Switched Inductor Z-Source Matrix Converter Operation and Analysis

A. Gopi and R. Saravanakumar

School of Electrical Engineering, VIT University, Vellore, India

Abstract: This paper proposed a new type of converter called Single Phase Switched Inductor Z-source Matrix Converter (SLMC). It is an ac-to-ac converter with diode bridge bidirectional switch cell. The limitations of existing matrix converter like voltage regulation and quality output issues are overcome in the proposed SLMC by adding the switched inductance. The simulation is performed for different frequencies. The simulation results are presented to verify unit gain operation and compared with the existing Z-source matrix converter. A prototype was constructed with a voltage of $20V_{rms}/50Hz$. The performance of the proposed converter verified with this hardware model. The experimental output voltage amplitude can be varied with the variable frequencies. The output voltage and Total Harmonic Distortion (THD) are observed with 100Hz and 25Hz frequencies for step-up operation.

Key words: Matrix Converter · Switched Inductor Z-source · Total Harmonic Distortion (THD) · Bidirectional Switch cell

INTRODUCTION

Matrix Converter (MC) is a single stage converter removing the need for energy storage components used in conventional rectifier-inverter based system. It uses bi-directional fully controlled switches for direct conversion from ac to ac. It can directly convert an ac supply voltage of fixed amplitude and frequency into an ac voltage of variable amplitude and frequency without a large energy storage element. Practical applications of the matrix converter are limited due to intrinsic limitation of output and input voltage ratio. Earlier 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]. In applications where only voltage regulation is needed, the family of single-phase Z-source ac-ac converter is proposed. Recently, the work on Z-source dc-ac inverters has focused developed impedance type that is termed as the Switched Inductor (SL) Z-source inverter. This is an impedance network consists of split inductors and capacitors connected in X-shape. This also provides high voltage conversion

ratios and improving output power quality that needed for low ac voltage applications [2]. In the proposed converter due to voltage transfer ratio the maximum output can be improved to 87% for any type of modulation when compared to indirect dc-link converters.

The first description of a matrix converter was published in 1976 by Gyugyi and Pelly [3]. M.Venturini [17] explained a new PWM technique was published in 1980 [17]. In the conventional single-phase matrix converter topology, the ac output voltage cannot exceed the ac input voltage [4]. So the impedance-source power converter employs a unique impedance network to couple the converter main circuit to the power source to overcome these limitations. This Z-source concept can apply to all dc-to-dc, ac-to-dc, dc-to-ac and ac-to-ac power conversion [5]. The family of single-phase Z-source ac-ac converters is proposed [6-8]. Bidirectional switches of a single phase leg with switching algorithm are implemented in computer simulation models used for ac-ac converters [9-10, 19]. Further sinusoidal pulse width modulation based commutation strategies without intermediate dc link is discussed in [11]. The various switching strategy and the comparison of modulation techniques such as PWM, SVPWM and SVM used in the Matrix Converters (MC) is analyzed [12]. Hidenori Hara explained and reported that the use of safe-commutation

Corresponding Author: A. Gopi, School of Electrical Engineering, VIT University, Vellore, India.
Tel: +919789255727.

switches with pulse width modulation (PWM) control can significantly improve the performance of ac-ac converters [16]. Bidirectional ac-ac converter topologies applied to industrial electronics-voltage regulators, induction motor drives, wind power systems is explained in [13]. Application of matrix converter to variable speed induction motor drive is explained by S. Sinter in [14]. Later Artificial Neural Network is introduced to replace the SVM in Field Oriented Control system for drives in [15]. Recently single phase switched Inductor Z-source matrix converter concept is used for voltage control on the transmission line [18].

The existing Z-source Matrix converters have limitations like voltage spectra, harmonics, power quality, commutation and range operation. These limitations can be overcome by using Proposed Switched Inductor Z-source converter. The Switched inductor Z- source is used to replace the Z-source; it consists of four inductors in two Switched inductor cells. Both of these Switched inductor cells are used to store and transfer the energy from the capacitors to the main circuit under switching action of main circuit. All inductors and capacitors are small which are used to filter switching noise. The waveform quality is tested in terms of Total Harmonic Distortion (THD). THD defined as the closeness in shape of output rms waveform to the fundamental sinusoidal waveform. The proposed output waveform met the IEEE/ANSI Standard 519 criteria for THD magnitudes limitation of 15.0% maximum.

Matrix Converter Modification: The single phase matrix converter modified with reduced the no. of controlled switches is shown in fig. 1. This proposed matrix converter is used to improve the limitation of existing matrix converter. The output voltage and input currents are shaped sinusoidal using a high pulse frequency. Along with a small input filter, the Switched inductor cell is also used as a filter to circulate the high–frequency switching harmonics.

The Diode Bridge Bidirectional Switch: The matrix converter requires a bi-directional switch which is capable of blocking voltage and conducting current in both directions. Unfortunately no such devices are currently available, so discrete devices needed to be used to construct suitable switch cells. These bi-directional switch arrangements consist of an IGBT or MOSFET at the center of a single-phase diode bridge arrangement as shown in Fig 2. The main advantage is that both current directions are carried by the same switch device therefore only one gate driver is required per commutation cell. The ac voltage across the single phase matrix convert V_a is maintained with unit gain by ac to ac switched inductor Z-source converter. Then the single–phase matrix converter modulates the frequency of V_a. Fig.2 shows the proposed single-phase Switched Inductance (SL) Z-source matrix converter. It consists of an LC filter, a SL Z-source network, bidirectional switches and RL load.
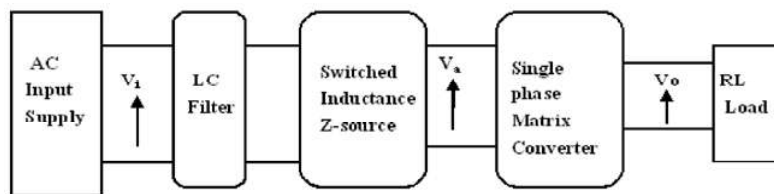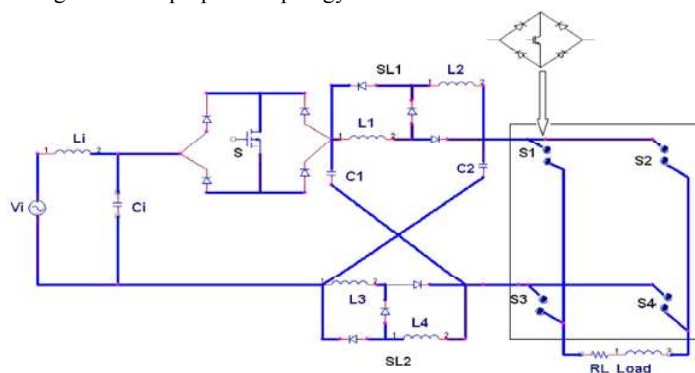

Fig. 1: General block diagram of the proposed topology

Fig. 2: Proposed single-phase switched inductance matrix converter

Circuit Equations

Analysis of Proposed Converter: The proposed SIMC analysis begins with the following assumptions:

All capacitors and switches are ideal, lossless, parasitic resistance of L_1 & L_2 is the same and equal. The parasitic resistance 'r' much smaller than the load impedance, hence it is neglected in this analysis. The converter is operating in the continuous conduction mode; and switching frequency is more than the cutoff frequency of the output filter and the frequency of the input and output voltages.

The Matrix Converter of 2×2 switches, shown in above Fig.2 it connects a single phase voltage source with a inductive load. So that the input terminals should not be short-circuited and an output phase must never be opened. The four power switching devices are switched at high frequency

$$fs \gg fi \,\& \, fo \quad (fi = \frac{\omega i}{2\pi} \,\& \, fo = \frac{\omega o}{2\pi})$$

Defining the switching function of a single switch as

$$Sab = \begin{cases} 1, switch\_Sab = clased \\ 0, switch\_Sab = open \end{cases}$$

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

The constraints discussed above can be expressed by

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

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

$$Vo = \begin{bmatrix} va(t) \\ 0 \end{bmatrix}; Vi = \begin{bmatrix} VA(t) \\ 0 \end{bmatrix}$$

The relationship between load and input voltages can be expressed as

$$\begin{bmatrix} va(t) \\ 0 \end{bmatrix} = \begin{bmatrix} S_{1x} & S_{1y} \\ S_{2x} & S_{2y} \end{bmatrix} \times \begin{bmatrix} Vi \\ 0 \end{bmatrix}$$
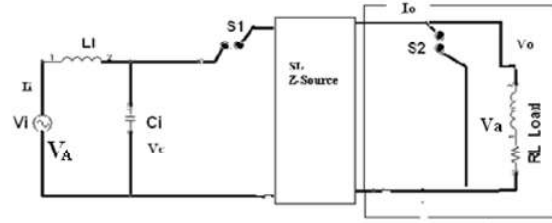
$$Va(t) = S1xVi(t) + S1y(0)$$

Fig. 3: Single phase switched inductor Topology

Now Vo can be derived by the following equations;

$$Vi(t) = \sqrt{2}Vi \sin \omega i(t) \tag{1}$$

$$\begin{cases} Vo(t) = Rio(t) + L\frac{dio(t)}{dt} \\ VSL1 = LL1 + LL2, VSL2 = VL3 + VL4 \\ VSL1 = VSL2 = \sin(\omega t + \theta L) \\ VC1 = VC2 = \sin(\omega t + \theta C) \\ Vout = \sin(\omega t + \theta o) \end{cases} \tag{2}$$

θ_L, θ_c, θ_0 are phase angles of Z-source inductor voltage and capacitor voltage and output voltage.

State 1: In tis mode, S_1 is turned ON and S_2 is turned OFF as shown in Fig. 3. In Active state (T_{on}), the time interval in this state (1-D)*T. Where 'D' is the duty ratio and 'T' is the switching period.

The equations during this state,
$$\begin{cases} (SL1)\frac{d}{dt}ii = Vi - Vc1 - rii \\ (SL2)\frac{d}{dt}isL2 = -Vc2 - risL2 \\ Li\frac{dii}{dt} = -Vi + Vc1 + Vc2 \\ C1\frac{dvc1}{dt} = -i_{Li} + ii \\ C2\frac{dvc2}{dt} = -i_{Li} + ii \\ Ci\frac{dvi_i}{dt} = -ii - \frac{V0}{R} \end{cases} \tag{3}$$

Here the $SL_1 = L_1 + L_2$ and $SL_2 = L_3 + L_4$

State 2: In this mode, S_1 is turned OFF and S_2 is turned ON as shown in Fig. 3. In Active state (T_{on}), At time interval in this state D*T. Then the equations becomes,

$$\begin{cases} (SL1)\dfrac{d}{dt}i_i = V_i + V_{c2} - ri_i \\[2mm] (SL2)\dfrac{d}{dt}i_{sL2} = -V_{c1} - ri_{sL2} \\[2mm] L_i\dfrac{di_i}{dt} = -V_i \\[2mm] C1\dfrac{dv_{c1}}{dt} = -i_{sL2} \\[2mm] C2\dfrac{dv_{c2}}{dt} = -i_{SL1} \\[2mm] C_i\dfrac{dv_{i_i}}{dt} = -i_i - \dfrac{V_0}{R} \end{cases} \qquad (4)$$

From state 1 and state 2 equations, we get the averaged equations

$$\begin{cases} (SL1)\dfrac{d}{dt}i_i = (1-D)(V_i - V_{c1} - ri_i) + D(V_i + V_{c2} - ri_i) \\[2mm] (SL2)\dfrac{d}{dt}i_{sL2} = (1-D)(-V_{c2} - ri_{sL2}) + D(V_{c1} - ri_{sL2}) \\[2mm] L_i\dfrac{di_i}{dt} = (1-D)(-V_i + V_{c1} + V_{c2}) + D(-V_i) \\[2mm] C1\dfrac{dv_{c1}}{dt} = (1-D)(-i_{Li} + i_i) + D(-i_{sL2}) \\[2mm] C2\dfrac{dv_{c2}}{dt} = (1-D)(-i_{Li} + i_i) + D(-i_{SL1}) \\[2mm] C_i\dfrac{dv_{i_i}}{dt} = (1-D)(-i_i - \dfrac{V_0}{R}) + D(i_i - \dfrac{V_0}{R}) \end{cases} \qquad (5)$$

In ideal cases when r = 0 Ω, From the averaged equation (6), the equations for capacitor voltages, output voltages and input currents and inductor currents are as follows,

$$\begin{cases} V_{C1} = \dfrac{1-D}{1-2D}V_i \quad V_o = V_a = \dfrac{1-D}{1-2D}V_i \\[4mm] i_i = \dfrac{1-D}{1-2D}\cdot\dfrac{V_i}{R} \qquad V_{C2} = \dfrac{1-D}{1-2D}V_i \end{cases} \qquad (6)$$

Analysis of SL Z-Source: The circuit diagram shown in Fig. 4. Consists of consists of inductors L1, L_2, L_3 & L_4 and capacitors C_1 & C_2 and six diodes. The combination of L_1-L_3-D_1-D_3-D_5, & L_2-L_4-D_2-D_4-D_6, perform the switched inductor cell in the top and the bottom respectively. Depends on the switching strategy the voltage and current stress are varied by connecting inductors series and parallel. Boost ability of SL Z-source described below.
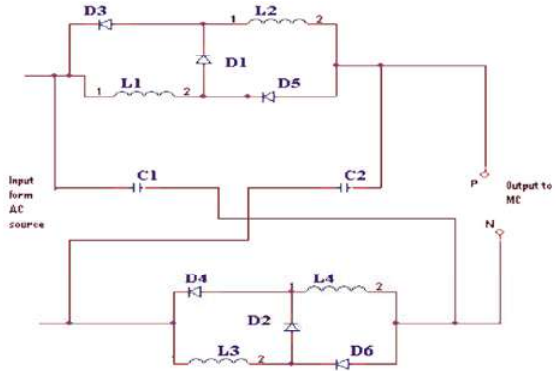

Fig. 4: Proposed SL Z-source diagram

$$\begin{cases} V_{SL1} = V(L1 + L2) \\ V_{SL2} = V(L3 + L4) \end{cases} \qquad (7)$$

At T_{on} state L_1, L_2, L_3 & L_4 are connected in series, net output voltage becomes,

$$V_{c1}(t) = V_{c2}(t) = V_o(t)$$
$$V_{ci}(t) = V_i(t)$$

The inductor current I_{SL1} is increases during switching ON and decreases during switching OFF. During switching ON, the corresponding voltage across V_{SL1}, $V_{SL1\text{-}ON}$ is equal to V_{C2} which is expressed by ,

$$V_{SL1-ON} = \frac{1-D}{(1-2D)}T(V_c) = V_{SL2-OFF} \qquad (8)$$

The inductor current i_{L2} is increases during switching ON and decreases during switching OFF. The corresponding voltage across V_{SL2} are equal to V_{C1} and $-(V_{C2}-V_{in}+V_{SL1\text{-}OFF})$

$$DTV_{C1} = (1-2D)T(V_{C2} - V_i - \frac{1-D}{1-2D}V_C) \qquad (9)$$

$$DTV_i = (1-2D)T(V_C - V_i - \frac{1-D}{1-2D}V_C) \qquad (10)$$

$$V_{C1} = V_{C2} = V_C$$

$$V_o = \frac{D}{(1-D)}V_{in} \qquad (11)$$

From the above input-output relationship, it can be observed that when D = > 0.5, V_o is more than the input voltage V_i. Hence this topology gives step-up or high gains.

The capacitor voltage gain

$$KC = \frac{VC}{Vi} \tag{12}$$

The output voltage gain

$$Ko = \frac{Vo}{Vi} = \frac{D}{1-D} \tag{13}$$

where V_i and V_o are the RMS value of input voltage and output voltages respectively.

RESULTS

Simulation Results: The proposed single phase Switched inductor Z-source matrix converter is simulated using ORCAD software and properties are described before implementing in to the hardware. The values for the LC input filter, switched inductor Z-source network, load is considered is as given below,

L_i= 0.1μH, C_i=0. μH,
$L_1 = L_2 = L_3 = L_4$ mH,
$C_1 = C_2 = 10$ μH,
$R = 10$ $k\Omega$ and L_f=3mH

The values for the switching frequency , input voltage and the output voltage 20kHz , 230V$_{rms}$/50Hz and 226.87V$_{rms}$/25Hz respectively is used for simulation. Table 1 shows the voltage gain K_o, T.H.D and Power factor for unit gain operation. Fig.5 & Fig.6 shows the simulation results for the proposed single–phase SL Z-source matrix converter at output frequencies of 100 Hz and 25Hz respectively. Table 2 shows the performance comparison of proposed Switched inductor Z-source with existing Z-source at different output simulated frequencies. The proposed Z-source circuit decreases the T.H.D. values from 26.30% to 23.18% and improves the power factor values from 0.69 to 0.82 when compare with the existing Z-source at output frequency 100Hz.

Fig. 7: Shows the simulated output voltage waveform at unity gain.

Experimental Setup: The proposed Switched inductor Z-source Matrix converter is constructed as a prototype which is shown in shown in Fig.8 and Fig.9.

Table 1: Simulation waveform for different output frequency

Input Freq. (f_i) Hz	Output Freq. (f_o) Hz	Input voltage (V_i)	Output voltage (V_o)	Voltage gain (K_o)	T.H.D.	P.F.
50	100	230	224.06	0.974	23.18%	0.82
	25	230	226.87	0.986	16.57%	0.88

Table 2: Performance Comparison of Proposed SL Z-Source with existing Z-Source

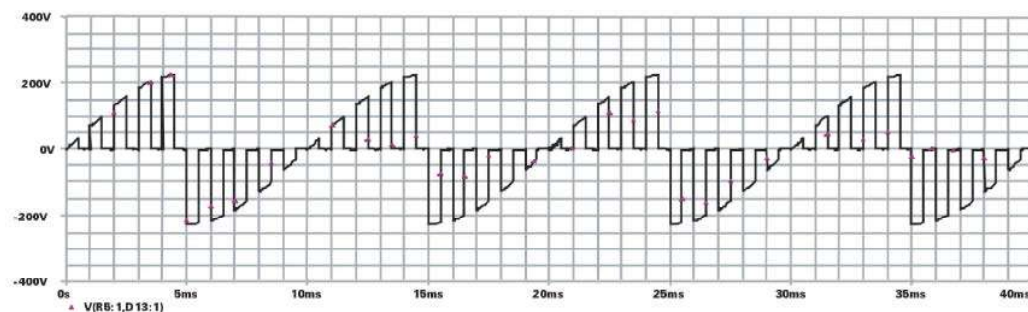| (f_i) Hz	(f_o) Hz	Z-source	SL	Z-source
50	T.H.D	100	26.30%	23.18%
	P.F.		0.69	0.82
50	T.H.D	25	18.73%	16.57%
	P.F.		0.78	0.88

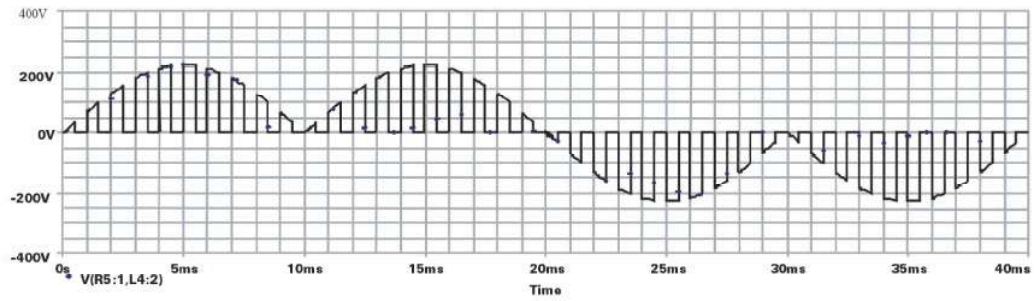Fig. 5: Simulated waveform for output frequency of 100 Hz

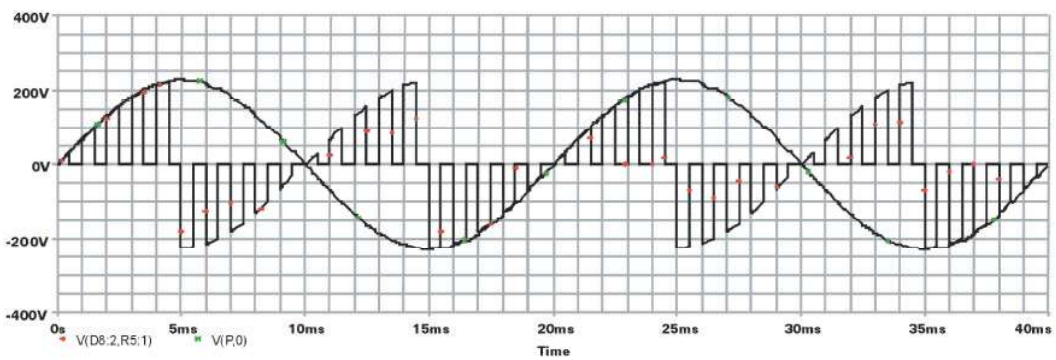Fig. 6: Simulated waveform for output frequency of 25 Hz

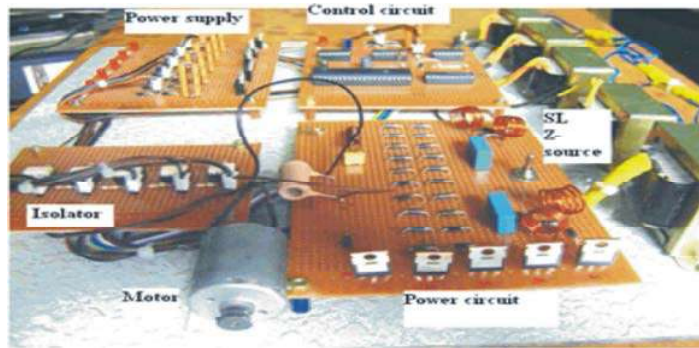Fig. 7: Unity gain simulated output Voltage waveform

Fig. 8: SL Z-source SPMC Hardware model Side View Photograph

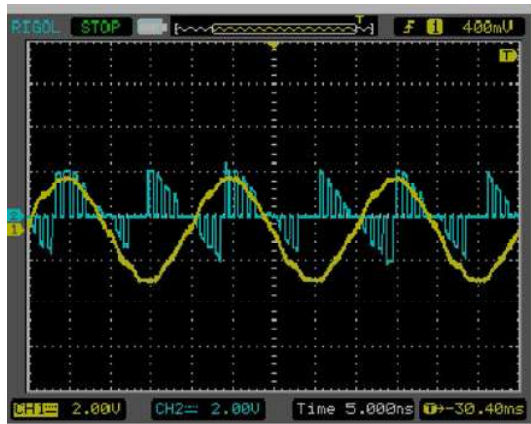

Fig. 9: Hardware experimental setup

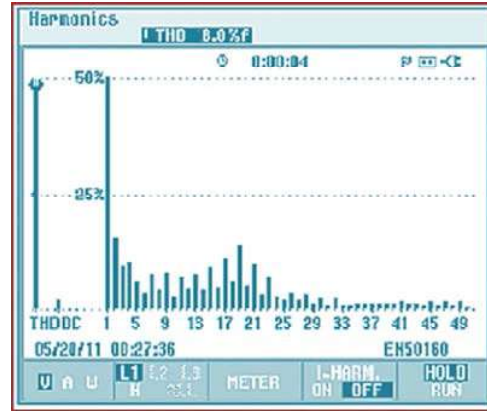Fig. 10: Experimental results 100 Hz Output frequency

Fig. 12: THD measurement for 100 Hz

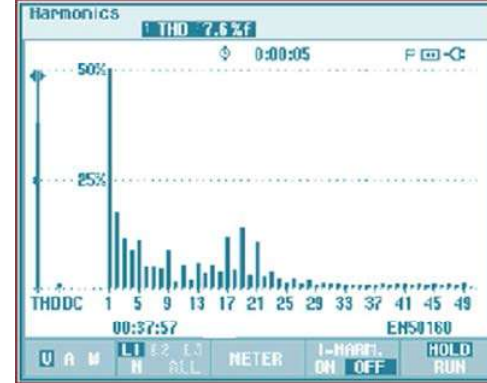Fig. 11: Experimental results 25 Hz Output frequency

Fig. 13: THD measurement for 25 Hz

Table 3: Experimental Results

Input			Output		T.H.D.	
Volt (V_i)	Freq. (*Hz*)	Freq. (*Hz*)	Unit gain	Volt Boost	Unit gain%	Boost Mode %
20	50	100	20.0	26	6.6	8.0
20	50	25	19.6	25.6	5.2	7.6

Table 4: Duty Cycle and output voltage for different frequencies

	100 *Hz*	25 *Hz*
Boost D = 0.56	26.0	25.6
Unit gain D = 0.5	20.0	19.6

The input to the prototype model is given through 230V/20V ratio, 50Hz single phase transformer. The transformer secondary is the main source input of SPSIMC. Hence the input to the prototype model is 20V, 50Hz. All bidirectional switches used for the prototype model is constructed with four diode and one MOSFET. MOSFET is used because prototype model is constructed for low power.

The control signal is generated form 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 SL Z-source of MC).

T.H.D. is measured using Fluke made Power Quality analyzer which shows as in Fig. 9. Different output frequency in different amplitude waveform are observed and measured.

Experimental Results: The use of the safe-commutation strategy provides an improvement in the waveform quality measured in the form of Total Harmonic Distortion (THD). The output waveform is observed by using Digital Signal Oscilloscope and THD is measured by using the Fluke made power quality analyzer. The output results obtained from the prototype for the 100 Hz & 25 Hz frequencies is in the Fig. 10. & Fig. 11 respectively. T.H.D output for 100 Hz and 25Hz frequency is shown in Fig. 12. and Fig. 13 respectively at D=0.56. The output voltage lifted up to 26V & 25.6V for the 100Hz & 25Hz frequencies respectively (Table No.5). Hence it is realized with the theoretical output voltage V_o equation (6). Here the harmonic spectrum shows the odd harmonics up to 21 frequencies are in higher magnitude. So the percentage distortion in the output looks higher the value up to 18% in case of 100Hz output frequency.

The experimental results show that the output voltage can be controlled at variable amplitude. Furthermore, an input frequency of 50Hz can convert an output frequency of 100Hz (step-up frequency); 25Hz (step down frequency). In other words, by changing the switching strategy, we can change output frequency. Thus, the proposed single-phase SL Z-source matrix converter is used to vary the voltage and frequency. The experimental results are tabulated in Table 4 and Table 5.

At unit gain operation T.H.D is reduced to 6.6% in 100Hz output frequency and 5.2% in 25Hz is shown in Table No.4. Hence 100Hz system the sequence of switching operation are more, so the T.H.D. value raised when compare to the lower frequency of 25Hz system. Because of limitations in the power hardware setup, the prototype was intended only to verify the operational concept.

CONCLUSION

In this paper, a new SI Z-source single phase matrix converter was proposed. The proposed SPSLMC can step-up and step-down the frequency with desired value. The simulation results with a passive RL load showed that it can be converted at different frequencies 100Hz and 25Hz. The high voltage gain maintained is in the case of inductive load due to the application of SI Z-source.

The simulated results compared with present Z-source in various frequencies. Based on the simulation results the use of safe commutation strategy is a significant improvement on voltage spectra. The maximum THD obtained from hardware and simulation is 8% which met the IEEE/ANSI standard 519. These simulation and experimental results are useful to demonstrate the new features of the improvement of this topology.

ACKNOWLEDGEMENT

REFERENCES

1. Minh-khai Nguyen, Young-Gook Jung and Young-Cheol Lim, 2010. A single-phase z-source buck–boost matrix converter, IEEE trans. Power electronics., 25(2): 453-462.

2. Miao zhu, Kun Yu and Fang Lin Luo, 2010. Switched inductor z-source inverter,"IEEE trans. Power electronics., 25(8): 2150-2158.

3. Gyugyi, L. and B.R. Pelly, 1976. Static power frequency changers: theory,performance and application. New york: wiley.

4. Zuckerberger D. Weinstock and A. Alexandrovitz, 1997. Single-phase matrix converter, in proc. Inst. Electr. Eng. Electric Power Appl., 144: 235-240.

5. Fang zheng Peng, 2003. Z-source inverter, In IEEE trans. on Industry Appl, 39: 504-510.

6. Ajay kumar Gola and Vineeta Agarwal, 2009. Implementation of an efficient algorithm for a single phase matrix converter, in Journal of Power Electronics, 9(2): 198-205.

7. Siinter, S. and O. Aydogmus, 2008. Implementation of a single-phase matrix converter induction motor drive, Springer Electr. Eng., 90(6): 425-433.

8. Nguyen-quang, N., D.A. Stone, C.M. Bingham and M.P. Foster, 2006. Single phase matrix converter for radio frequency induction heating, in Proc. Speedam pp: S18-28-s18-32.

9. Ljusev, P. and M.A.E. Andersen, 2004. Safe-commutation principle for direct single-phase ac-ac converters for use in audio power ampli?cation, pre-sented at the nordic workshop power and. Electron., Trondheim, Norway, 2004, cd-rom.

10. Youm, J.H. and B.H. Kwon, 1999. Switching technique for current-controlled ac-to-ac converters, IEEE trans. Ind. Electron., 46(2): 309-318.

11. Idris, Z., M.K. Hamzah and M.F. Saidon, 2006. Implementation of single-phase matrix converter as a direct ac-ac converter with commutation strategies, in conf. Rec. IEEE pesc, pp: 2240-2246.

12. Karpagam, J., A. Nirmalkumar and V. Kumar Chinnaiyan, 2010. Comparison of modulation techniques for matrix converter, IACSIT Intl. Journal of Engg. And Tech. 2(2): 189-194.

13. Vasil Mihav and Emil Dinkov, 2007. AC-AC power converters- overview and application, in Conf. Electonics pp: 121-126.

14. Siinter, S. and O. Aydogmus, 2008. Implementation of a single-phase matrix converter induction motor drive, springer electr. Eng., 90(6): 425-433.

15. Venugopal Chitra, K.S. Ravichandran and R. Varadarajan, 2012. Artificial neural network in field oriented control for matrix converter drive, World Applied Sciences Journal, 16(4): 560-567.

16. Hidenori Hara, Eiji yamamoto, Jun-koo kang and Tsuneo Kume, 2009. Improvement of output voltage control performance for low-speed operation of matrix converters, IEEE trans. Power Electron., 20(6): 1372-1378.

17. Venturini, M. and A. Alesina, 1980. A new sine wave in, sine wave out conversion technique eliminates reactive elements, Proceedings of Powercon, pp: 7.

18. Gopi, A., M. Kowsalya and D. Elangovan, 2012. Single Phase Switched Inductor Z-Source Matrix Converter for Voltage Control, EJSR, 75(2): 169-178.

19. Anusuya and R. Saravana Kumar, 2012. Simulation of a Single Phase Matrix Converter with Reduce Switch Count as a Buck/Boost Rectifier with Close Loop Control, International Journal of Computer and Communication Technology (IJCCT), 3: 1.