MATRIX-Z-CONVERTER WITH MAXIMUM VOLTAGE TRANSFER RATIO: AN EXPERIMENTAL STUDY

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The potential of matrix converter is enormous and the electrical power derived from it free almost from harmonics as it does not possess an intermediate dc link storage. This work presents a novel idea of utilizing a Z-Source converter in three-phase to single-phase matrix converter for a variable speed single phase induction motor in order to achieve maximum output voltage ratio. The maximum input voltage is fully utilized with Z source converter to achieve better performance of the motor speed characteristics. The larger magnitude of harmonics and limited voltage ratio in m X n phase matrix converter is overcome significantly by using Z source converter with achievement of 100% voltage transfer ratio. Xilinx Spartan 3E Field Programmable Gate Array (FPGA) controller for speed regulation of Induction Motor has been proposed with Very High Speed Hardware Description Language (VHDL)platform. The MATLAB/SIMULNK simulation analysis & experimental results for R, R-L and induction motor loads. The test results prove the possibility to develop and evaluate an single-phase induction motor fed by a Z source matrix converter with maximum voltage transfer ratio for changing input conditions. Further, as a part of future work ,the solar photovoltaic can be used as source if the mains AC supply is disconnected.

Keywords: Z-source, matrix converter, voltage transfer ratio, harmonics, variable speed controls, induction motor

1. Introduction

The most familiarised converter in the family of ac–ac direct converters is the matrix converter introduced by Venturini and Alesina [1-2]. In recent years, Enormous publications have illustrated with modulation schemes [3], load voltage generation issues, semiconductor device technology, gate drive issues [4], and the vibrant commutation procedure [5] for bi-directional switches . Matrix Converter technology has enhanced the household, industrial applications, aerospace applications and military electric vehicle applications with the availability of faster and efficient switching devices such as IGBT's , RB-IGBT's and GTO's. The drawback is overcome by the analysis of Conduction and Switching losses of Matrix -Z-Source converter in recent studies [6]. Studies on Adjustable speed drives using Z source converters have been more efficient[7]. The complex

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control algorithms, multi-step commutation strategies, more number of switching elements, low voltage transfer ratio are inherent drawbacks observed from many publications. The barriers and limitations of traditional matrix converters are overcome by combining ac-ac Z source converters with m phase to n phase matrix converters[8-9].

Though the matrix converters has the advantages such as bi-directional power flow, better sinusoidal input and output waveforms, minimum reactive energy storage components requirement ,it has the disadvantage of maximum output voltage limited to 86.6% of the input voltage. To the author's knowledge, there are very few efforts taken for improving the voltage transfer ratio in three phase to single matrix converter. Hence an attempt has been made to improve the voltage transfer ratio to unity and more than unity with the design of Z source network in a three phase to single-phase matrix converter and has been successful after implementation to validate the simulation results.

The paper is organised as follows. In section 2, the basic theory of commutation strategies and modulation scheme for Z source matrix converter are discussed. In section 3, the implemention of proposed topology using SPWM technique in Xilinx Spartan 3E compatible FPGA board with sophisticated algorithm for variable speed applications[10] is discussed. In section 4, the results and discussions are presented. Finally, the section 5 concludes with the finding s of the study.

2. Three phase to Single Phase Matrix converter

2.1 Commutation switching strategy

The prototype is designed using a bi-directional switch capable of blocking voltage and conducting current in both directions. The converter has common emitter bidirectional switch arrangement with two IGBT's connected in anti-parallel and diodes for having reverse blocking capability as shown in Fig. 1.

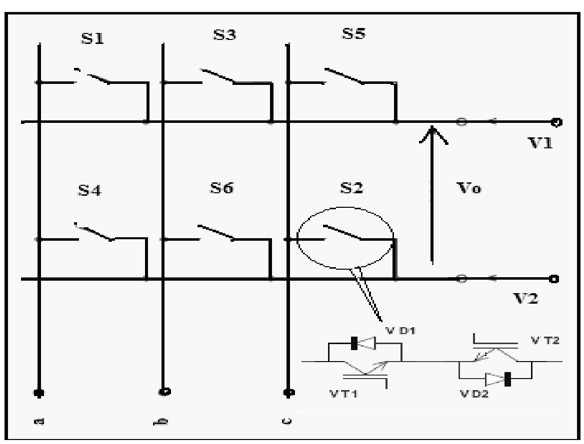


Fig. 1. Bidirectional switch configurations

For a faulted condition, all the switches in the converter are turned off such that the clamp de-energizes the load current without damaging the switches [11]. Through the strategy shown in Table [2.1], the direction of current flow through the commutation switch is controlled.

Table 1

Commutation switching strategy

	MOST POSITIVE		MOST NEGATIVE		OUTPUT (r, s)
ACTIVE COMMUTATION SWITCHES	Sw1,sw 4	0 To 60	Sw 2,3,5,6	120 To 180	
	Sw 1		Sw 2,sw 3		+ve cycle of O/P
	Sw 4		Sw 5,sw 6		- ve cycle of O/P
	Sw 3,sw 6	60 To 120	Sw 1,4,5,2	60 To 120	
	Sw3		Sw1,sw2		+ve cycle of O/P
	Sw 6		Sw 4, sw 5		- ve cycle of O/P
	Sw 5,sw2	120 To 180	Sw1,6,4,3	0 To 60	
	Sw5		Sw1,sw 6		+ve cycle of O/P
	Sw2		Sw 4,sw 3		- ve cycle of O/P

The desired single phase output from a three phase supply is achieved with the switches closed sequentially, at a fixed switching period.

2.2 Modulation scheme.

The system consists of a three-phase supply, Z- source network, Matrix converter, filter, capacitor start induction motor. A Z-source network was designed to attain high voltage transfer ratio with base equation (1). The Z-Source network has two operating states: shoot and non-shoot-through states[12].

$$\begin{bmatrix} v_a(t) \\ v_b(t) \\ v_c(t) \end{bmatrix} = \mathbf{Vs} \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - 120^\circ) \\ \sin(\omega t + 120^\circ) \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} v_{zxa}(t) \\ v_{zxb}(t) \\ v_{zxc}(t) \end{bmatrix} = \mathbf{Vzx} \begin{bmatrix} \sin(\omega t + \theta zx) \\ \sin(\omega t + \theta zx - 120^\circ) \\ \sin(\omega t + \theta zx + 120^\circ) \end{bmatrix} \tag{2}$$

Where, x = L and C for Inductive voltage and Capacitive voltage equations respectively in equation (2). Switch S1 is 'ON' in the non shoot-through states with DT interval as the capacitor charges in the Z network and the energy is transferred to load. The line voltages and z network output voltages are represented in equation 4 & equation 5 respectively. Switch S1 is 'OFF' in the shoot-through states with (1-D)T interval as the capacitor in the Z network discharges . The inductive and capacitive voltages become equal as shown in the equation (6).

$$V_{zab}(t) = V_{C1} - V_{L2};\quad V_{zbc}(t) = V_{C2} - V_{L3};\ V_{zca}(t) = V_{C3} - V_{L1};\quad (4)$$
$$V_{ab}(t) = V_{C1} - V_{L1};\quad V_{bc}(t) = V_{C2} - V_{L2};\quad V_{ca}(t) = V_{C3} - V_{L3};\quad (5)$$
$$V_{L1} = V_{C1};\quad V_{L2} = V_{C2};\quad V_{C1} = V_{C2};\quad (6)$$

The output line to- line voltage of z-source network is equal to V_C, if the inductance is of low value and the line frequency voltage drop is absent across inductor. Hence the voltage gain g' across capacitor of z-source network is expressed in equation (6) as the average value of inductors is zero in steady state. By the control of g', bucking and boosting of output voltage is possible in the proposed converter,

$$g' = Vo / Vi \;;\quad (7)$$
$$D = (1 - g') / (1 - 2g') \text{ for boost mode };\quad (8)$$
$$D = (1 + g') / (1 + 2g') \text{ for buck mode };\quad (9)$$

Where, D is the dutycycle. The voltage transfer ratio of Z-Source is unity, which was greater than 0.866.The output filter design reduces ripple frequency to maximize the displacement power factor cos (pi) for output power P. The duty cycle calculations from equations (7) & (8) results in the voltage gain. The circuit of a three phase to single phase matrix converter is shown in the Fig.2

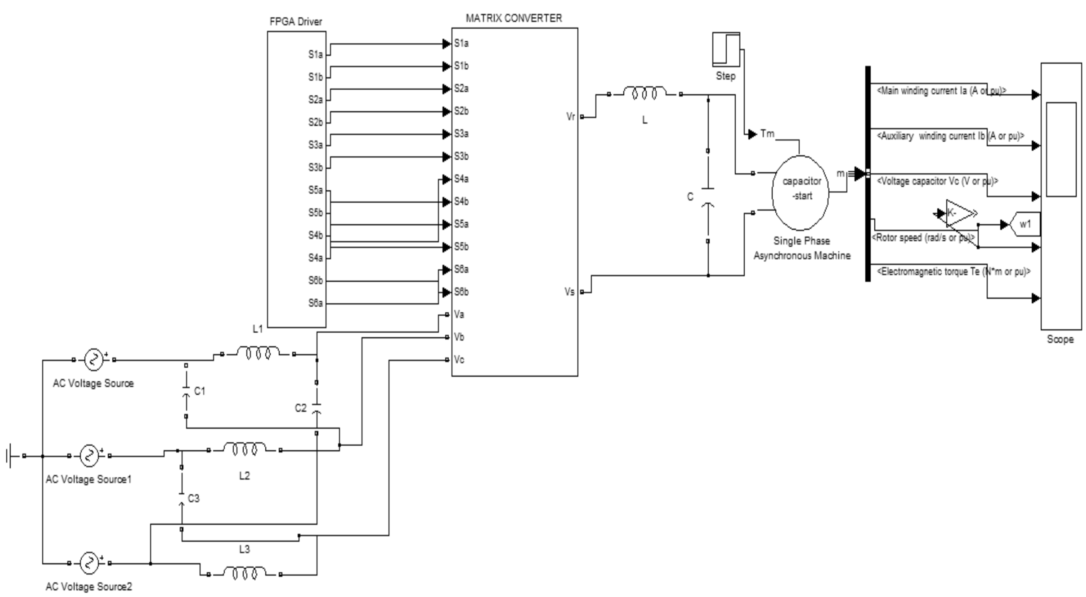


Fig. 2. Simulation Circuit of Three phase to Single phase Matrix Converter for Induction Motor

The three phase line voltages are expressed by equations(7).

$$\begin{bmatrix} v_{za}(t) \\ v_{zb}(t) \\ v_{zc}(t) \end{bmatrix} = \mathbf{V}\,\mathbf{z} \begin{bmatrix} \sin(\omega t + \theta z) \\ \sin(\omega t + \theta z - 120^\circ) \\ \sin(\omega t + \theta z + 120^\circ) \end{bmatrix} \quad (10)$$

The matrix representation of the switching states are given as follows in equations (8).

$$[\mathrm{SW}] = \begin{bmatrix} sw1 & sw3 & sw5 \\ sw4 & sw6 & sw2 \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} v_r(t) \\ v_s(t) \end{bmatrix} = \begin{bmatrix} sw1 & sw3 & sw5 \\ sw4 & sw6 & sw2 \end{bmatrix} \cdot \begin{bmatrix} v_{za}(t) \\ v_{zb}(t) \\ V_{zc}(t) \end{bmatrix} \quad (12)$$

The output voltage $v_o(t)$ is the difference of $v_r(t)$ and $v_s(t)$.

The magnitude of harmonics which is large in single phase to single phase matrix converter was reduced conveniently by using three phase input supply. The modulation index of switching angle α was varied to reduce the harmonics. The output voltage has been increased to 100**%,** with minimum distortions. The single phase output power is maintained constant at unity power factor[13].

3. Prototype design topology:

Matrix Converter is employed with six number of insulated gate bipolar transistors (IGBT) switches and internal anti-parallel diodes for each switch. Three IGBT drivers (IR2110) of high-speed high voltage capability was used to afford accustomed gate signals to the power switches. The PWM signal generation algorithm along with v/f speed control algorithm are implemented using Xilinx Spartan 3E FPGA board using the Very High Speed Hardware Description Language (VHDL) package. The PWM pulses proportional to the speed regulation are directly generated and downloaded in FPGA Sparton 3E starter kit to produce base drive signals for converter power device switches. The TOSHIBA 6N137 opto-couplers are used to afford an isolation between the FPGA board and the power circuit.

The flexibility as a motor controller platform, fault detection functionality and user interface controls in the Xilinx Spartan 3E FPGA board, minimizes the requirement for additional external components[14]. The phase shift generator unit and zero-crossing detector produces the time delay(α) in degrees and phase generation sequences respectively. The circuit generates two different pulses for the positive and negative half-cycles of the single phase. The switching frequency of 10 kHz and modulation index of 0.8 has been fixed . The inputs such clock, reset, increment and decrement of frequency are adjusted by pushbuttons. A Comparator block was used to compare two signals coming from sine wave generator and from Up-down counter. The output of comparator block was the PWM signal.

Further, the speed control system of Induction motor was developed with feedback unit. The speed encoder producing 3000pulses/revolution is used for the speed feedback. The actual Induction motor speed is sensed, sampled and compared to a reference speed signal to determine the error. The error is analysed through FPGA controller algorithm to make a prompt decision on the speed regulation through the selection of the optimum PWM signals which in turn controls the V/f ratio of converter. However, closed loop action of speed controller causes the rotor speed to recover back to defined reference value and hence minimizes the steady state error. The Constant volts per Hertz (V/f) mode of speed control [15] for single phase induction motors was found satisfactory. The prototype structure is shown in Fig. 3.

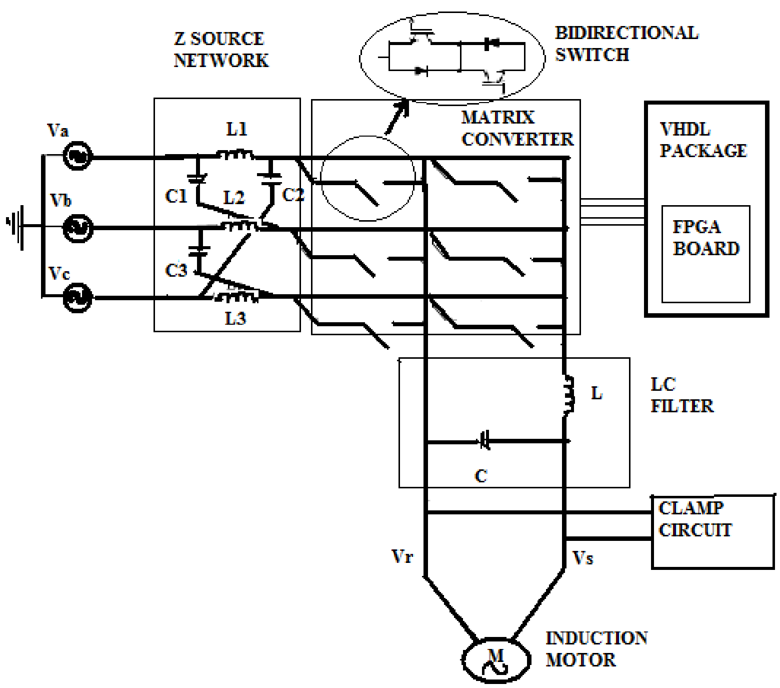


Fig. 3. Prototype structure of three phase to single phas matrix converter

4. Results & Discussion

The three phase to single phase matrix converter feeding R, R-L and Motor load was simulated . The values of parameters used in teh simulation are shown in Table 2.

Table 2

Simulation Parameters

Balanced three-phase input voltage	*220 V/50Hz*
Carrier frequency	*5kHz.*
.. *Z-source network*	*L1=L2=L3=1.0 mH & C1=C2= C3=50 µF.*
Voltage gain: g'	*1.0 to 2.3*
Output inductor	*1 mH*
Output capacitor	*50 µF*
Load	*R,RL and Induction motor*

The prototype converter was analysed for the set modulation index of 0.8. The voltage ratio between the output and input using sinusoidal modulation signal was observed to be unity. Table 3 shows the Effect of Voltage gain variation.

Table 3

Effect of Voltage gain variation

Voltage gain	**Input voltage**	**Output voltage**	**THD%**	**Dutycycle**
0.5	220	110	7.02	0.3
1. 0	220	220	1.28	0.5
1.4	220	330	1.60	0.55

The total harmonic distortion (THD) for sine wave modulation was less than 3% for a resistive load and less than 5% for Non-linear load. Performance of the proposed system with dynamic load change state was studied for different speed variations. Table 4 and 5 shows the speed control logic and the obtained results with FPGA based V/f speed control system.

Table 4

Speed Control logic

Diff between ω_o & ω_{ref}	Relation	State
Positive	$\omega_o > \omega_{ref}$	Reduces the Switching angle state
Zero	$\omega_o = \omega_{ref}$	Preserves the current state
Negative	$\omega_o < \omega_{ref}$	Increases the Switching angle state

Table 5

Performance details

Effect on Percentage load change		With FPGA controller	Change in speed, rpm
For a change in 10 % load (T = 0.25 Nm)	Trailing shoot Time (sec)	0.42	240
	Settling time (sec)	1.4	

For a change in 20 % load (T = 0.45 Nm)	Trailing shoot Time (sec)	0.51	420
	Settling time (sec)	1.8	
For a change in 45 % load (T = 1.0 Nm)	Trailing shoot Time (sec)	0.92	645
	Settling time (sec)	2.08	

Influence of high order harmonics was minimized by natural filtering effect and as the low order harmonics are not easily filtered, a LC filter eliminates the effects of the harmonics at the output.

The experimental tests are performed to validate the simulation results of the single-phase matrix converter operation. The Fig. 4. (a–c) shows the simulation results for the input voltage, output voltage and input current waveform respectively.

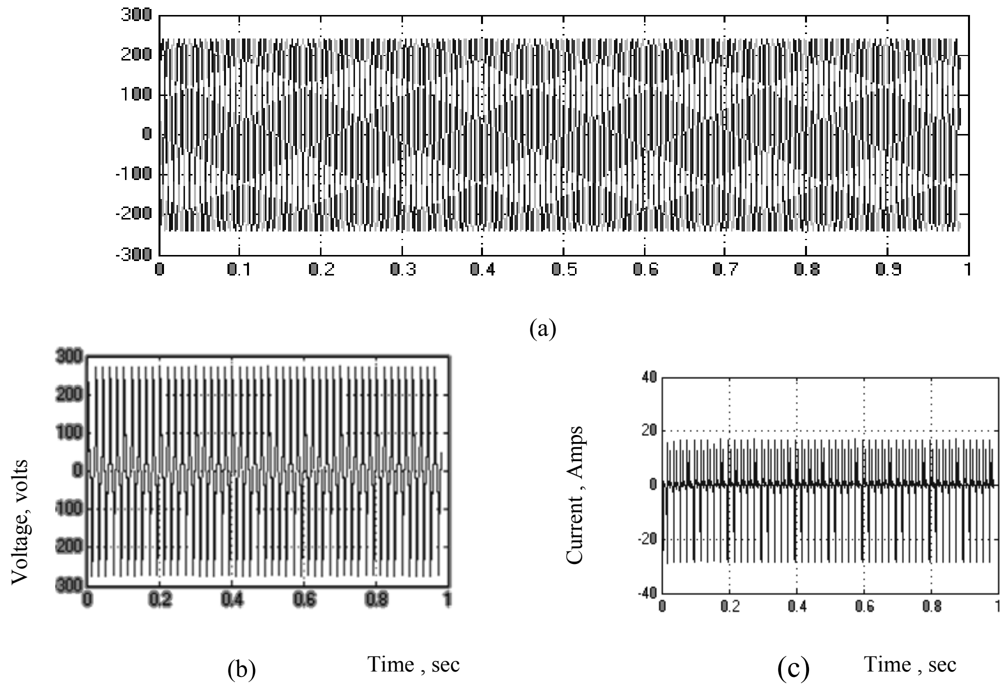


Fig. 4. Three phase to Single phase Matrix Converter (a) Three phase Input Voltage waveform (b) Single phase Output Voltage fed to SPIM (c) Output current fed to SPIM

The output voltage and current waveforms for R load and R-L load are shown in Fig. 5. (a-c).

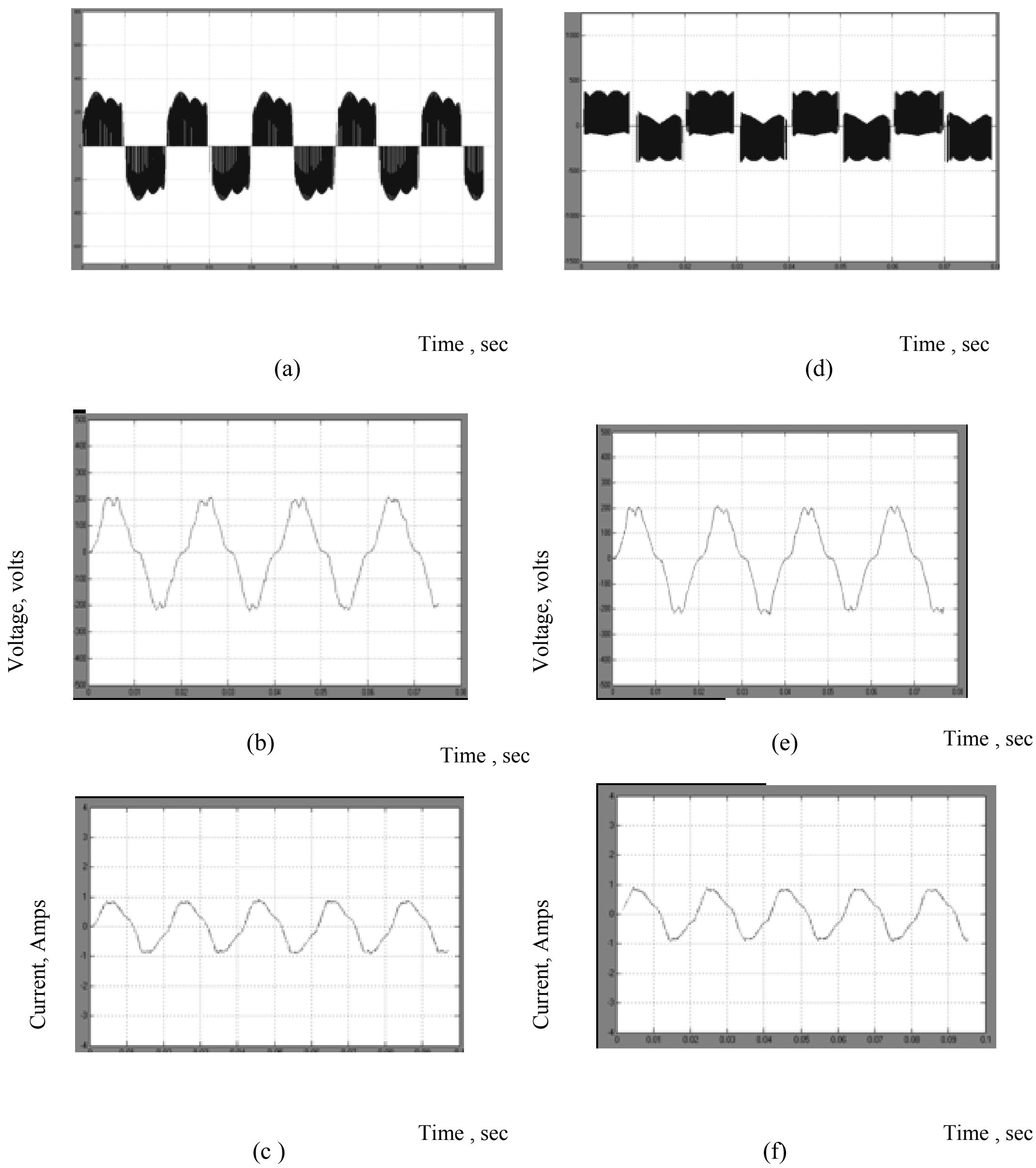
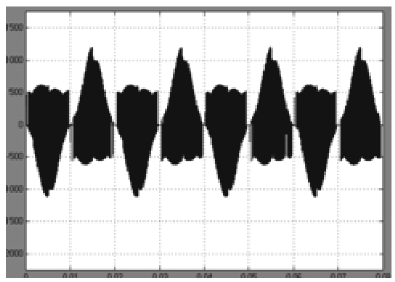
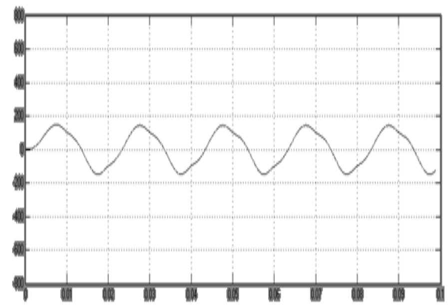


Fig. 5. (a) Output Voltage without filter : R load (b) Output Voltage with filter : R load (c) Output current : R load (d) Output Voltage without filter : R-L load (e) Output Voltage with filter: R-L load (f) Output current : R-L load

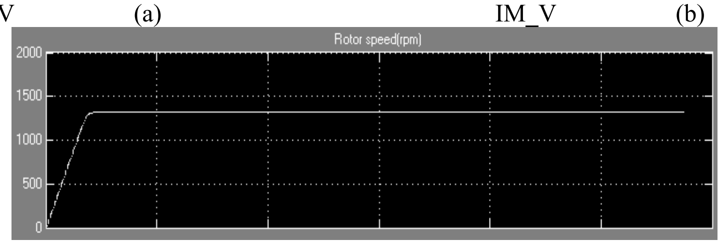
Fig. 6. (a-g) shows the Output voltage, Main winding, Auxiliary winding current, Capacitor Voltage, Rotor speed and Torque waveform of the Single Phase Induction Motor.





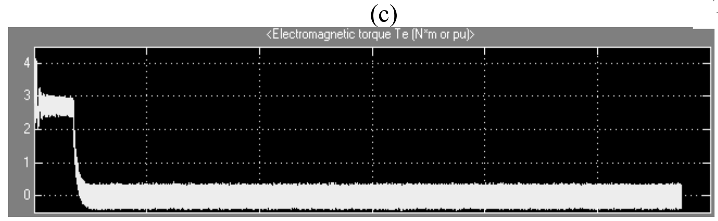
IM_V (a) IM_V (b)

Rotor Speed, rpm



(c) Time , sec

Torque,N-m



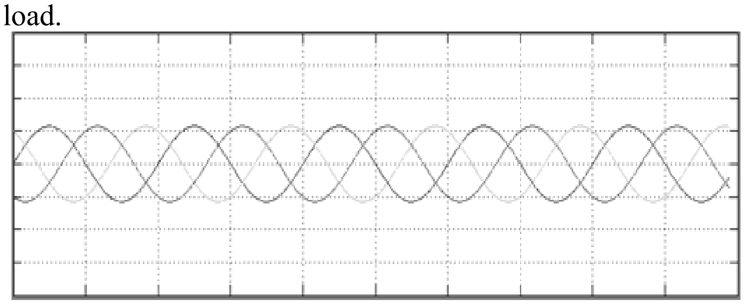
Time , sec

(d)

Fig. 6. Single Phase Induction Motor (a) Output voltage without filter (b) Output voltage with filter (c) Rotor speed waveform (d) Torque waveform.

Fig. 7(a-f) shows the experimental results of a single-phase induction motor fed by the Z source network enabled three phase to single-phase matrix converter with the same operating conditions as that of simulation.

Fig. 8. shows the speed control response of 50% dynamic (increase) change in load.



(a)

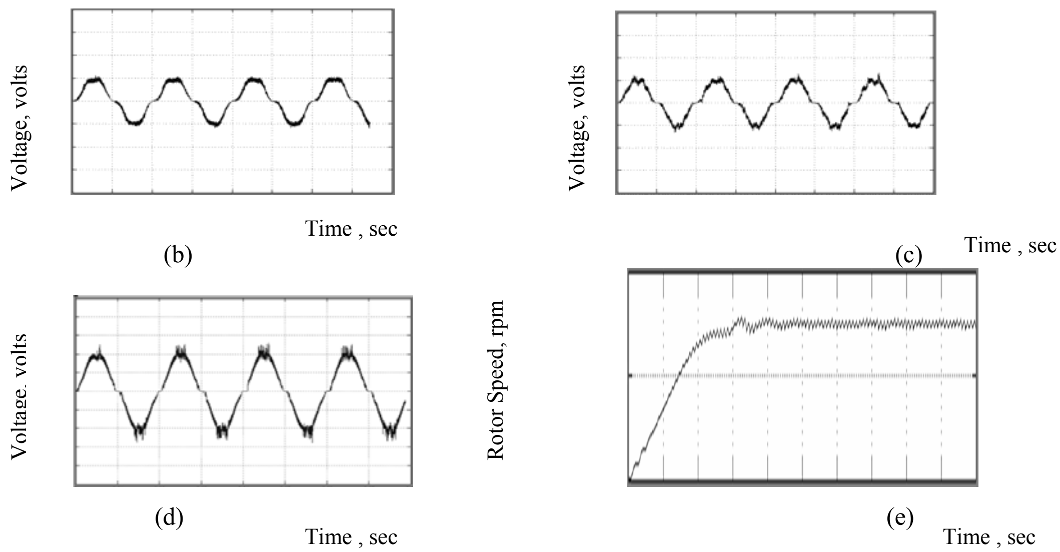


Fig. 7. (a- g): Experimental results of Single Phase Induction Motor (a) Input voltage waveform (b) Output voltage with R Load (c) Output voltage with R-L Load (d) Output voltage with Motor Load (e) Rotor speed waveform.

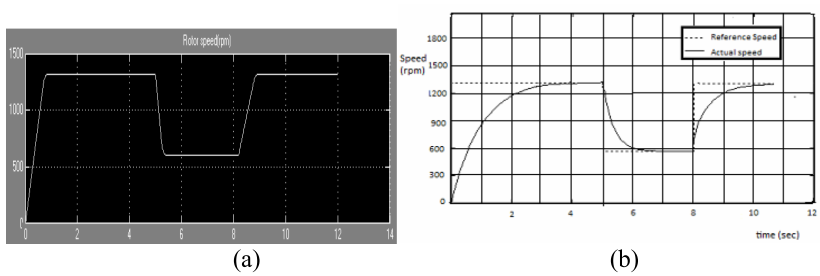


Fig 8. Speed control response of change in torque from 0 to 1 Nm. (a) Simulation results (b) Experimental results

With very few investigations carried on this 3 X 2 phase combinations for maximum voltage transfer ratio , the results obtained were promising. The motor parameters are given in Appendix.

5. Conclusion

A Z source network enabled three phase to single-phase matrix converter feeding an induction motor has been simulated and implemented. From the presented results ,the following conclusions could be drawn.

- A configurable Field Programmable Gate Array (FPGA) hardware controller implemention has significantly improved the performance of the induction motor with utilization of maximum input voltage.

- The voltage ratio is proved as 100 % using the Z-source matrix converter compared to the conventional matrix converter limited to 86.6%.
- Simulation and experimental results validates the performance of the three phase to single-phase matrix converter system with better quality output for household and industrial applications.

Appendix

Motor Nameplate Data: 0.25kW; 220V; 50Hz; ; *R*s*(*main*)* = 2.02_; *R*s*(*aux.*)* = 7.14_; Lm = 0.177; J = 0.0146 kgm^2; Cstart = 255 µF ;Pole pairs =2 ;Turns ratio = 1.18 ; MODEL : PEC6DSMOS MC POWER MODULE

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