RECTIFIER USING SINGLE PHASE MATRIX CONVERTER (SPMC) TOPOLOGY CONTROLLED USING XILINX FPGA

Norazman Bin Abu Hassan
Faculty of Electrical Engineering
Universiti Teknologi MARA
40450, Shah Alam
nazzeo10@gmail.com

Abstract – **This work presents development of basic rectifier operation using Single Phase Matrix Converter (SPMC) topology. An outline of the basic principle of rectifier operation is defined; Insulated Gate Bipolar Transistor (IGBTs) are used as a power switch and Pulse Width Modulation (PWM) technique is used to synthesize the output waveform. The proposed design enabled the user to do variation of output voltage of 5 kHz and 10 kHz switching frequency using Modulation index. MATLAB/Simulink (MLS) model is developed to study the basic behavior of SPMC. Safe commutation strategy is developed to avoid voltage spike due to inductive load. A basic load represented by R load is used for this investigation. Xilinx FPGA is used as a heart of the control electronics employing the use of digital technique.**

Keyword - **Single Phase Matrix Converter (SPMC), Insulated Gate Bipolar Transistor (IGBT), Pulse Width Modulation (PWM), Matlab/Simulink (MLS), Xilinx Field Programmable Gate Array (Xilinx FPGA).**

I. INTRODUCTION

Development of advanced power semiconductor devices, increased usage of power switching circuits and other power electronic applications are becoming a common place within modern commercial and industrial environment particularly in applications for AC-DC conversions [1]. This thesis is a research about how power electronics can be implementing on embedded system program. Previous published works on SPMC operating as an AC-DC converter includes; controlled rectifier [2], boost rectifier [3], dual converter [4], regenerative operation [2] and active power filter function [5].

This paper presents a single phase matrix converter topology operation as rectifier. Insulated Gate Bipolar Transistor (IGBT) is used as a power switch and Pulse Width Modulation (PWM) technique is used to synthesize the output waveform. The proposed design enabled to do variation of output voltage and change the modulation index and switching frequency externally. Safe commutation strategy is developed to avoid voltage spike due to inductive load. A basic load represented by R load is used for this investigation. Xilinx FPGA is used as a heart of the control electronics employing the use of digital technique. Computer simulation model will be developed using MATLAB/SIMULINK (MLS) to study the basic behavior of SPMC.

II. CLASSICAL RECTIFIER

Classical rectifier normally uses bridge-diode without affording any control function and is unidirectional in nature. Bidirectional operation is also possible with the inclusion of anti-parallel switch in H-bridge topology but is not fully controllable [1].The circuit required to do this may be nothing more than a single diode, or it may be considerably more complex. Classical rectifier has intrinsic limitation since they are using bi-directional uncontrollable switches. The most important disadvantages of classical rectifiers are: low order current harmonics generation on the AC line, lagging displacement factor establishment to the utility grid that in its turn consume an important amount of reactive power, unidirectional power transmission and large DC link filter [6]. Basic circuit of rectifier is shown in figure 1.

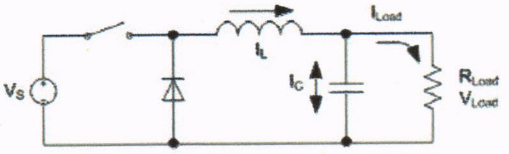

Figure 1: Basic Circuit Rectifier

III. SINGLE-PHASE MATRIX CONVERTER

The Single-phase matrix converter (SPMC) was first realized by Zuckerberger in 1997 [1,7,9] with other works on AC-AC, DC-DC and some works on AC-DC conversion [7,13]. This SPMC requires 4 bi-directional switches, each capable of conducting current in both directions, blocking forward and reverse current [4,12]. In the absence of bidirectional switch module, the common emitter anti-parallel insulated gate transistor (IGBT), with diode pair is used. The IGBT were used because of its high switching capabilities and high current carrying capacities desirable for high-power applications [8].

The basic component of a SPMC can be described in Figure 2. This could be used to develop the overall concept in the implementation of the SPMC. The input source of a SPMC circuit can be either a DC or Single Phase AC [7].

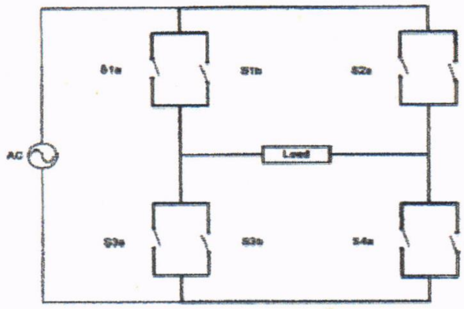

Figure 2 Single Phase Matrix Converter Circuit

Theoretically, SPMC can do all the four types of power conversion; DC to AC, AC to DC, DC to DC and AC to AC. However this work will only focus on AC to DC Single Phase Matrix Converter. The SPMC consist of input and output lines with four-bidirectional switches as in figure 2 connecting the single phase input to the single phase output at the intersection [10]. The switching of these bi-directional switches is then modulated using suitable PWM modulation to produce the desired output voltage and frequency. In this work a direct AC to DC converter was presented to operate as a direct straight line converter with simulations presented using MATLAB/Simulink [11].

Single Phase Converter has been presented SPMC operates with four bidirectional switches in rectifier circuit. The commutation problems occur when inductive load is used and because the characteristics of IGBTs [5,15]. The safe commutation strategy was implemented to avoid voltage spike is also described [14].

IV. PROPOSED RECTIFIER OPERATION

The proposed rectifier operation using single phase matrix converter are shown in figure 5 for positive cycle with commutation strategies and figure 6 for negative cycle with commutation strategies. Insulated Gate Bipolar Transistor (IGBTs) is used as a power switch and Pulse Width Modulation (PWM) technique is used to synthesize the output waveform. The PWM signal waveform is shown in figure 3. The modulation or carrier signal is the output of multiplying the modulation index (MI) with per unit MI. The triangular waveform 'W' shape is use as a carrier signal with switching frequency. The proposed design enabled the user to do variation of output voltage using modulation index with 5 kHz and 10 kHz switching frequency. Safe commutation strategy is developed to avoid voltage spike due to inductive load

In comparison the SPMC requires 4 bi-directional switches as illustrated in Figure 4 for its rectifier operation. It requires the use of bidirectional power switches capable of blocking voltage and conducting current in both direction [5,14].The IGBTs were used due to its high switching capabilities and high current carrying capacities desirable amongst researchers for high-power applications [3].

The proposed rectifier operation is presented schematically in Figure 4 based on switching strategies in Table 1. Only three switches are use for rectifier operation. For this work, only positive cycle and negative cycle are used to implement SPMC as a controlled rectifier. For positive cycle, S1a was set as control switch (PWM); the commutation switch is between S3b and S4a. Meanwhile for negative cycle the control switch (PWM) was turn off resulted the inductor start to discharge, the commutation switch is between S4a and S3b. Resistor is used as the load at the output.

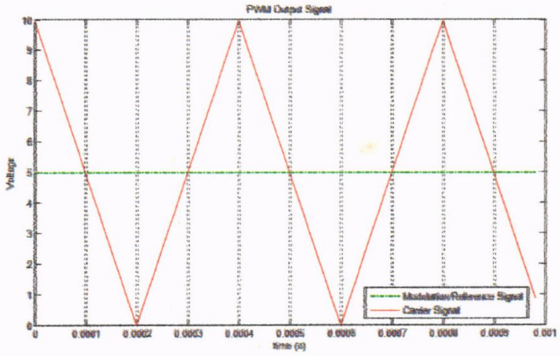

Figure 3: PWM Signal Waveform

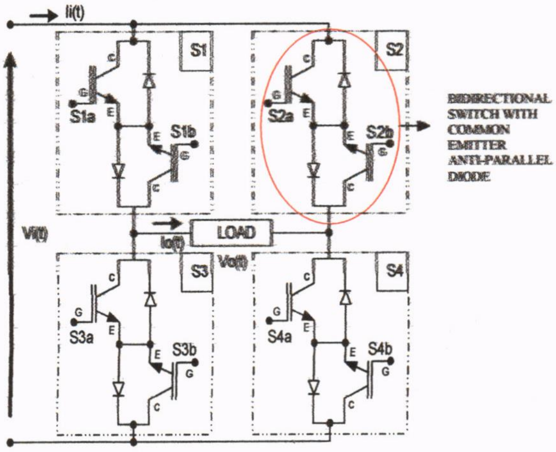

Figure 4: Proposed Single Phase Matrix Converter Topology

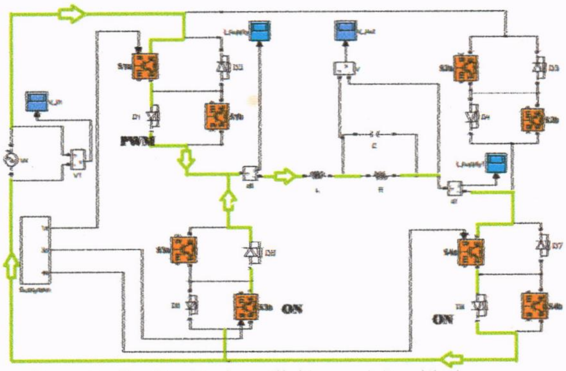

Figure 5: Positive Cycles with Commutation Strategies

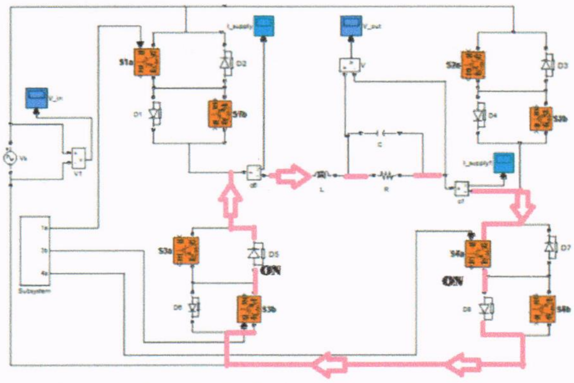

Figure 6: Negative Cycle with Commutation Strategies

V. MODELING AND SIMULATION

Proposed operation is developed and implemented using MATLAB/Simulink Software (MLS). MLS software was used as simulation tools to study the behavior of rectifier operation. For designing and developing power electronic circuits without suitable computer simulation are extremely laborious, error-prone, time consuming and expensive. This simulation tools is to ensure the expected results is accurate and achieved. The simulation has been setup to observe the characteristic of the output waveform hence providing the required result or output.

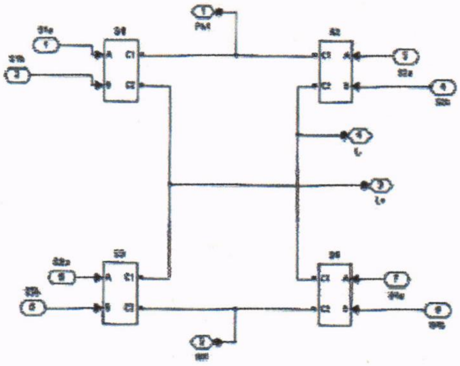

Figure 7: SPMC subsystem model in MLS

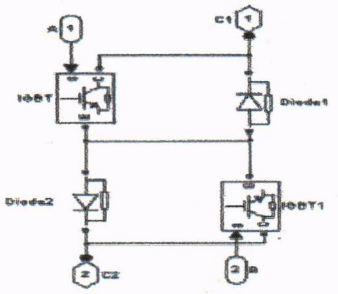

Figure 8: Bidirectional Switch Modules

Figure 7 show the subsystem contains in SPMC block includes four bidirectional switches as in Figure 8. The block diagram of PWM/Commutation generator was shown in Figure 9. Modulation index (MI) is multiplied with per unit modulation index using dot product to produce the reference signal then the output signal is compared with Triangular wave 'W' shape to produce PWM output. Commutation is used to turn ON S3b and S4a as per commutation strategies. Simulation parameter used as shown in Table I. S1a is connected to PWM and will turn ON during positive cycle PWM and turn OFF during negative cycle. S3b and S4a are connected to the constant signal which continuously ON during positive and negative cycle. Others switches are not used. Table II shows the switching strategies of the converter.

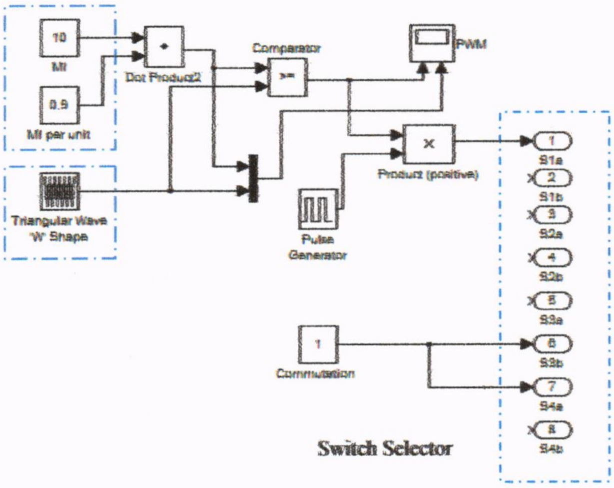

Figure 9: Block Diagram of PWM/ Commutation generator

Table I: Simulation Parameter

Parameter	Value
Input Voltage, Vac	20V
Resistive load, R	25Ω
Inductive Load, L	0.9H
Capacitor, C	10uF
Modulation Index, *MI*	0.5
Switching Frequency, *fs*	5 kHz , 10 kHz

Table II: Switch strategies for positive cycle and negative cycle

Switch	Positive cycle	Negative cycle
S1a	PWM	OFF
S1b	OFF	OFF
S2a	OFF	OFF
S2b	OFF	OFF
S3a	OFF	OFF
S3b	ON	ON
S4a	ON	ON
S4b	OFF	OFF

Figure 10 shows Top Model of Single Phase Matrix Converter model as rectifier using MATLAB/ Simulink. Eight IGBTs with series diodes were used as power switches for this SPMC circuit. In rectifier operation, S1a was set as a control switch (PWM) while S3b and S4a were set to be ON continuously. PWM generator with "W" shape triangular waveform carrier signal was used with 5 kHz switching frequency. The output of PWM has only positive cycle. 20V AC voltage source was used as input supply of the SPMC. SPMC was connected to the R load with low pass filter (LC filter) at the output.

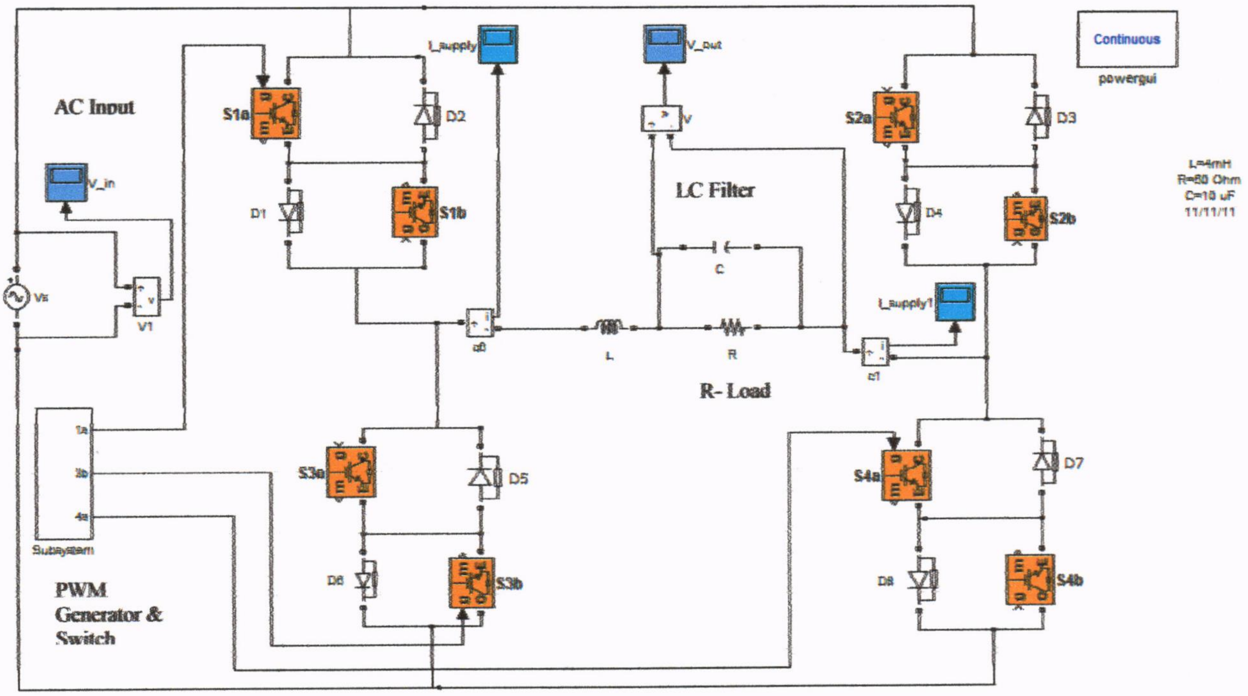

Figure 10: Top Model of Single Phase Matrix Converter as Rectifier in MLS

VI. XILINX FPGA

In this work, as shown in figure 11, the FPGA was designed using four major components; External Clock, 'W' shape carrier signal, 8-bit up/down counter, Comparator and Modulation index. The PWM signal was generated by comparing the 'W' shape triangular wave signal with the DC reference signal which can be controlled to generate the required Pulse Width Modulation signal. Up/Down counter CB8CLED used in this work is clocked at 2.551 Hz to produce 5 kHz carrier signal. Toggle Flip-Flop is used to count and change the counting direction of up/down counter. The counter start to counting from 0 to 255 will count back to 0 as programmed in the detector.

The detector (DET) module is developed using VHDL program. The detector will detect the clock signal. This process will produce 'M' shape carrier signal. Inverter, INV8 was used to change 'M' shape to 'W' shape as shown in figure 11. This triangular 'W' shape then will be compared with the modulation index by using 8-bit identity comparator (COMPM8) and will produce PWM pattern. The AND gate are used in the switch selector to ensure that the PWM pulse follows the switching strategy sequence as in Table II. Figure 12 shows the overall block diagram of FPGA PWM generation algorithm for rectifier

The first counter is used as a switch. This switch module will act as a controller or switch selector. This switch selector is developed using VHDL program. The block is used to select which switch should be ON and OFF at certain cycle. The carrier 'M' shape waveform is shown in figure 13. An external main clock was used as a clocking signal for the FPGA counter. For this work, 5 KHz carrier signal was used. The 8 bit up/down counter, CB8CLED is clocked at 2.551 MHz to produce carrier signal. The determination of the clock frequency can be derived from equation (6.1) to (6.3) based on figure 13:

$$T_{carrier} = \frac{1}{fcarrier} \qquad \text{.... (6.1)}$$

$$T_{step} = \frac{Tcarrier}{Steptotal} \qquad \text{.... (6.2)}$$

$$f_{clock} = \frac{1}{Tstep} \qquad \text{.... (6.3)}$$

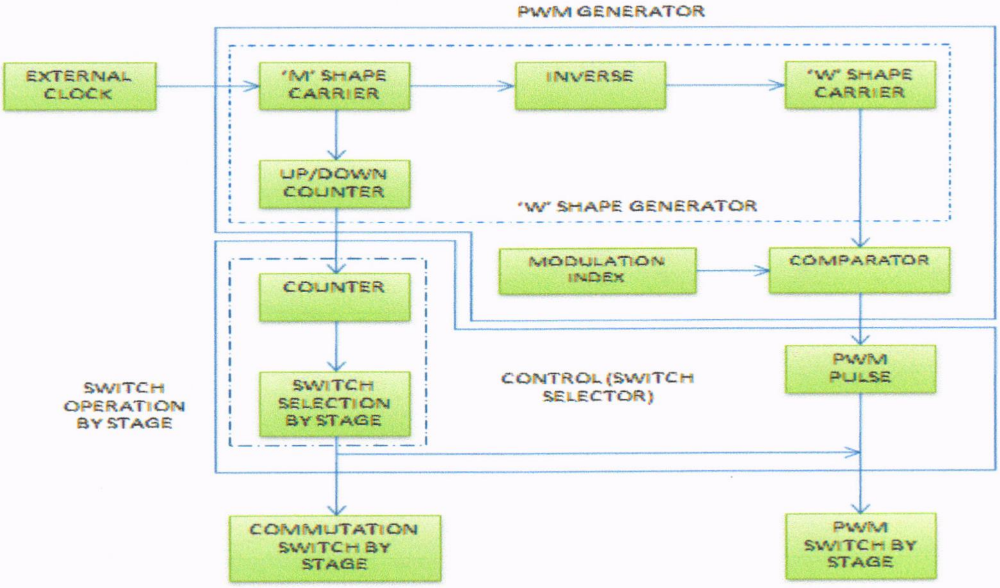

Figure 11: FPGA PWM Generation Algorithm for Rectifier

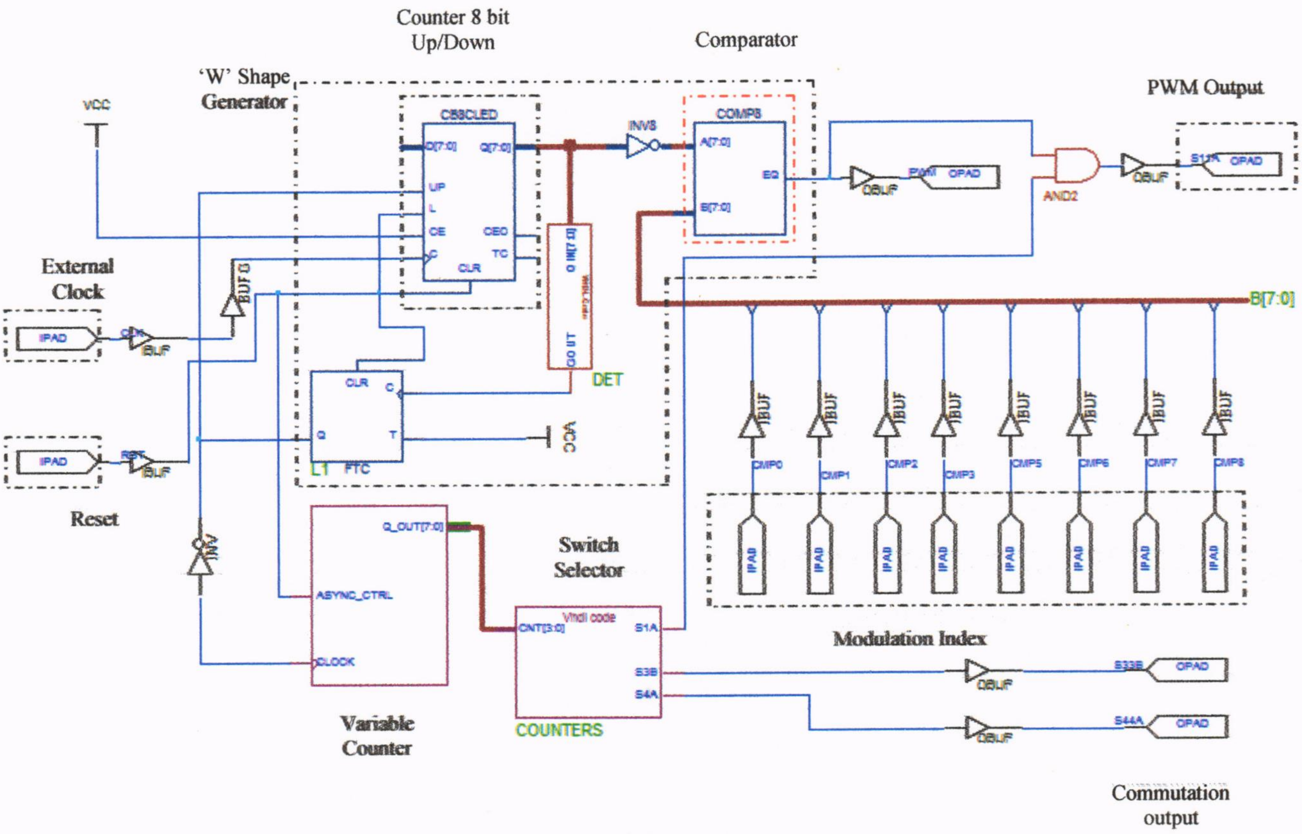

Figure 12: Schematic diagram of XILINX FPGA

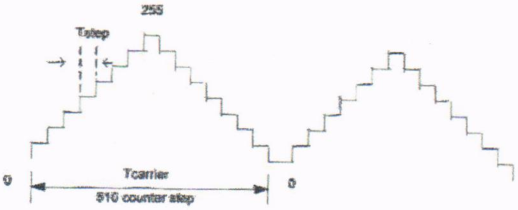

Figure 13: 'M' Shape Carrier Signal

VII. RESULT AND DISCUSSION

A. Result of Matlab/Simulink

To study the characteristic of rectifier operation, a computer simulation using MATLAB/Simulink is developed. Results are taken for every modulation index varies from 0.1 to 1.0 for selected switching frequency 5 kHz. 20V AC supply is used. Voltage output and current output were taken at the load. Pulse generator, the S1a was strategized to be set as PWM resulted the S1a will follow the PWM signal where during the positive cycle S1a will turn ON and will turn OFF during negative cycle. During this time S4a and S3b also set to be ON with the constant signal. Figure 14 and 15 are the results of the output voltage taken at the load for different Modulation index.

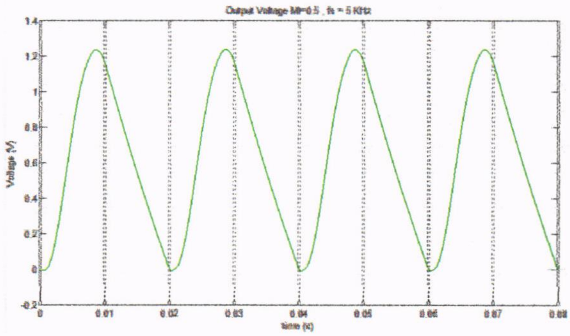

Figure 14: Peak Output Voltage for V*in peak* =20V, *fs*=5 kHz, MI=0.5, V*out peak* =1.241V

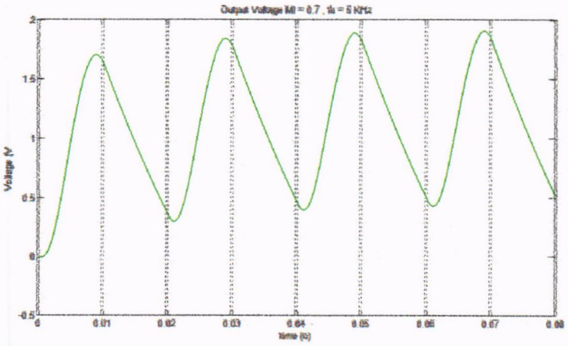

Figure 15: Peak Output Voltage for V*in peak* =20V, *fs*=5 kHz, MI=0.7, V*out peak* =1.916V

Figure 14 shows the Peak DC output Voltage is 1.241Vpeak using MI=0.5 at 5 kHz switching frequency and figure 15 shows the Vout peak is 1.916V at MI=0.7 at 5 kHz switching frequency. The result shows the output peak voltage varies when the different modulation index is set or controlled.

Figure 16 and 17 shows the output current after commutation strategy implemented.

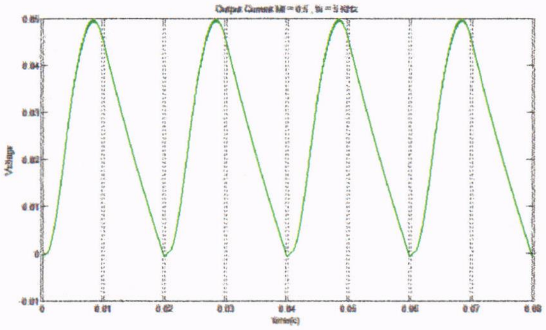

Figure 16: Peak Output Current for V*in peak* =20V, *fs*=5 kHz, MI=0.5, I*out peak* =0.05A

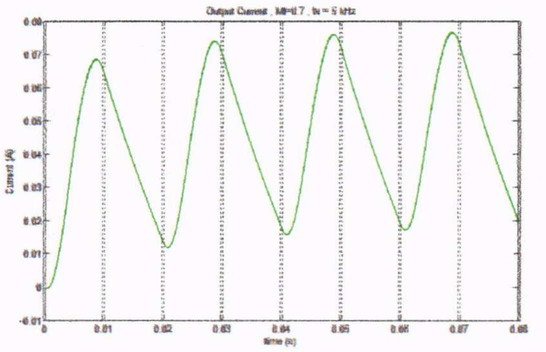

Figure 17: Peak Output Current for V*in peak* =20V, *fs*=5 kHz, MI=0.7, I*out peak* =0.075A

The result shows during the positive cycle, the current will charge the inductor and during the negative cycle, the inductor will start to discharge until the next positive cycle. The peak output current is 0.05A using MI=0.5 at 5 kHz switching frequency. The peak output current varies to 0.075A using MI=0.7 at 5 kHz switching frequency. The result shows the different peak output current when the different modulation index is set or controlled.

Figure 18 and 19 shows the peak output voltage and peak output current for MI = 0.5 using 10 kHz switching frequency.

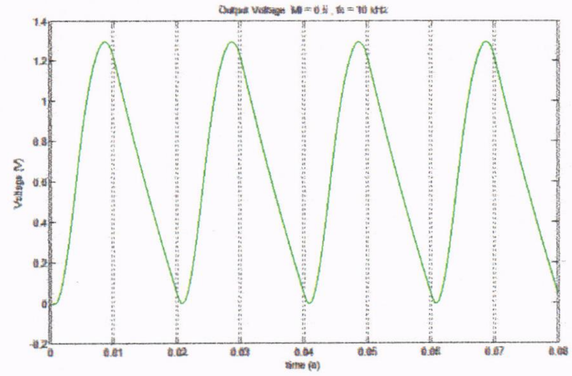

Figure 18: Peak Output Voltage for V*in peak*=20V, *fs*=10 kHz, MI=0.5, V*out* =1.297V

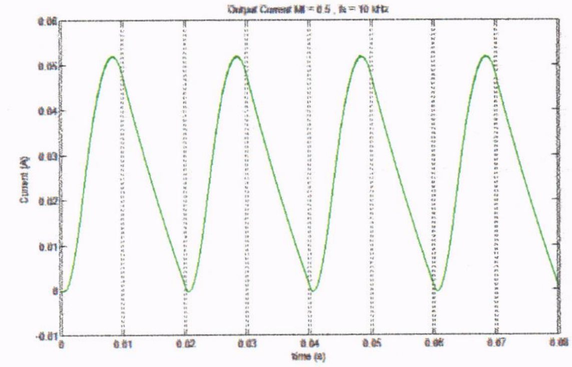

Figure 19: Peak Output Current for V*in peak* =20V, *fs*=10 kHz, MI=05, I*out* =0.052A

Figure 18 and 19 shows the result of the Peak DC output Voltage and peak output current MI=0.5 at 10 kHz switching frequency. The result shows the peak output voltage is 1.297V and the peak output current is 0.052A.

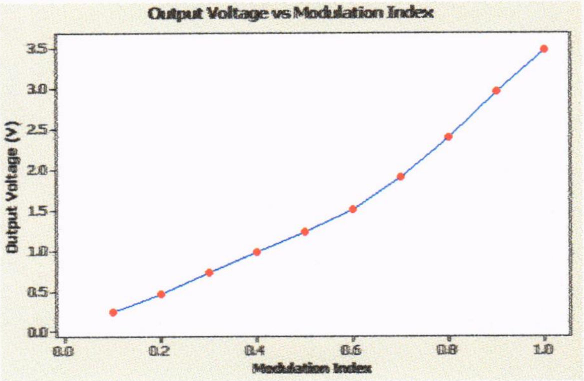

Figure 20: Peak Output Voltage versus Modulation Index at Vin peak =20V, fs = 5 kHz

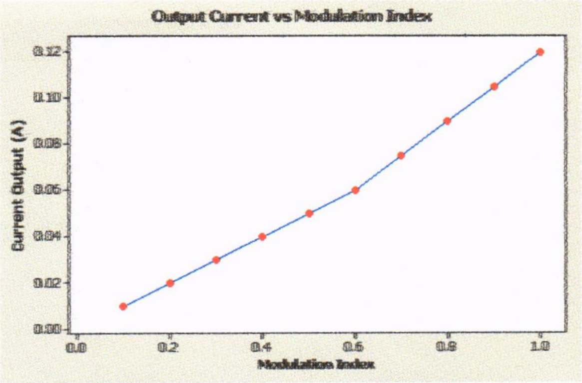

Figure 21: Peak Output Current versus Modulation Index at Vin peak =20V, fs = 5 kHz

Figure 20 and 21 shows the Output Voltage and Output Current versus Modulation Index for peak input voltage 20V and switching frequency 5 kHz. The output voltage and output current is linear correlation to the Modulation index. Table III shows the percentage of peak output voltage increase by the change of modulation index for 5 kHz and 10 kHz switching frequency.

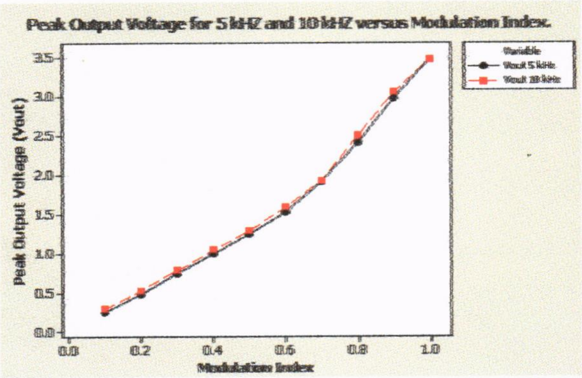

Figure 22: Peak Output Voltage for V*in peak* =20V, *fs*=5 kHz and 10 kHz, versus MI

Table III: Percentage Vout increased with the change of MI

Modulation Index		% increase of Vout peak, Vin 20V	
From	**To**	**5 kHz**	**10 kHz**
0.1	0.2	52.42%	57.11%
0.2	0.3	64.71%	67.34%
0.3	0.4	74.21%	75.52%
0.4	0.5	79.69%	80.96%
0.5	0.6	81.59%	81.32%
0.6	0.7	79.38%	82.60%
0.7	0.8	79.83%	77.09%
0.8	0.9	80.91%	81.89%
0.9	1.0	85.06%	87.73%

Figure 23 show the graph of peak output voltage versus switching frequency using MI=0.5 and MI=0.7 for both 5 kHz and 10 kHz switching frequency. The percentage increase of peak output voltage is about 65% when MI changes from 0.5 to 0.7 for both 5 kHz and 10 kHz switching frequency.

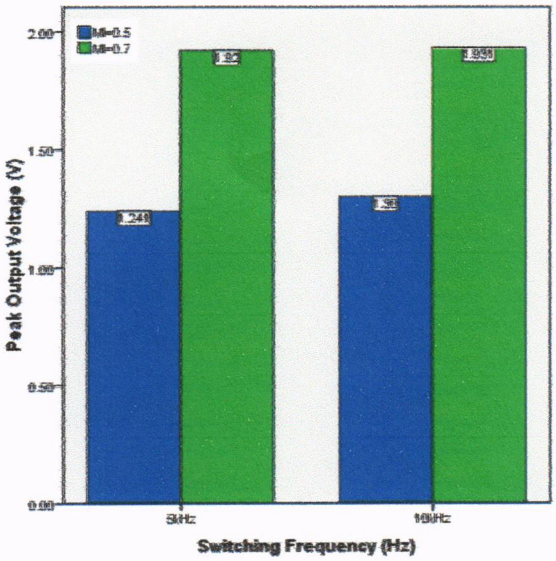

Figure 23: Peak Output Voltage versus Switching frequency at MI=0.5 and MI=0.7, using Vin peak =20V

B. Result of Xilinx FPGA

Figure 24 shows the Xilinx FPGA simulation output using Xilinx Foundation Software. The simulation parameter is similar to MATLAB/ Simulink. 5 kHz switching frequency is used and the modulation index is set to 0.5, clock (CLK) is set to B0 and with external clock frequency 2.551 MHz. Table IV shows the t_{clock} and f_{clock} for 5 kHz and 10 kHz switching frequency.

Table IV: The tclock and fclock for 5 kHz and 10 kHz switching frequency

fs	*f clock*	*t clock*
5 kHz	2.551 MHz	392 ns
10 kHz	5.100 MHZ	196 ns

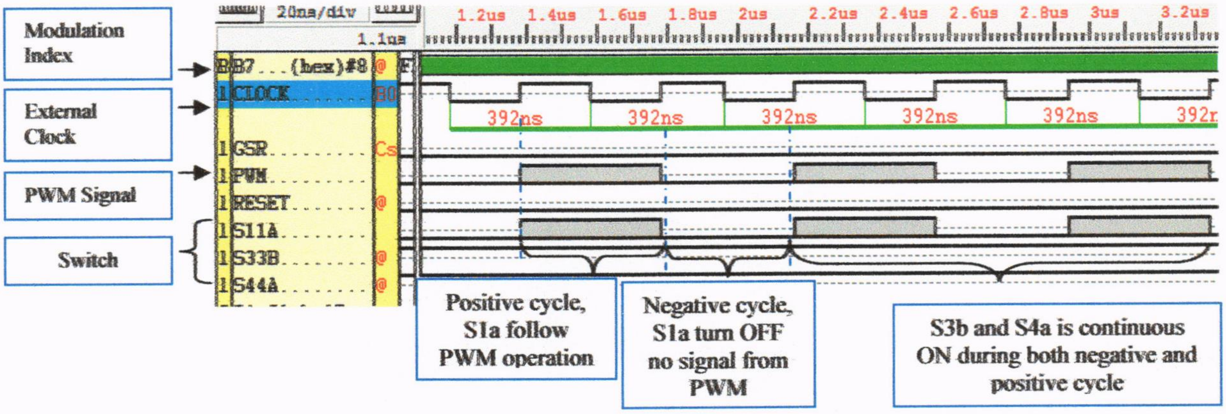

Figure 24: Xilinx FPGA Simulation Output, fclock = 2.551 MHz, fs= 5 kHz, tclock =392ns

VIII. CONCLUSION

The MATLAB simulation result has been presented for rectifier operation using SPMC topology. Voltage output and Current Output can be controlled by adjusting modulation index (MI). The result for Output Voltage and Output current for Modulation index 0.5 and 0.7 using 5 kHz and 10 kHz switching frequency were presented. The output voltage and output current are linear correlation to the modulation index. The operation of using single phase matrix converter as rectifier with variation of output voltage and output current is achieved by changing the modulation index. A computer simulation model was successfully developed using MATLAB/ Simulink to study the behavior of the converter and verify using Xilinx FPGA Foundation Software.

Authors Contribution to Knowledge:

i. Rectifier operation is successfully developed using Single Phase Matrix Converter.
ii. Modeling and simulation of SPMC using MATLAB/ SIMULINK (MLS) is successfully developed to study the basic behavior of SPMC.
iii. Pulse Width Modulation (PWM) is successfully implemented to synthesize the output of the converter.
iv. Xilinx FPGA is successfully implemented as digital control electronic for the SPMC .

IX. RECOMMENDATION FOR FUTURE WORK

This project can be improved further as per below recommendation:

i. Rectifier operation can be controlled using PIC, Xilinx Spartan, Altera FPGA and other simulation tools.
ii. Further investigations may include passive filter design for current source harmonics mitigation. Active filter can be used to modify compensation characteristic for the dynamic change of non-linear load

ACKNOWLEDGMENT

Thank you to Madam Siti Zaliha Bt Mohammad Noor for her guidance, advice, idea, support and knowledge given until completion of this work and to other FKE lecturer for the knowledge given. Their contribution really much appreciated.

REFERENCES

[1] Baharom, R. Hamzah, M.K. Hamzah, N.R. Mohd Kasim, L. "Boost Rectifier Using Single-Phase Matrix Converter with Bipolar Output", *IEEE 2nd International on Power and Energy Conference, 2008. PECon 2008.*

[2] Baharom, R. Hamzah, M.K. Saparon, A. Noor, S.Z.M. Hamzah, N.R "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.*

[3] Baharom, R. ; Hamzah, M.K. ; Muhammad, K.S. ; Hamzah, N.R. "Boost rectifier using single-phase matrix converter"; *3rd IEEE Conference on Industrial Electronics and Applications, 2008. ICIEA 2008.*

[4] Baharom, R. Hamzah, M.K. "A New Single-Phase Controlled Rectifier Using Single-Phase Matrix Converter Topology Incorporating Active Power Filter", *IEEE International on Electric Machines & Drives Conference, 2007. IEMDC '07.*

[5] Idris, Z. ; Mohammad Noor, S.Z. ; Hamzah, M.K. "Safe Commutation Strategy in Single Phase Matrix Converter" ; *International Conference on Power Electronics and Drives Systems, 2005. PEDS 2005.*

[6] H.Azizi and A.Vahedi "Performance Analysis of Direct Power Controlled PWM Rectifier under Disturbed AC Line Voltage"; Power Engineering Department-Iran University of Science &Technology.

[7] M.K.; Saidon, M.F.; Noor, S.Z.M "Application of Single Phase Matrix Converter Topology in Uninterruptible Power Supply Circuit incorporating Unity Power Factor Control"; *1st IEEE Conference on Industrial Electronics and Applications, 2006 on 24-26 May 2006*

[8] Baharom, R.; Hamzah, M.K "Computer simulation of single-phase matrix converter operating as buck or boost rectifier"; *2nd International Conference on Mechanical and Electronics Engineering (ICMEE), 2010*

[9] 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.*

[10] Jai P. Agrawal, "Power Electronic System; Theory and Design", Prentice Hall, Inc, 2001

[11] Mohd Azizonazwan Bin Ab Rahman;"Single Phase Matrix Converter (SPMC) for Rectifier Operation (AC-DC), *UITM Thesis.*

[12] Mohd Faudzan b Abd Latib "Single-Phase Matrix Converter for Rectifier Operation Control Using PIC", *UITM Thesis*

[13] Idris, Z. ; Hamzah, M.K. ; Hamzah, N.R. "Modelling & Simulation of a new Single-phase to Single-phase Cycloconverter based on Single-phase Matrix Converter Topology with Sinusoidal Pulse Width Modulation Using MATLAB/Simulink"; *International Conference on Power Electronics and Drives Systems, 2005. PEDS 2005.*

[14] Baharom, R.; Hamzah, M.K.; Saparon, A.; Hamzah, N.R.; "Single-phase matrix converter operating as buck and boost rectifier", *4th IEEE Conference on Industrial Electronics and Applications, 2009. ICIEA 2009.*

[15] Mohammad Noor, S.Z. Baharom, R. Hamzah, M.K. Hamzah, N.R. "Safe-commutation strategy for controlled rectifier operation using single-phase matrix converter", *International Conference on Power Electronics and Drive Systems, 2009. PEDS 2009.*