Single Phase Matrix Converter operate as Rectifier Controlled by Xilinx FPGA

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Abstract - This paper present a single phase matrix converter (SPMC) topology that use to operate as a rectifier (AC-DC). Pulse Width Modulation (PWM) was use as a controlled signal to synthesize output voltage. Insulated Gate Bipolar Transistor (IGBT) was used as the power switch. Computer simulation model was developed by using MATLAB/Simulink (MLS). Experiment Test-Rig was constructed using Xilinx Field Programmable Gate Array (FPGA) as a heart to controlled IGBT. The selected simulation results of MATLAB/Simulink (MLS) and XILINX FPGA were presented to verify the proposed switching strategies.

Keywords : Single Phase Matrix Converter (SPMC), Pulse Width Modulation (PWM), Insulated Gate Bipolar Transistor (IGBT), MATLAB/Simulink (MLS), Field Programmable Gate Array (FPGA).

I. INTRODUCTION

Revolution in the power semiconductor devices has lead the usage of power electronic devices to another step within modern commercial and industrial environment particularly in application for AC-DC conversion. Conventionally, AC-DC converter which is commonly called as rectifier was developed using bridge-diode without giving any control function and unidirectional power flow. Alternative, topology has been introduced such as matric converter (MC) hold future potential in advanced power conversion. The Matrix Converter topology has offer many advantages with unrestricted switch control, possible "all silicon" solution, minimal and removing the need for reactive device in conventional converter system [1]. The topology was first introduced by Gyugyi in 1976 [2]. Matrix Converter is able to operate in four quadrant bidirectional switch which allow operating in high frequency. Previous study was focus on Three Phase Matrix Converter (TPMC) which was first introducing in 1980 by Alesina and Venturini [3]. Their represent the circuit as a matrix of bidirectional power switch which force commutated converter use an array of controlled bidirectional switches as the main power element to create a variable output voltage with unrestricted frequency. Zuckerberger was first introduced [4], the single phase version called Single Phase Matrix Converter (SPMC) using MOSFETs as switching device based on AC-AC conversion [5]. The SPMC topology has offering very wide application but very little attention. Previous studies on SPMC operating as an AC-DC converter includes; controlled rectifier [6], boost rectifier [7], active power filter function [8], regenerative operation [9] and dual converter [10].

This paper discussed the design and development of Pulse Width Modulation (PWM) as controlled signal on controlling rectifier operation by suitable switching scheme for SPMC. It based on the Xilinx chip XC4005XL FPGA with 8 bit modulation index. SPMC four set of bidirectional switch with IGBTs as the power switching devices. Modulation index and the switching frequency can be changed externally based on the proposed design. Pulse Width Modulation (PWM) was used to synthesized the output voltage. The selected simulation results of MATLAB/Simulink (MLS) and XILINX FPGA were presented to verify the proposed switching strategies.

II. CONVENTIONAL RECTIFIER

A rectifier is an electrical device that converts alternating current (AC) to direct current (DC).Rectifiers has many uses including controlling DC motor for household or industry. Single Phase rectifier commonly used bridge-diode as in Figure 1 without giving any control function and unidirectional in nature. Bidirectional operation is also possible with the inclusion of anti-parallel switch in H-bridge topology as in Figure 2 but it's not offer full controllable.

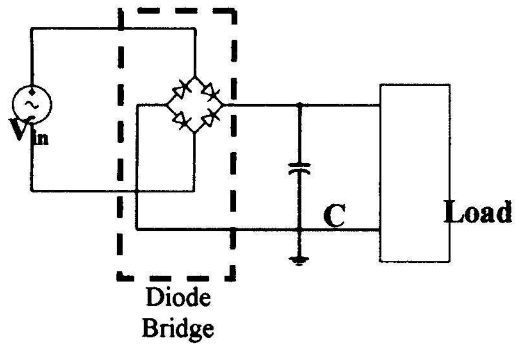


Figure 1: Single phase bridge-diode rectifier with capacitive filter.

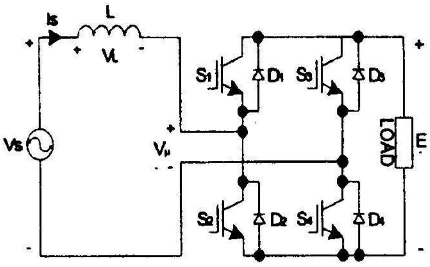


Figure 2: H-Bridge topology

III. SPMC

The SPMC required 4-bidirectional switches as shown in Figure 3; each was capable to conducting current and blocking voltage in both directions. However, no discrete semiconductor devices could fulfill the needs [11], therefore IGBTs was use as the controllable power switching devices and pair diode as in Figure 4 making the system capable to operate in bidirectional.

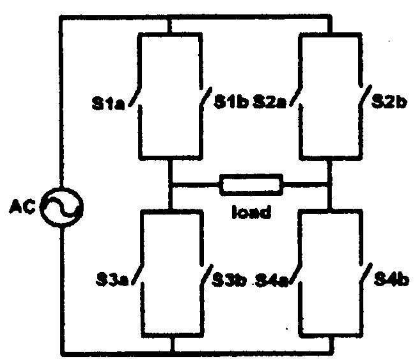


Figure 3: Single Phase Matrix Converter (SPMC) topology

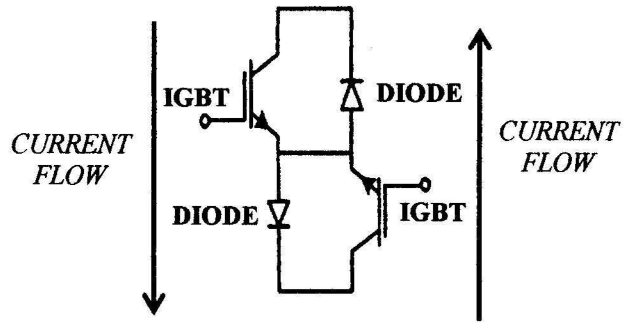


Figure 4: Bidirectional switch

IV. PROPOSED RECTIFIER

The proposed controlled rectifier using SPMC has four switching state is presented in Figure 5 to 8. Resistor and inductor were used as the load at the output. When inductive load were used, commutation occur result with reversal current and voltage spike. Freewheeling diodes were used for this purpose. Therefore switching sequence need to be developed as illustrated in Figure 9 to allow force controlled freewheeling diode. In consequence the switching in SPMC must be theoretically instantaneous and simultaneous but it is impossible for practical practice realization because of the turn-off time within IGBTs characteristic where the tailing-off of the collector current will create a short circuit with the next switch turn-on [12]. This will create a short circuit illustrated in Figure 10 during commutation. A change in current due to PWM switching will effect in current and voltage spikes being generated causing in the occurrence of a dual situation. First current spikes will be generated in the short-circuit path and secondly voltage spikes will be induced as a result of change in current direction across the inductance. Both will destroy the switches in use due to stress [13]. Therefore a systematic switching sequence is required to provide a flow for energy during off time to avoid current spike and at the same time to establish a path for current of the inductive load to avoid voltage spikes.

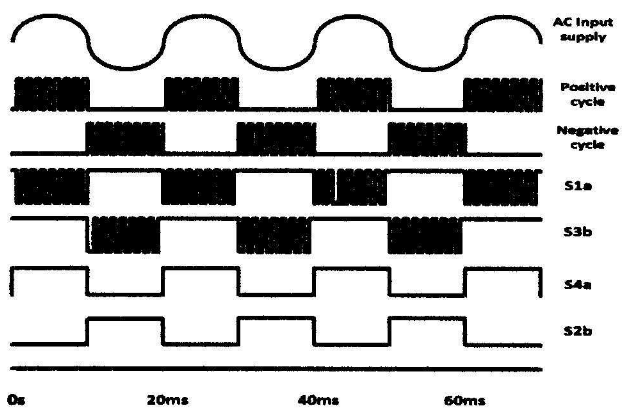


Figure 9: Switching algorithm for commutation strategy

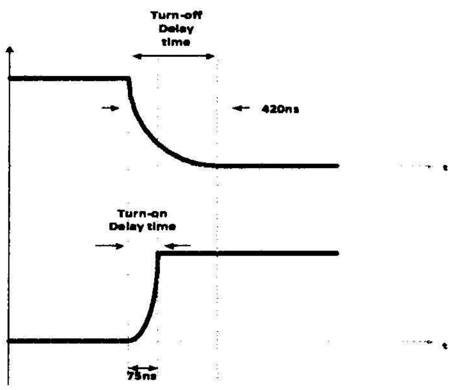


Figure 10: Time on/off proposed switch

V. SWITCHING STRATEGIES

Switching operation in the SPMC has been divided into two modes for each cycle. For positive cycle, in mode 1; a pair of switches S1a and S4a is turn ON whilst in mode 2; a pair of switches S3b and S4a is turn ON as shown in Figure 5 and Figure 6. Similarly for the negative cycle, mode 2 has S2b and S3b turned ON whilst mode 4; a pair of switches S1a and S2b is turn ON as in Figure 7 and Figure 8. This sequence was presented in the Table I and the theoretical waveform as illustrated in Figure 9 which output voltage synthesize using Pulse Width Modulation (PWM) as in Figure 11 and in Figure 6 and Figure 8 PWM was illustrated as a dash line to show on/off switching. Pulse Width Modulation (PWM) was generate by comparing the triangle waveform with reference signal which is straight line and adjustable. The crossover point was used to determine the switching orders.

Table I. Switching mode for rectifier

SWITCH		S1a	S2b	S3b	S4a
POSITIVE CYCLE	MODE 1	ON	OFF	OFF	ON
	MODE 2	OFF	OFF	ON	ON
NEGATIVE CYCLE	MODE 3	OFF	ON	ON	OFF
	MODE 4	ON	ON	OFF	OFF

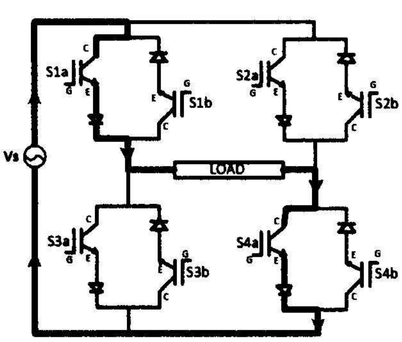


Figure 5: Mode 1 (positive cycle)

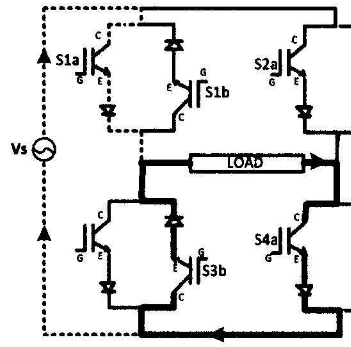


Figure 6: Mode 2 (positive cycle with commutation)

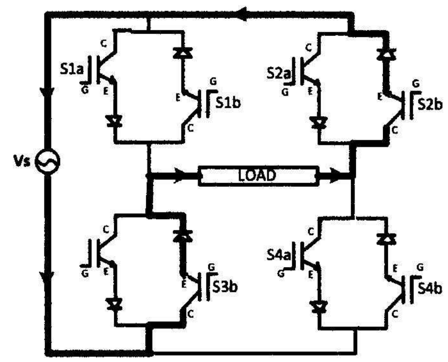


Figure 7: Mode 3 (negative cycle)

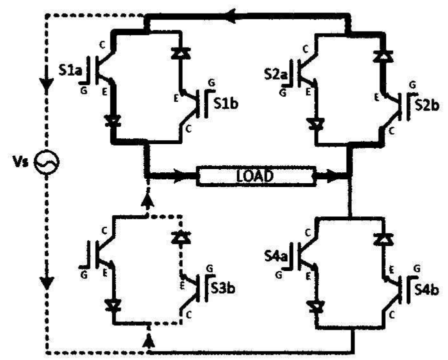


Figure 8: Mode 4 (negative cycle with commutation)

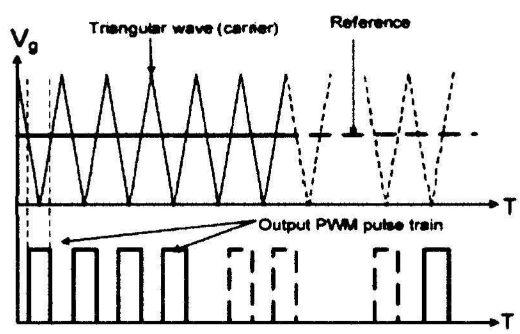


Figure 11: PWM waveform

The positive cycle commutation and negative cycle commutation was representing as a bold line as illustrated in Figure 6 and Figure 8. At this time the energy stored in the inductor is released and free to circulate without a change in direction during switch turn off.

VI. MODELING AND SIMULATION

The proposed control concept is verified through simulation using MATLAB/Simulink (MLS) to study the behavior of rectifier operation. Figure 12 shows the modeling of SPMC and Controller which is to operate as rectifier with switching sequence as shown in Table I. Subsystem is used by breaking up large model into a hierarchical set of smaller models as shown in Figure 13 to Figure 17. SPMC that show in Figure 12 consist of 4 bidirectional switch and each switch have a diode pair and IGBTs as illustrated in Figure 13 and Figure 14.Controller in Figure 12 consists of Pulse Width Modulation (PWM) generator and Phase detector, as illustrated in Figure 15. The subsystem for PWM and Phase detector is shown in Figure 16 and Figure 17. Modulation index that show in Figure 17 is to vary the PWM by comparing reference signal with triangle signal. Triangle signal block in Figure 17 represent the carrier frequency and Phase detector block as illustrated in Figure 16 and Figure 17 used to assign either positive cycle or negative cycle.

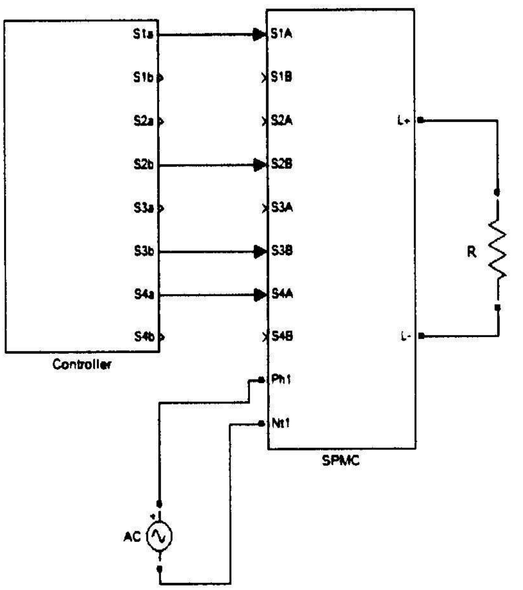


Figure 12: Modeling of Rectifier in MATLAB/Simulink.

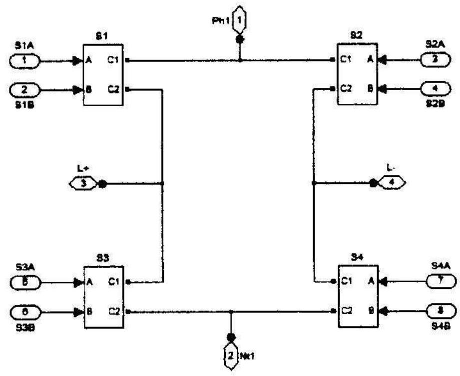


Figure 13: SPMC switch arrangement.

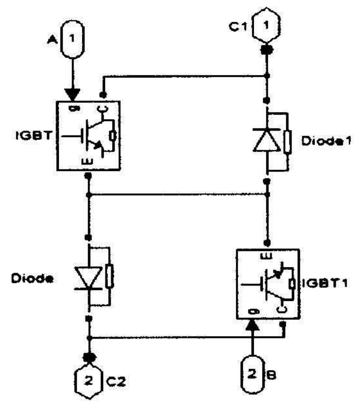


Figure 14: Bidirectional switch with diode pair.

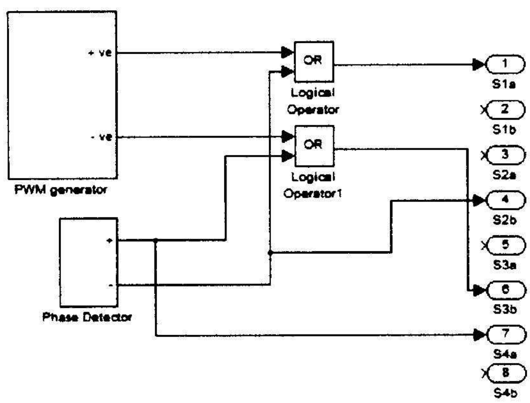


Figure 15: Controller unit for rectifier.

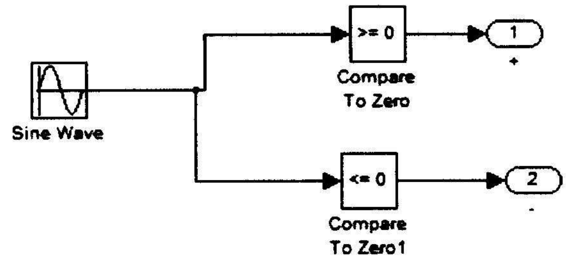


Figure 16: Phase detector model

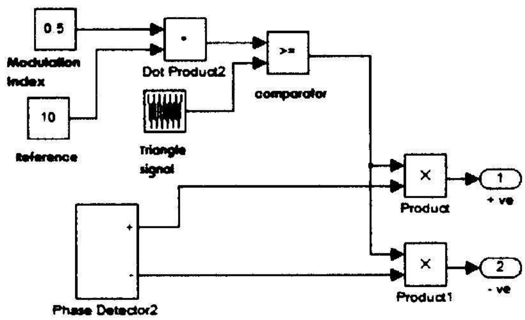


Figure 17: PWM generator model

VII. XILINX FPGA

The overall block diagram for PWM generator in Xilinx FPGA is shown in Figure 18. There are four major components include in the Xilinx FPGA schematic for PWM generator which is; External Main Clock, 'W' shape carrier signal, Comparator and Modulation Index as shown in Figure 21.

$$T_{carrier} = \frac{1}{f_{carrier}} \quad \text{-----------------------------} \quad (1)$$

$$T_{step} = \frac{T_{carrier}}{Step_{total}} \quad \text{-----------------------------} \quad (2)$$

$$= \frac{T_{carrier}}{510}$$

$$f_{clock} = \frac{1}{T_{step}} \quad \text{-----------------------------} \quad (3)$$

An external main clock was used as a clocking signal for the counter. A 5 KHz was used as a switching frequency and 8 bit up-down counter, CB8CLED is clocked at 2.55MHz to produce switching frequency 5 KHz by using an equation (1) to (3).

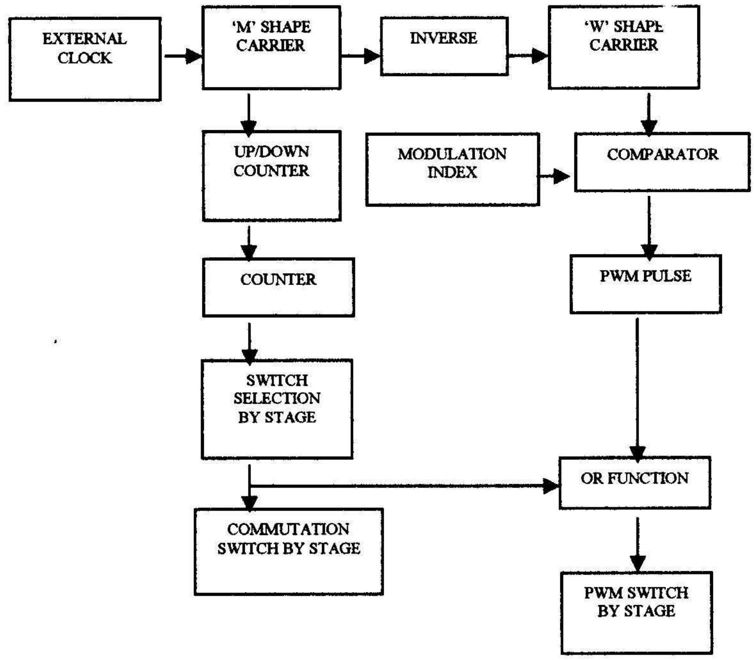


Figure 18: PWM block diagram for Xilinx

The toggle flip-flop, FTC is used to count and changes the counting direction of the up-down counter. The counter start counting from 0 to 255 when to reset signal is received, RST is received and it will count back to 0. This process will produce an 'M' shape carrier signal as illustrated in figure 19.

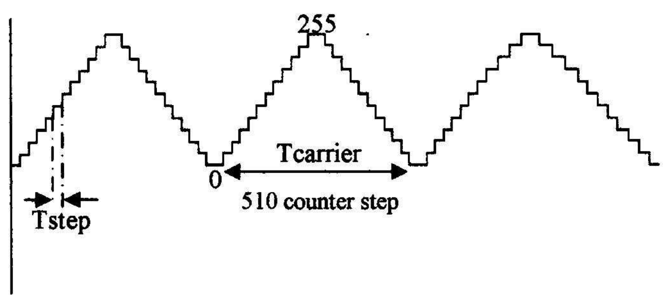


Figure 19: 'M' shape carrier signal.

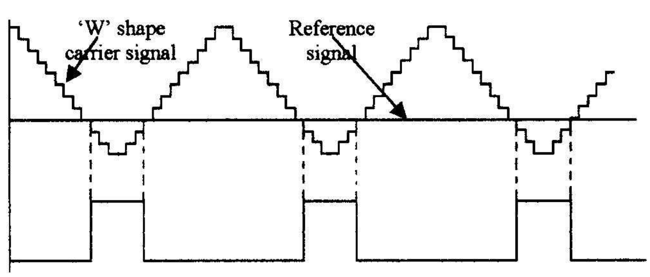


Figure 20: PWM pattern

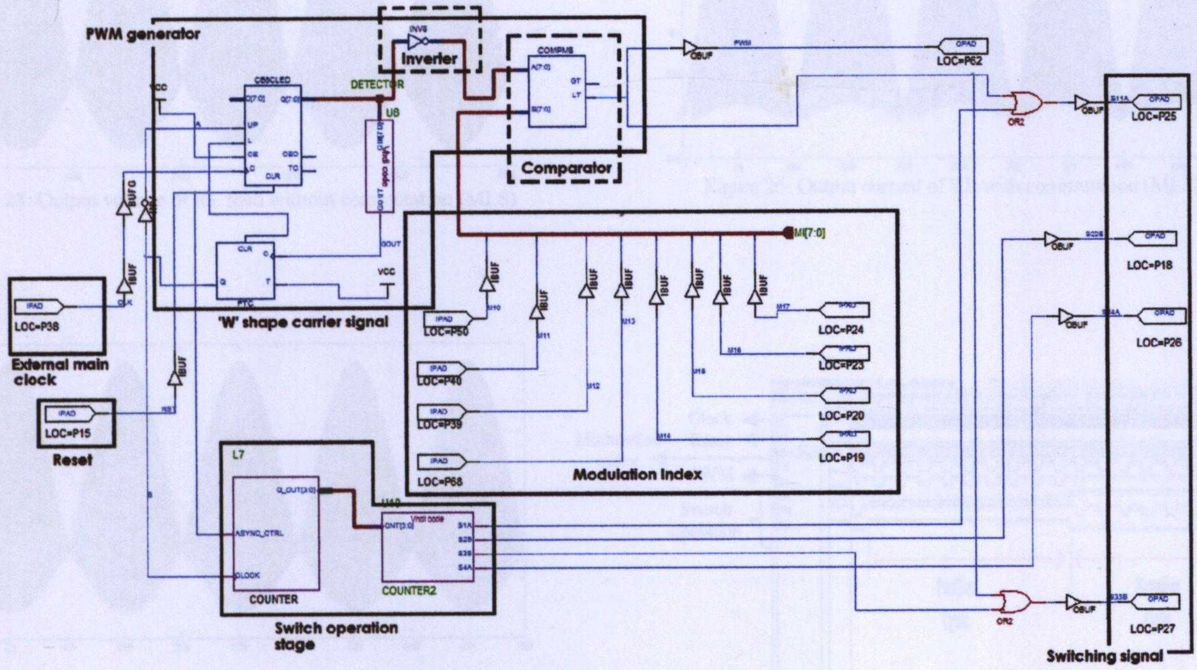


Figure 21: Schematic diagram Xilinx FPGA

To change from the 'M' shape to W shape, inverter; INV8 was used. The 'W' shape that produce then compare with modulation index by using logic block 8 bit comparator then PWM pattern will be reveal as illustrated in Figure 20. The OR gate as illustrated in Figure 21 was used at the end of the PWM to make sure that it follow the switching sequence that been set as illustrated in Table 1.

VIII. Result and Discussion

Modulation index 0.5 was used for the simulation in MATLAB/Simulink (MLS) and others parameter as in Table II. The result from the simulation was presented in Figure 22 to Figure 26. Figure 22 shows no voltage spike because only R load was used but in Figure 23 and Figure 25 shows spike on DC side for both voltage and current when RL load was substitute. The implementation of the switching strategy as illustrated in Table 1 was proposed to eliminate the spike that appear on the DC side as in Figure 25 and Figure 26. Table III shows the voltage spike when commutation strategies was not implemented. Simulation output of Xilinx FPGA design was illustrated in Figure 27 with modulation index 0.5. Figure 28 shows turn on and off time in PWM and the data was tabulated in Table IV with change in Modulation Index.

Figure 31 shows the connection between the switching frequency and turn-on time PWM, as the switching frequency getting higher, turn-on time getting smaller same with the time delay as illustrated in Figure 30.

Table II. Simulation parameter

V_{in}	100V
R	300Ω
L	10mH
f_s	5kHz
f	50Hz

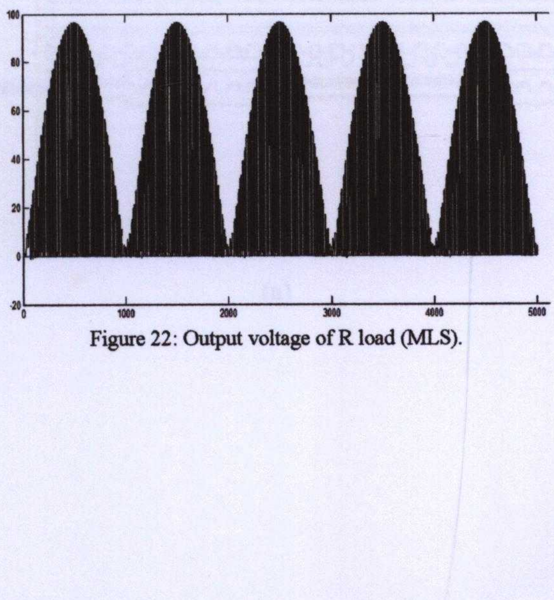


Figure 22: Output voltage of R load (MLS).

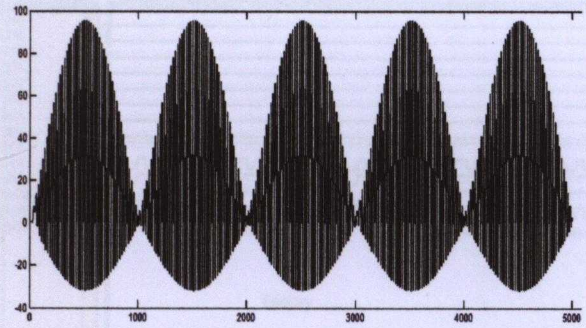


Figure 23: Output voltage of RL load without commutation (MLS)

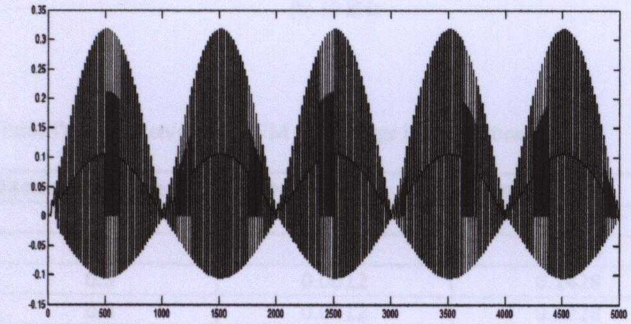


Figure 24: Output current of RL load without commutation (MLS)

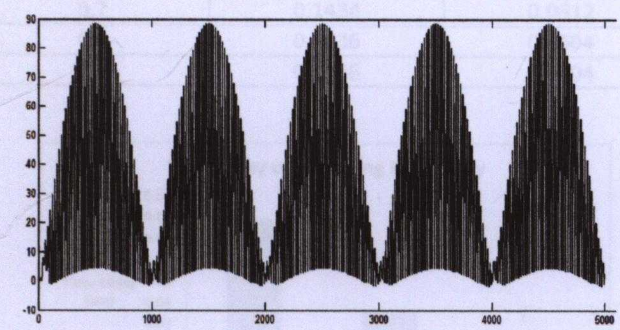


Figure 25: Output voltage of RL with commutation

Table III: Voltage and Current spike when inductive load used and without commutation strategies implementation.

Vin	Vo (spike)	Io (spike)
100V	-31.5726 V	-0.1052 A

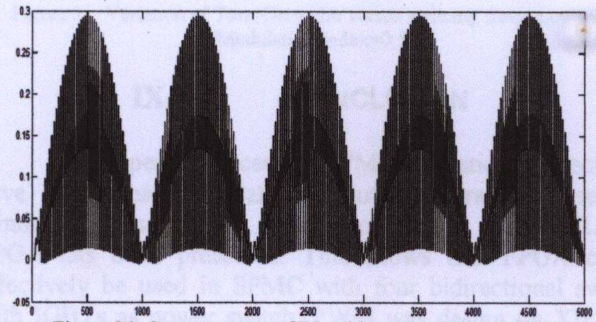


Figure 26: Output current of RL with commutation (MLS)

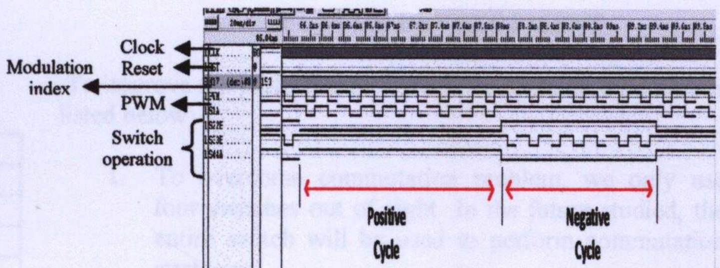


Figure 27: Xilinx FPGA simulation output

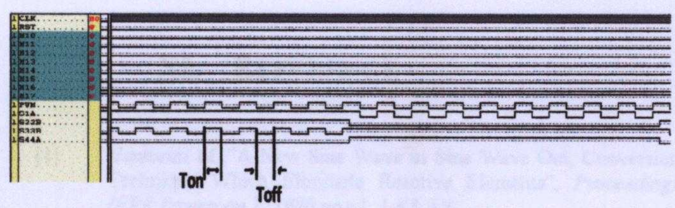
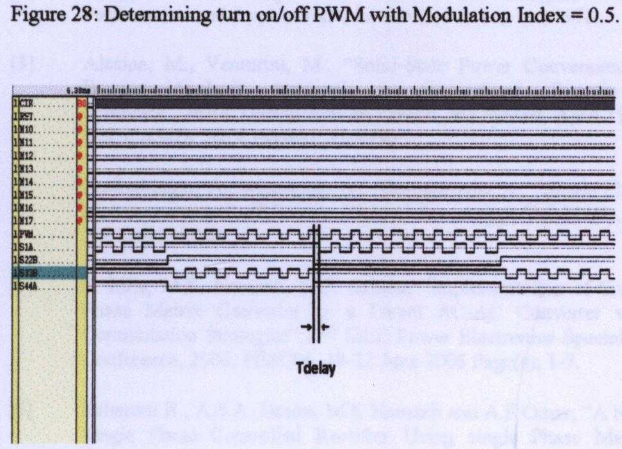
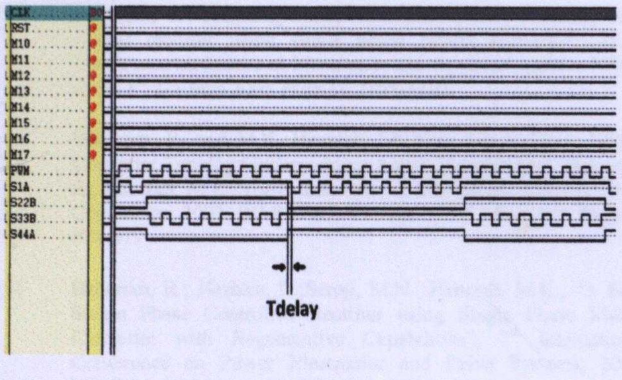


Figure 28: Determining turn on/off PWM with Modulation Index = 0.5.



(a)



(b)

Figure 29: Time delay with changes in switching frequency; (a) 3 kHz (b) 10 kHz

Table IV: Turn on/off for PWM with change in Modulation Index.

Modulation Index	Turn-On (ms)	Turn-Off (ms)
0.1	0.0204	0.1836
0.2	0.0404	0.1636
0.3	0.0612	0.1428
0.4	0.0812	0.1228
0.5	0.102	0.102
0.6	0.122	0.082
0.7	0.1434	0.0612
0.8	0.1636	0.0404
0.9	0.1836	0.0204

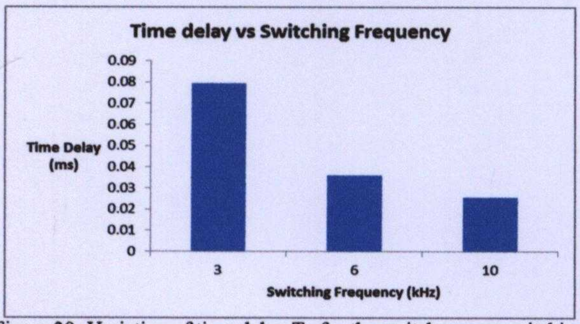


Figure 30: Variation of time delay,T_D for the switch versus switching frequency,f_s with Modulation index=0.5

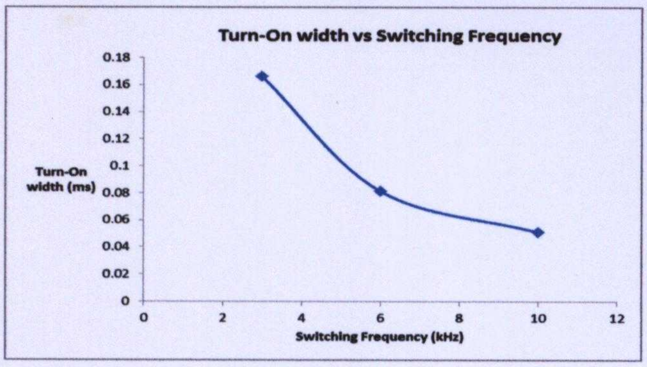


Figure 31: Variation of Turn-On width versus switcing frequency with Modulation Index=0.5

IX. CONCLUSION

The performances of SPMC operation as rectifier have been presented. Safe commutation strategies used to eliminate voltage spike. Simulation result using XILINX FPGA has been presented. This shows that FPGA could effectively be used in SPMC with four bidirectional switch with IGBTs as power switch. PWM was design on XILINX FPGA and capable to produce the required pattern. The rectifier operation with commutation strategies was successfully implemented using XILINX FPGA.

X. FUTURE DEVELOPMENT

To improve the performance of rectifier some modification is listed below:

1. To overcome commutation problem, we only use four switches out of eight. In the future studied, the entire switch will be used to perform commutation strategies.
2. In future studied, rectifier can be applying with passive filter to overcome the harmonic at the supply.
3. Uninterruptable Power Supply (UPS) circuit will be applied together with SPMC in the future studied.

XI. REFERENCE

[1] Venturini M.,"A New Sine Wave in Sine Wave Out, Conversion Technique Which Eliminate Reactive Elements", *Proceedings IEEE Powercon 7, 1980,pp.e3_1-E3_15.*

[2] Gyugyi, L and Pelly, B.R, "Static Power Charger, Theory Performance and Application", John Wiley & Son Inc, 1976.

[3] Alesina, M., Venturini, M., "Solid-State Power Conversion: A Fourier Analysis Approach to Generalized Transformer Synthesis", *IEEE Transaction on Circuit and System*, April 1981, Vol. CAS-28, No.4 Page(s): 319-330.

[4] Zuckerberger, A., wienstock, D., Alexandrovitz A., "Single Phase Matrix converter", *IEE Proc. Electric Power App*, Vol.144(4), Jul 1997 pp.235-240.

[5] Z. Idris, M.K. Hamzah, M.F. Saidon, "Implementation of Single Phase Matrix Converter as a Direct AC-AC Converter with Commutation Strategies";37th IEEE Power Electronics Specialists Conference, 2006. PESC06. 18-22 June 2006 Page(s); 1-7.

[6] Baharom R., A.S.A. Hasim, M.K Hamzah and A.F Omar; "A New Single Phase Controlled Rectifier Using single Phase Matrix Converter Topology". Baharom, R.; Hasim, A.S.A.; Hamzagh, M.K.; Omar, M.F.; IEEE International Power and Energy Conference, 2006. PECon'06. 28-29 Nov. 2006 Page(s): 453-458.

[7] Baharom, R.; Hamzah, M.K.; Muhammad, K.S; Hamzah, N.R; "Boost rectifier using single phase matrix converter", IEEE Conference on Industrial Electronics and Application,2008. ICIEA 2008. 3rd 3-5 June 2008 Page(s): 2205-2210

[8] Baharom, R. and M.K. Hamzah, "A New Single Phase Matrix Converter Topology Incorporating Active Power Filter". Baharom, R.; Hamzah, M.K.; IEEE International Electric Machines & Drive Conference, 2007. IEMDC'07. Volume 1, 3-5 May 2007 Page(s): 874-879

[9] Baharom, R.; Hashim, H.;Seroji, M.N.; Hamzah, M.K.; "A New Single Phase Controlled Rectifier using Single Phase Matrix Converter with Regenerative Capabilities", 7th International Conference on Power Electronics and Drive Systems, 2007. PEDS'07. 27-30 Nov. 2007 Page(s): 1477-1482.

[10] Baharom, R.; Hashim, H.; Seroji, M.N.; Hamzah, M.K.;"A new single-phase dual converter using single-phase matrix converter", 3rd IEEE Conference on Industrial Electronics and Applications, 2008. ICIEA 2008. 3-5 June 2008 Page(s):1151 – 1156.

[11] Wheeler, P.W., Clare, J.C, Empringham, L., Bland, M., Kerris, K.G., "Matrix converters," *IEEE Industry Applications Magazine*, Vol. 10(1), Jan-Feb2004, pp, 59-65.

[12] Baharom, R,: Hamzah, M.K, : Muhammad, K.S.; Hamzah, N.R; "Boost rectifier using single phase matrix converter", *IEEE Conference on Industrial Electronics and Applications*, 2008. ICIEA 2008. 3rd 3-5 June 2008 Page(s): 2205-2210.

[13] M. K. Hamzah, M.F.Saidon, S.Z.M. Noor "Application of Single Phase Matrix Converter Topology in Uninterruptible Power Supply Circuit incorporating Unity Power Factor Control", ICIEA 2006.