>
</tr>
<tr>
<td>R BOTTOM</td>
<td>V a bottom</td>
<td>PWM4</td>
</tr>
<tr>
<td>Y BOTTOM</td>
<td>V b bottom</td>
<td>PWM5</td>
</tr>
<tr>
<td>B BOTTOM</td>
<td>V c bottom</td>
<td>PWM6</td>
</tr>
</tbody>
</table>
The PWM signal to the other switches is obtained by AND operation of generated PWM signals as given by Equations (6.34) – (6.36).

\[(\text{PWM1}).(\text{PWM4}) = \text{PWM7} \quad (6.34)\]
\[(\text{PWM2}).(\text{PWM5}) = \text{PWM8} \quad (6.35)\]
\[(\text{PWM3}).(\text{PWM6}) = \text{PWM9} \quad (6.36)\]

PWM output is terminated in the box type header. Bidirectional voltage translator (SN74LVCC3245A) is used in between FPGA I/O lines and box type header to translate 3.3 V to 5 V and vice-versa.

### 6.8.3 Protection Circuits

In a matrix converter, over voltages and over currents can appear from the input side. When the switches are turned OFF, the current in the load is suddenly interrupted. The energy stored in the motor inductance (if load used is motor) has to be discharged without creating over voltages. A clamp circuit shown in Figure 6.57 is a common solution to avoid both input and output over voltages. This clamp circuit has 12 fast –recovery diodes to connect capacitor to input and output terminals.

**Figure 6.57 Clamp circuit for over voltage protection**

An isolation transformer with symmetrical windings is used to decouple two circuits. It allows an AC signal or power to be taken from one device and fed into another without electrically connecting two circuits. The
transmission of DC signals from one circuit to other is blocked while allowing AC signals to pass. They also block interference due to ground loops. This isolation transformer is used to give supply to ZCD (Zero Crossing Detector). ZCD is used for comparing the phase signal with the reference signal. The circuit diagram is shown in Figure 6.58.

Figure 6.58 Circuit diagram of zero crossing detector
6.8.4 Circuit Diagram

The overall circuit diagram of the prototype model is given in Figure 6.59. The photographs of the experimental set-up are shown in Figures 6.60(a, b).

![Figure 6.59 Complete hardware circuit diagram](image-url)
6.8.5 Results and Discussion

The results of the experimental set-up are analyzed for both R-load and a R-L load. V/f control is used to get a controlled output with required
frequency. The model validates the variable frequency output for different load conditions. After setting the desired frequency, the input to the converter is given from the supply mains or the from the prototype model of the wind turbine driven self-excited induction generator. Also a single phase supply of 230 V / 9 V is given to the gate driver circuit. A variable resistive load is connected across the converter.

(a) Input Voltage \(f_i = 50\, \text{Hz}\)  
(b) ZCD Output of R-Phase  
(c) PWM Pulses to the Gate Circuit of One Leg

Figure 6.61 (Continued)
(d) Output Line Voltage (between R & Y) \((f_0 = 50 \text{ Hz})\)

(e) Input Current \((f_i = 50 \text{ Hz})\)

(f) Output Current \((f_0 = 50 \text{ Hz})\)

Figure 6.61(a, b, c, d, e, f) Hardware results for 50 Hz frequency

Figures 6.61(a) – 6.61(f) illustrate the hardware outputs for an input voltage of 110 V, 50 Hz frequency and the output voltage of 110 V, 50 Hz frequency. The switching frequency is 10 kHz. It is seen that output waveforms are almost sinusoidal and the THD level is found to be 7.9% for the output voltage and 8.2% for the output current. The PWM pulses generated is also given in Figure 6.61(c) for one leg of the converter circuit. The output voltage and current for another resistive load is shown in Figures 6.62.
Figure 6.62 Output voltage and current for varying resistive load conditions

Figure 6.63(a, b, c, d) Hardware results for 25 Hz frequency
A variable R-L load is connected across the converter and the results are observed for a set frequency of 25 Hz. The input line voltage of 60 V at a frequency of 50 Hz is given as input. The PWM pulses, the output R-phase voltage and line voltage between R and Y phases, output current in R-phase at 25 Hz are shown in Figures 6.63. The harmonic spectrum of the output voltage is shown in Figure 6.64 where the THD level is 7.4 % of the fundamental frequency of 50 Hz.

![Harmonic spectrum of the output voltage](image)

**Figure 6.64 Harmonic spectrum of the output voltage**

6.9 CONCLUSION

Matrix converters are reality and can be physically realized up to 100 kW in a single silicon structure. In this chapter, the concepts and feasibilities of direct AC-AC matrix converter in wind turbine generators is proposed. Matrix converter replaces the use of DC-link converters which reduces losses produced due to the energy storage elements.

Single phase matrix converter feeding an R-L load and induction motor has been simulated and implemented through hardware set-up. Sinusoidal wave modulation algorithms have been used to see the input voltage utilization and harmonic effects on the output. However, using the
sine waveform in the PWM algorithm, the amplitude of the output voltage has increased. It is also found that using low frequency ratio, the lower order harmonic contents increases in addition to higher amplitudes of the other harmonic voltages. Simulation results illustrate good performance of the single phase matrix converter based drive system. Therefore, this converter is a good alternative to DC link converters at low output frequencies for industrial applications. The converter has also an advantage of bi-directional power flow between the input and load over diode rectifier front end inverters.

The experimental set-up is based upon square wave PWM technique, which is used for reducing harmonics and ripples in the output. This technique, as compared to the sinusoidal PWM has reduced harmonic content and hence less heat dissipation. As the output frequency increases, lower order harmonics appear at the output. The results also show that the single phase matrix converter provides quality output waveforms.

The simulated results of AC-DC-AC Converter, Indirect Matrix Converter and Matrix Converter (Nine Switch Topology) based on several modulation algorithms are compared and the results are validated. The power quality studies based on THD levels are presented for different loading conditions.

The hardware module of three phase matrix converter is realized by employing Xilinx Spartan-3E XC3S100E FPGA controller for generating SPWM signals to the IGBT switches. By keeping V/f ratio constant the magnitude and frequency of the output voltage are controlled. The experimental results of the matrix converter connected to R-Load and R-L load are presented for different operating conditions. These matrix converters can be employed in stand-alone wind energy conversion systems where the output voltage or frequency control is required.