Single-Phase Z-source Matrix Converter with High Voltage Gain

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***Abstract*— This paper proposes a new type of converter called Single Phase Z-source Matrix Converter (SPZMC). The SPZMC is an ac-to-ac converter device. Simulated using diode bridge bidirectional switch cell. The simulation is performed in different loads with fixed input and variable output frequency. Pulse Width Modulation (PWM) switching strategy is used to obtain the variable frequency. The Z-source network provided the good voltage regulation with change in load conditions. The proposed converter presented improvements in power factor and achieved low total harmonic distortion (THD) level. And SPZMC also improves the output waveform quality with high voltage gain.. The simulation results are verified with the prototype hardware model. The results are presented to verify the operation.**

Keyword - Single phase matrix converter, Z-source converter, Pulse Width Modulation (PWM), D**iode bridge bidirectional switch cell.**

I. INTRODUCTION

Development of an advanced semiconductor devices in power electronics are increased. Matrix Converter (MC) which used the recent power semiconductor devices. Matrix Converter is a single stage converter. It uses bi-directional fully controlled switches for direct conversion from ac to ac. A matrix converter that can directly convert an ac power supply voltage into an ac voltage of variable amplitude and frequency without a large energy storage element. Earlier Z-source converter have a number of merits, such as providing a larger range of output voltages with the buck–boost mode, reducing inrush, and harmonic current. However, no one has designed a converter based on a Z-source structure and a matrix converter topology that can provide ac-ac power conversion with both a variable output voltage and a step-changed frequency [1]. Recently the Z-source converter topologies and their different structures are studied for further application to the ac-ac network.[2]. The matrix converter is subjected to operating various passive loads , also with dc motor load the behaviour and operation of MC studied [3]. In the conventional single-phase matrix converter topology, the ac output voltage cannot exceed the ac input voltage [4]. The impedance-source power converter employs a unique impedance network to couple the converter main circuit to the power source. Z-source concept can apply to all dc-to-dc, ac-to-dc, dc-to-ac and ac-to-ac power conversion [5]. Z-source converter solved the problem of commutation in ac-ac converters [6]. Input voltage disturbed due to the load drives [7]. Single phase switched inductor Z-source matrix converters with passive load conditions was presented with variable frequency and voltage operation [8].

In applications where only voltage regulation is needed, the family of single-phase Z-source ac-ac converters proposed [9],[10]. An ac-ac converter topologies applied to industrial electronics-voltage regulators, induction motor drives, wind power systems and other [11],[12]. Pulse width modulation (PWM) control can significantly improves the performance of ac-ac converters [13]. Analysis and simulation of matrix converter using different software such as PSIM, PSPICE and MATLAB presented [14], Simulation study of the field oriented matrix converter-fed induction motor drive discussed in[15]. The simulation of power electronic circuits using Pspice, analysis are given in [16].

The proposed Z- source used to store and transfer the energy from the capacitors to the main circuit under switching action of main circuit. In SPZMC bidirectional switches of any phase leg can never be turned on at the same time, other wise current spikes generated this way will destroy switches. These limitations can be overcome by using z-source converter. The inductors and capacitors are small and used to filter switching noise. Matrix converter removes the need for the large reactive energy storage components used in conventional inverter based converters. Due to limitation of voltage transfer ratio the maximum output can be improved to 87% for any type of modulation. When compared to indirect dc-link converters, with matrix converters full power utilization from the grid network cannot be achieved. Practical applications of the matrix converter limited due to intrinsic limitation of the output –input voltage ratio.

II. MATRIX CONVERTER TOPOLOGY

Figure 1 shows a block diagram of the proposed topology. The ac voltage input V_{in} and V_{out} is obtained in the output of the single phase matrix converter with step changed variable frequency. The single phase matrix converter modified with reduced the no. of controlled switches as shown in figure 2 single switch with diode bride bidirectional switch cell. The matrix converter requires a bi-directional switch capable of blocking voltage and conducting current in both directions. Unfortunately there are no such devices currently available, so discrete devices need to be used to construct suitable switch cells. Figure 3 shows the proposed Z-source coupled with this matrix converter to improve the limitation of existing MC. Using a sufficiently high pulse frequency, the output voltage and input current both are shaped sinusoidal. It also consists of a LC filter, a Z-source network, bidirectional switches and dynamic load.

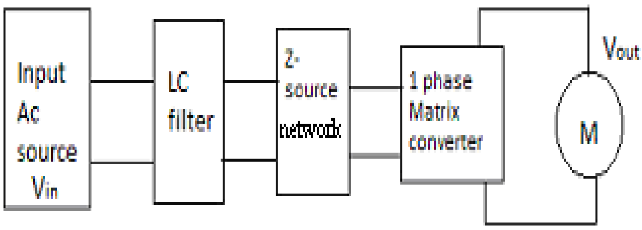

Figure 1. General block diagram of the proposed topology

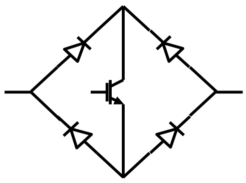

Figure 2. Diode bridge bidirectional switch cell

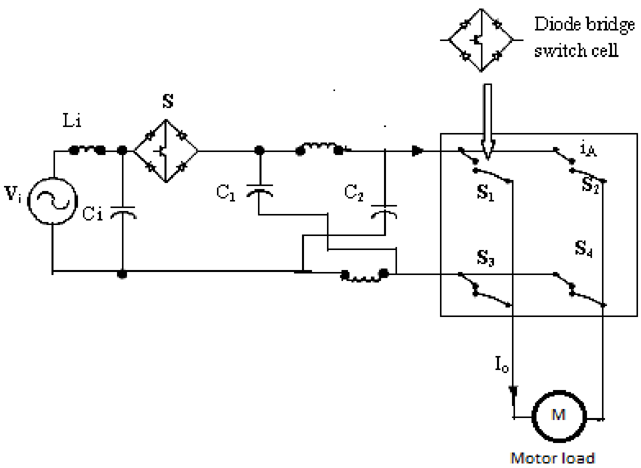

Figure 3 . Proposed single-phase z-source matrix converter

Defining the switching function of matrix converter using a single switch as

$$S_{ab} = \begin{cases} 1, switch\_S_{ab} = clased \\ 0, switch\_S_{ab} = open \end{cases}$$

$$a = \{1, 2\}$$
$$b = \{x, y\}$$

$$S_{1x} + S_{2y} = 1$$

The load and source voltage are referenced to the supply neutral, '0' in the Fig.3, and can be expressed as vectors defined by

$$V_o = \begin{bmatrix} v_{a(t)} \\ 0 \end{bmatrix}; V_i = \begin{bmatrix} V_{A(t)} \\ 0 \end{bmatrix}$$

The relationship between load and input voltages can be expressed as

$$\begin{bmatrix} va\,(t) \\ 0 \end{bmatrix} = \begin{bmatrix} S_{1x} & S_{1y} \\ S_{2x} & S_{2y} \end{bmatrix} \times \begin{bmatrix} V_i \\ 0 \end{bmatrix}$$

$$V_{a(t)} = S_{1x} V_{i(t)} + S_{1y}(0)$$

Now V_o can be derived by the following equations;

The input and output voltage of the matrix converter which presented in Figure 3 is given by

$$V_{i(t)} = \sqrt{2} V_i \sin \omega_{(t)}$$

$$V_{o(t)} = \sqrt{2} V_o \sin \omega_{(t)}$$

Where V_i = input voltage.

V_o = output voltage

ω = the angular frequency of the fundamental

L_1, L_2, L_3 and L_4 = Inductors

$C_1 \& C_2$ =Capacitors

$$V_{o(t)} = R i_{o(t)} + L \frac{di_{o(t)}}{dt}$$

$$V_{l1} = V_{l2} = \sin(\omega t + \theta_L)$$

$$V_{C1} = V_{C2} = \sin(\omega t + \theta_C)$$

$$V_{out} = \sin(\omega t + \theta_o)$$

θ_L = phase angle of Z-source inductor voltage

θ_C = phase angle of Z-source capacitor voltage

θ_0 = phase angle of Z-source output voltage

The LC filter and the Z-source network employing active power filter function and inject the compensation current to the system. The Z-source network improve the supply current waveform to a form that is continuous, sinusoidal and in phase with the supply voltage to become a unity power factor correction.

The connected nonlinear load current can be written as

$$I_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\,\omega_t + \theta_n)$$

Where, I_n = Amplitude of the nth order harmonic of the load current.

θ_n = Phase of the n^{th} order harmonic of the load current

For the performance of the active power filter, the current supplied from the mains is expected as;

$$I_s(t) = I_1 \cos \theta_1 \sin(\omega_t)$$

Where, $I_s(t)$ = Compensated supply current

In the proposed method; during the positive cycle of current flows through the appropriate pair of switches S1 and S4 [Figure.3]. During this time the inductor stores enough energy in such a way that the value of supply current Energy is subsequently discharged to the load using the appropriate pair of diode bridge switches. During the negative cycle operation, the switches S2 and S3 is used to charge the inductor and diode cell switches for discharging operation.

The fundamental power factor, also called the displacement factor, is defined as $\cos\phi_1$, where ϕ_1 (termed the displacement angle) is the phase angle difference between the phase voltage and the fundamental component of the current.

The input power factor (PF) for a matrix converter is defined as $PF = \dfrac{meanpower}{apperentpower}$

The alternating current waveforms with a time period 2π. Denoting this current as i_s and using Fourier analysis, it can be decomposed as

$$i_s = \sum_{n=1}^{\infty} a_n \cos n\omega t + b_n \sin n\omega t$$

Where a_n and bn the n^{th} order Fouier co-efficient respectively.

The T.H.D. indicates the amount of harmonics present in the system expressed as a percentage. The lower value of T.H.D. specifies the lesser harmonics in the output waveform. Also having the advantage of sinusoidal output current and controllable current displacement factor. So the output power factor improved by when Phase angel displacement θ.

$$Displacementfactor\,(DF) = \theta$$

$$Powerfactor = \frac{\theta}{\sqrt{1+(T.H.D)^2}}$$

The inductor current i_l increases when switching ON and decreases when switching OFF.

$$Vo = \frac{1}{1-2D} V_{in} = V_{C1} = V_{C2}$$
$$D = Dutycycle$$

Fixed frequency method used, the fixed T_{on} and T_{off} PWM switching control, hence only the dead time delay

$$V_{out} = V_{in}$$

The capacitor voltage gain

$$K_C = \frac{V_C}{V_i}$$

The output voltage gain

$$K_o = \frac{V_o}{V_i} = \leq 1$$

Where V_i and V_o are, respectively, The rms value of input voltage and output voltage.

III. ANALYSIS OF Z-SOURCE

Let consider the Figure 4 inductors, L_1 and L_2 Two capacitors C_1 & C_2. Depends on the switching strategy the voltage and current stress are varied by connecting inductors series and parallel.

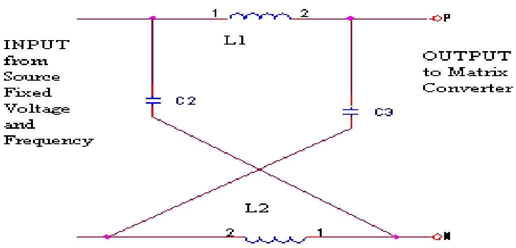

Figure 4 Proposed Z-source diagram

V_{in} is usually fixed.

$$I_L = \frac{(1 - f_{sw}T_{on})V_{in}}{R_L}$$

Inductive impedance

$$Z_L = R_L + X_L$$

Voltage Stress is same as Z-source converter

$$V_{C1} = V_{C2} = V_{C3}$$

Due to the symmetry of the I_{L1} & I_{L2} are same in the existing Z-source. So the response in change current causes the stronger power processing capability. Output current flows the output voltage in quick action reducing the phase angel increasing the power factor and voltage gain $Ko = \frac{Vo}{Vin}$

IV. MODES OF OPERATION

Mode 1 (Positive half cycle) Figure.5 shows the switching strategies for proposed SPMC. Let the frequency of output voltage (f_{out}= 50 Hz) is the input source frequency. T_{on} interval of the converter operating in the active state capacitors, the inductors discharge and transfer energy to the load; S_1 & S_4 turns on. S_2 & S_3 are turned off; Switch S is turned on; the Z-source network discharge, while the inductors charge and store energy; the load current freewheeled through diodes corresponding switch cell.

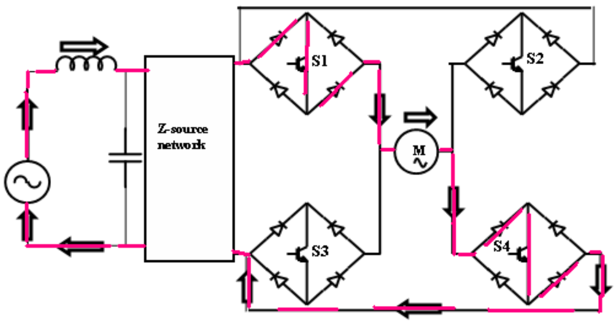

Figure 5. Mode 1(current flow during "+"ve cycle of input source)

Mode 2: (Negative half cycle) In active state, as shown in Figure.6 , the switches S_2 & S_3 turned on; the ac source charges the Z- source network capacitors, while the inductors discharge and transfer energy to the load, the Z-source network discharge, while the inductors charge and store energy; the load current freewheeled through Diodes corresponding switch cell.

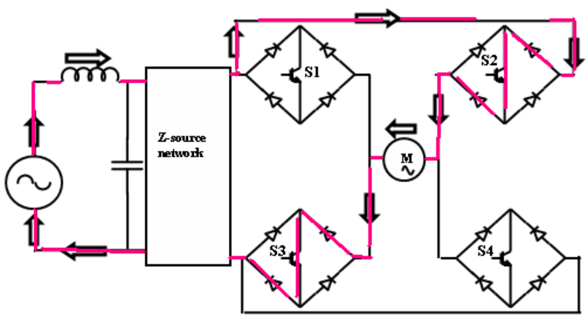

Figure 6. Mode2 (current flow during "-"ve cycle of Input source)

V. SWITCHING STRATERGY AND COMMUTATION

Four bi-directional switches S_1, S_2, S_3, S_4 are able to block voltage and conduct current in both directions. Because the bi-directional switches are not available, they can be implemented by connection of four diodes and single Metal Oxide Field Effect Transistor (MOSFETs) as a bridge form as shown in Figure.2 MOSFETs are used in the simulation because of its high frequency and low current application can be useful to implement in the low current laboratory prototype model. These MOSFETs are drives by using optocoupler drive circuit . Fig. 8

shows the digital stimulus pulse generation for the which is applied to the switches S1,S4 & S2, S3 respectively.

The sequences of switching control at different frequencies either step-up and step -down frequencies also we can get in the output. Here for study purpose only fixed supply frequency used for different load variations in the output. The sequence of switching action for 50 Hz and 100 Hz shown in Table1. Fig. 9 shows the sample triggering pulse pattern for mode 1 and mode 2 operation at 50Hz frequency system. The commutation problem appears when inductive loads are used. A change in current due to PWM switching will result in current and voltage spikes being generated resulting in the occurrence of a dual situation. First current spikes will be generated in the short-circuit and secondly voltage spikes will be induced as a result of change in current direction across the inductance. Both these occurrence may damage switches because of stress. The proposed topology is based on Z-source converter allows reduce the occurring these stress, which cannot destroy the switches. Thus, the commutation problem is only to avoid the voltage spikes when inductive loads are used. Fig.10 shows the Time On and Off of the switch with time delay.

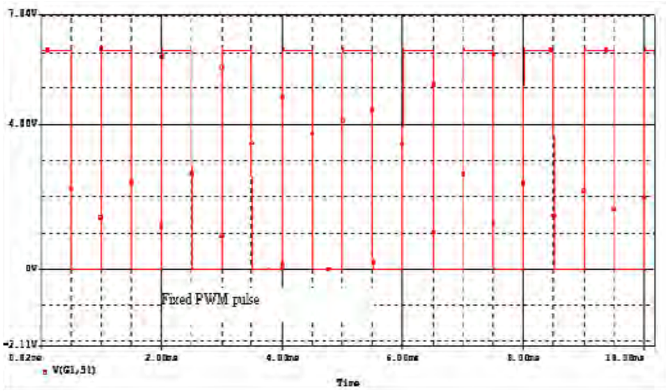

Figure 9. Sample triggering pulse pattern for Mode 1 & Mode 2

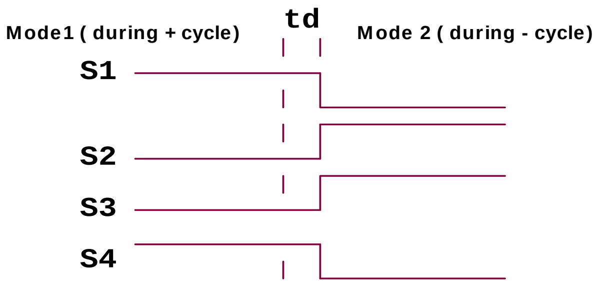

Figure 8 Digital trigger pulses for Switch S1 to S4

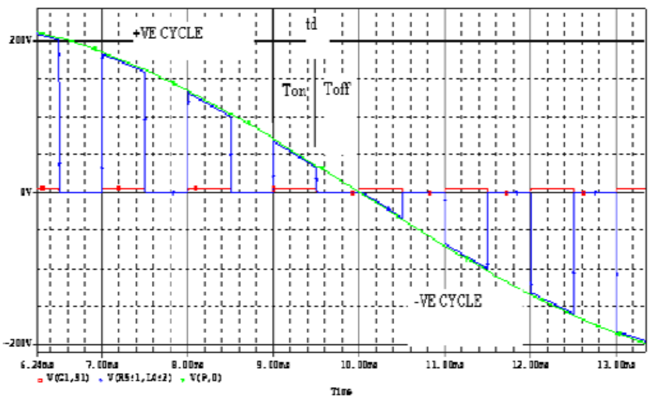

Figure 10. Time ON and OFF of switch

I. HARDWARE EXPERIMENTAL SETUP

The proposed system constructed as a prototype. The Z-source MC hardware model and experimental setup are shown Fig.11 and Fig.12 respectively. The input voltage

Table 1 Sequence of switching control for 50 Hz and 100 Hz step up frequency

Input Freq. f_i	Output Freq. f_o	Mode	Active Switch	Safe Commutation	PWM pulse
50	50	1	S1,S4	S2,S3	1001
		2	S2,S3	S1,S4	0110
	100	1	S1,S3	S2,S4	1010
		2	S2,S3	S4,S1	0110
		3	S4,S1	S4,S1	0011
		4	S4,S1	S3,S2	1001

single phase 230V/50Hz is fed to the single phase transformer 230V/20V, 50Hz. The transformer secondary is the main source input of SPZMC. Hence it is prototype model the experiment carried out with low voltage 20V input.

The control signal obtained from the programmed microcontroller. Depending on the desired output frequency, the controller generates four control signals (four PWM signals to control four switches S_1&S_2 and S_3&S_4 of the single-phase matrix converter, and one PWM signal to bidirectional switch connected series with the Z-source of MC).

T.H.D. measured using Fluke made meter. Different output frequency in different amplitude waveform are observed and measured.

The SPZMC also simulated using Pspice. The dynamic load designed by equation given below.Load dynamics equation given by the moments on the rotor shaft, we can write the balance equation

$$J_M \frac{d\omega}{dt} = M_R - M_L - M_F$$

$$\text{Here } M_R = C_1 \varphi I_R$$

$$M_F = C_2 \omega$$

M_R is the rotor driving torque which is a linear function of excitation flux φ and rotor current I_R multiplied by constant C_1. M_L is the given load moment and M_F is the internal friction moment of the motor which is assumed to be a linear function of angular velocity ω multiplied by constant C_2. J_M is the moment of inertia of all rotating masses mechanically connected the rotor.

The Pspice circuit design Figure13 consists of a stator and which produces a constant magnetic flux for excitation. This winding is modeled by inductance L_S and resistance R_S. When voltage V_S is applied to the stator winding, current I_S flows which produces flux φ. In Figure 14 the rotor winding is also modeled by its inductance L_R and resistance R_R. When V_R is the output rotor winding, the rotor current I_R flows.

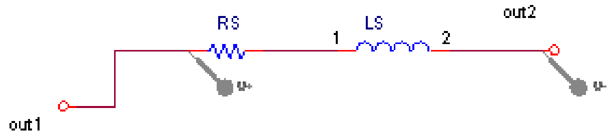

Figure 13 Pspice stator model

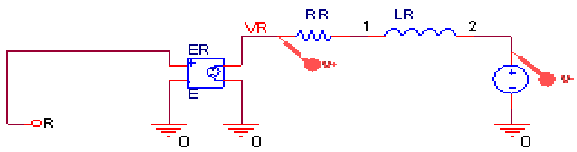

Figure 14 Pspice Rotor model

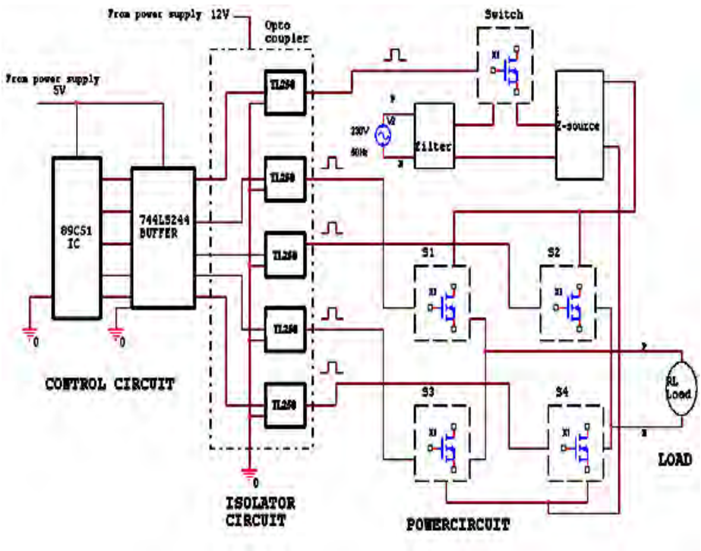

Figure 11. Hardware circuit diagram

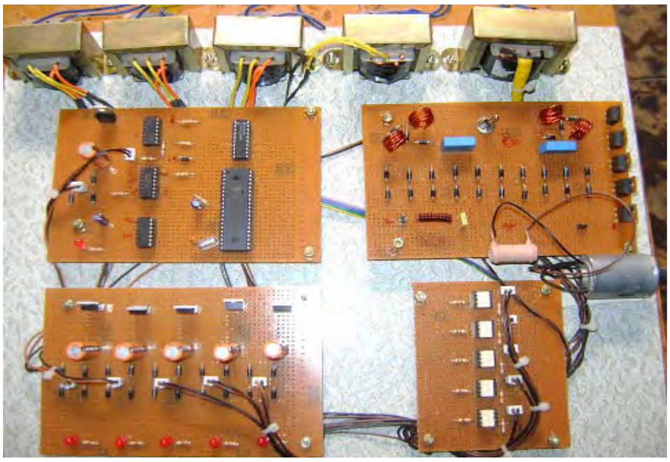

Figure 12 Hardware model

RESULTS

The proposed single phase Z-source matrix converter Experimental results are verified using ORCAD software and MatLab simulink interface tool. The simulation parameters are the LC input filter, Z-source network, and load to be L_i =1mH, C_i =0.01μF, $L_1 = L_2 = 10mH$, $C_1 = C_2 = 10\mu F$, $R = 10k\Omega$ and L_f =3mH. The switching frequency was set to 20 kHz. The input voltage was 230 V_{rms} /50Hz, and the output voltage 229.87 V_{rms} /50 Hz with voltage gain K_o = 0.999 when using the highly inductive load, Table 2 shows the voltage gain K_o, T.H.D and Power factor at the different loads.

Fig 15 shows the stator input voltage frequency and rotor voltage frequency waveforms. Fig.16 & Fig.18 simulation results for the proposed single phase Z-source matrix converter at output frequencies of 50 Hz and 100

Hz. Fig. 17 is the hardware output measured using digital signal oscilloscope at 100Hz output frequency operation.

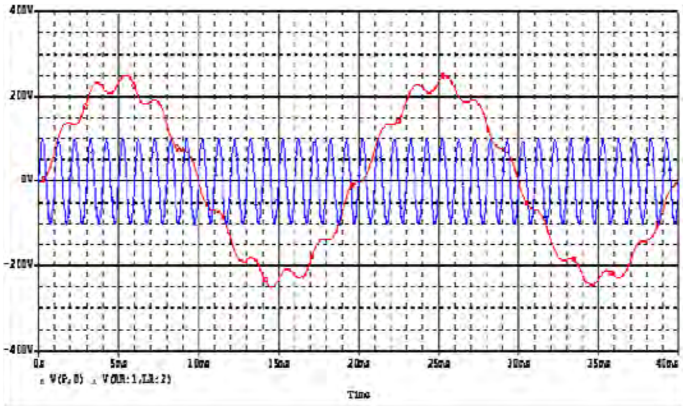

Figure 15 Stator input frequency and rotor frequency

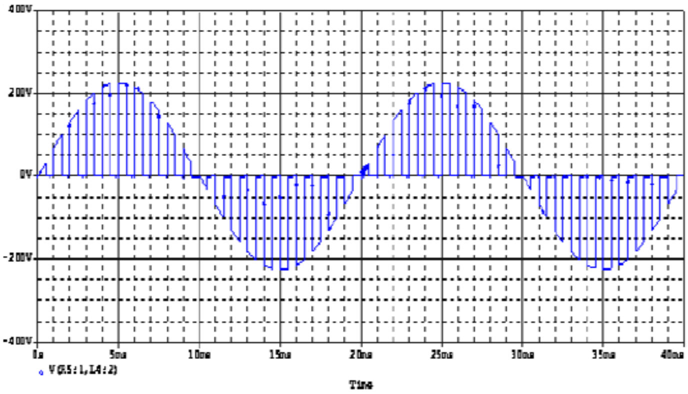

Figure 16 Simulated output frequency 50 Hz

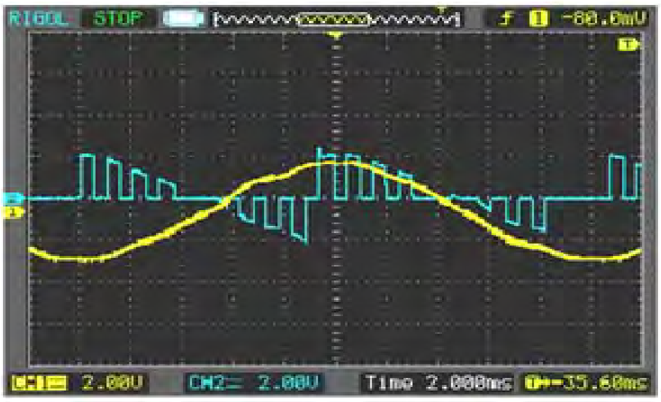

Figure 17 Experimental output frequency at 100Hz

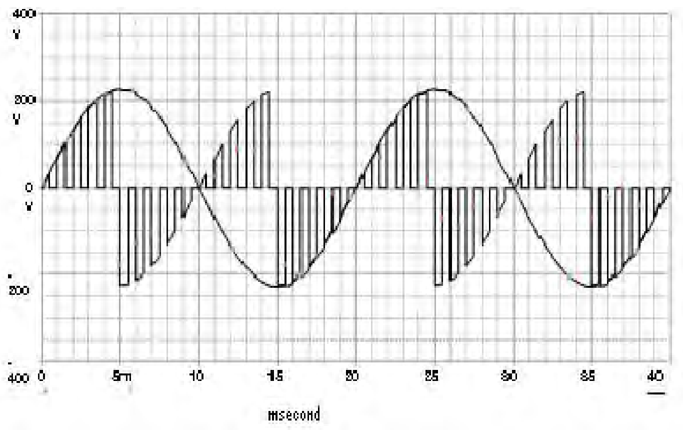

Figure 18 Simulated output frequency 100 Hz

Table 2. shows the various parameters during the load changes. Each load variation the input and output voltages measured and seems to be unit gain value. The values are tabulated. The % THD values maintained the permissible limit. Power factor improves when load increases.

Table 2 Experimental Output at different power loads

Input Freq. (f_i) Hz	Output Load. (P_o) W	Input voltage V_i	Output voltage V_o	Voltage gain K_o	T.H.D %.	P.F.
50	25	230	229.06	0.998	7.630	0.95
	50	230	229.87	0.999	1.50	0.98
	100	230	228.36	0.992	5.45	0.99

II. CONCLUSION

In this paper, a new Z-source single phase matrix converter proposed with dynamic load conditions. The proposed SPZMC can produce the system frequency and also with desired value. The output voltage boosted when change in pulse with of the switching frequency. The experimental results with a passive dynamic load showed that can be produced at three different range of loads 25W , 50 W and 100W. The high voltage gain maintained when the use of Inductive loads. This is due to the application of Z-source. Based on the simulation results the use of safe commutation strategy is a significant improvement on voltage spectra. The simulation results are helpful to implement in hardware for the further purpose of industrial applications. Also these simulation and experimental results are useful to demonstrate the new features of the improvement of this topology.

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