Power Losses and Switching Effects in Single-Phase Matrix Converter for Rectifier Operation

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Abstract: - **This paper describes the power losses and the switching effects that might occur in single-phase matrix converter (SPMC) as an AC-DC controlled rectifier if frequencies vary. The MPWM technique was used to synthesize the DC output. Switch commutation arrangements were developed that allow dead time to avoid current spikes of non-ideal switches whilst providing a current path for the inductive load to avoid voltage spikes. Loads represented R, RL and RC circuit are used for this investigation.**

Keywords:---Single Phase Matrix Converter (SPMC), Multiple Phase Width Modulation (MPWM), Insulated Gate Bipolar Transistor (IGBT), Alternating Current (AC), Direct Current (DC)

1. INTRODUCTION

The Matrix Converter (MC) is an advanced circuit topology that capable of converting AC to AC, AC to DC, DC to AC and DC to DC. It is originally developed based on cyclo-converter principle for frequency changer application. Matrix Converter offers many advantages such as the ability to regenerate energy back to the utility, sinusoidal input and output current and controllable input current displacement factor [1]. It has the potential of affording an "all silicon" solution for AC-AC conversion, removing the need for reactive energy storage components used in conventional rectifier-inverter based system.

The topology was first proposed by Gyugyi [2] in 1976. Previous published studies mainly dealt with three-phase circuit topologies [3]. The Single-phase matrix converter (SPMC) was first realised by Zuckerberger [4]. All previous works have focussed attention to direct AC-AC single-phase converter [3] and DC chopper [4] but none on rectifier & inverter operation. MC in the three-phase variant is widely researched whilst the Single-Phase Matrix Converter (SPMC) has very little attention whilst offering possibilities of very wide application.

In this work the single phase matrix converter topology are used to operate as a controlled rectifier by suitable switching scheme, where IGBTs are used for the main power switching devices. The switching algorithm need to be carefully calculated to ensure that the switches do not short-circuit the voltage sources, and do not open-circuit the current sources, thus the continuous currents at the output terminal are always needed to ensure reliable operation.

2. SINGLE PHASE MATRIX CONVERTER (SPMC)

The SPMC consists of a matrix of input and output lines with 4 bi-directional switches connecting the input or sources either of a single phase AC or DC to the output at the intersections. The SPMC is presented schematically in Fig 1. Output voltage is V_o (t). It comprises four ideal switches SW1, SW2, SW3 and SW4 known as IGBTs switches that capable of conducting current in both directions, blocking forward and reverse voltages as shown in Fig. 2. The switches turn-on and turn-off without any delay [3]. The switching of these bi-directional switches is then modulated using suitable PWM modulation to produce the desired output voltage and frequency.

3. SWITCHING OF SPMC

SPMC consists of four set bi-directional switches to control the output, where one set of bi-directional switch is built by a set of two IGBTs, two diodes, and it is arranged in anti-parallel as previously described [5]. A sample of switching state is illustrated as in Fig.3 to 6.

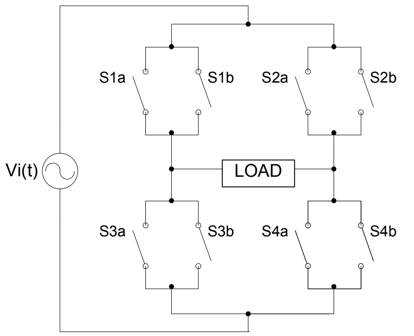

Figure 1: AC-AC Single-Phase Matrix Converter Topology

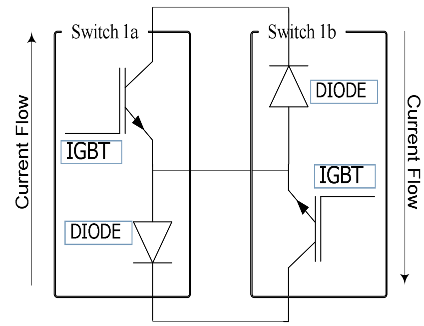

Figure 2: Bi-directional switch

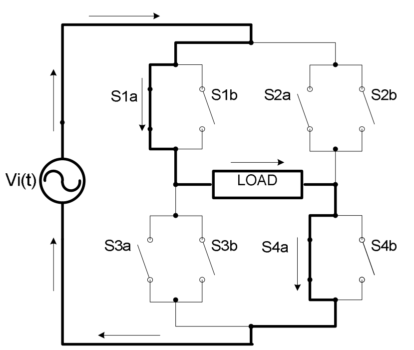

Figure 3: State 1 AC Input (Positive Cycle)

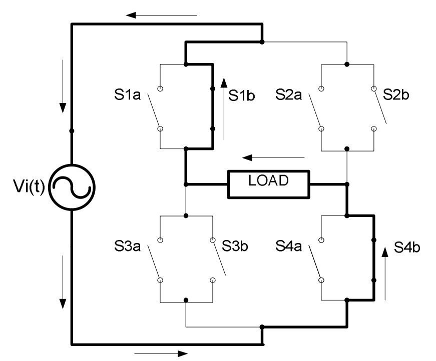

Figure 4: State 2 AC Input (Negative Cycle)

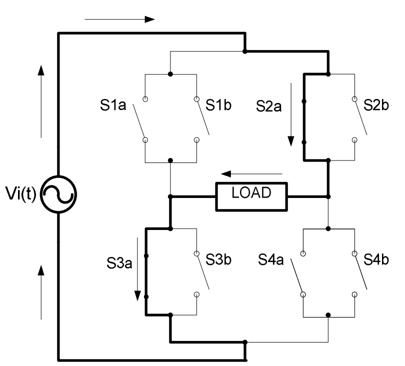

Figure 5: State 3 AC Input (Positive Cycle)

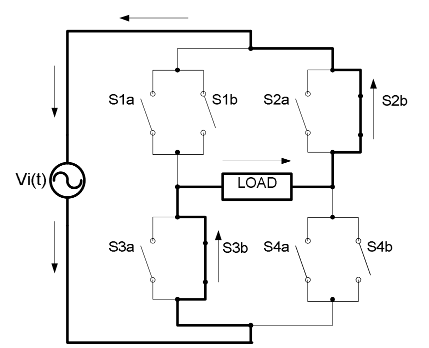

Figure 6: State 4 AC Input (Negative Cycle)

4. CONTROLLED RECTIFIER

The classical rectifier normally uses a bridge-diode in execution without affording any control function. The ease makes it universal for rectification of low-power application and some common high-power applications but are major contributors to power factor and current distortion problems. Sensitive equipments are less tolerable to nuisances caused by harmonics penetration into the supply system. Associated problems such as poor overall power factor, heating effects, device malfunction and destruction of other equipment caused by nonlinear loads such as bridge diode rectifier with capacitor filter have been recorded [6] Therefore the demand for high quality power supply has shown an upward increase in recent years. This trend reflects in the increase use of provision of unity supply power factor [7].

To implement SPMC as a controlled rectifier, only State 1 and 4 are used, making State 2 and State 3 redundant. However, these redundant switches could be used to add features to the controlled rectifier operation that may include, amongst others; safe-commutation and unity power factor operation particularly when RL load are used.

5. COMMUTATION PROBLEM

To understand the actual problem of commutation in SPMC, let consider an AC-DC converter referred to Figure 1. The switching sequences to produce DC output are stated as below:

Input voltage	Output	ON State
positive	positive	1) S1a & S4a
negative	positive	4) S3b & S2b

Table 1: Switching sequences of AC-DC converter

During positive input voltage, there are two ON state, state 1 and state 4. In state 1, S1a & S4a is ON and after a time when it is needed to commutate the current to state 4. If S2a & S3a is ON before S1a & S4a is OFF, a short circuit path will appear and current spike occur. However, if S1a & S4a is OFF before S2a & S3a is ON, a path for inductive load current is absent causing large over voltages across switches. The switching need to be instantaneous and it is not possible due to propagation delays and finite switching times.

Furthermore, the control strategy for SPMC is utilizing PWM, mean, a stream of pulses are sent to IGBTs. The time between PWM pulses are also need to be arranged so that the inductive load current is freewheeled. Thus, any novel commutation proposed for SPMC must obey those rules:

I. Providing delay between the transitions of ON State.
II. Providing path for inductive load current during delay in I.
III. Providing path for inductive load current between PWM pulses.

In other word, there must be a path for the load current and particular switches that must be ON at any time.

6. COMMUTATION STRATEGY

In conventional controlled rectifier, free-wheeling diodes are used for this purpose. In SPMC this does not exist, hence the need to develop a switching sequence to allow for forced free-wheeling action. This is to protect the converter from being damaged as a result of voltage and current spikes as described. In conventional converter this is normally implemented in the form of free-wheeling diodes in rectifier systems arranged in anti-parallel with power switching devices. In this study, we will focus our attention to switching spikes and assume that there is no-change in the direction of current so as to minimize complexities.

State	Control Switch (MPWM sequence)	Commutation Switch "ON"
1	S4a	S1a & S2b
4	S2b	S3b & S4a

Table 2: Proposed switching sequence

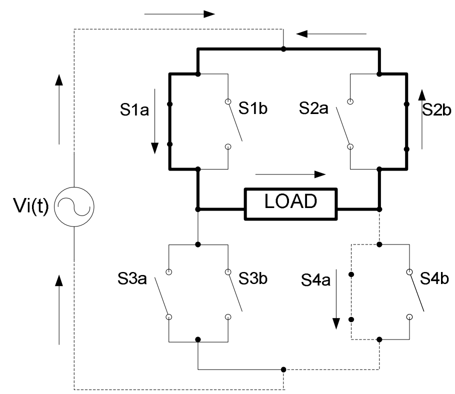

Figure 7: State 1 switching sequence

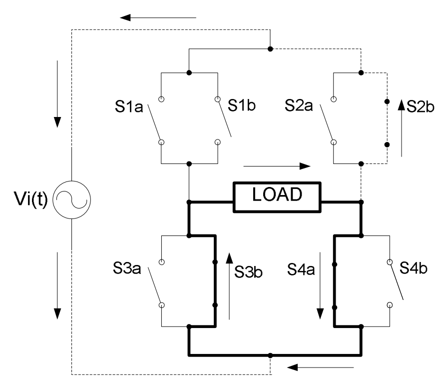

Figure 8: State 4 switching sequence

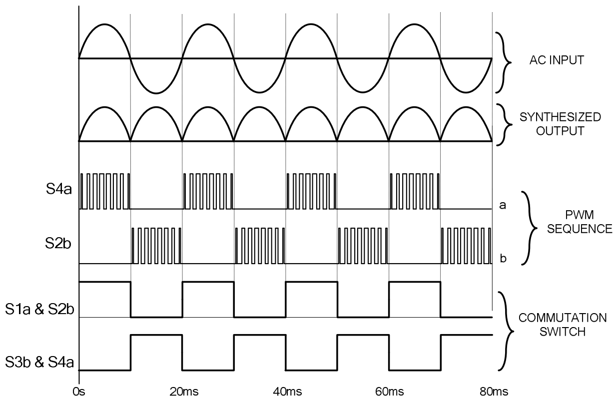

Figure 9: Switching Pattern Commutation Strategy

7. MPWM IMPLEMENTATION

Of the various type of modulation technique, the PWM Implementation is chosen for its simplicity to be used with the SPMC circuit. DC output in rectifier is synthesized using the simple Multiple Pulse Width Modulation (MPWM).

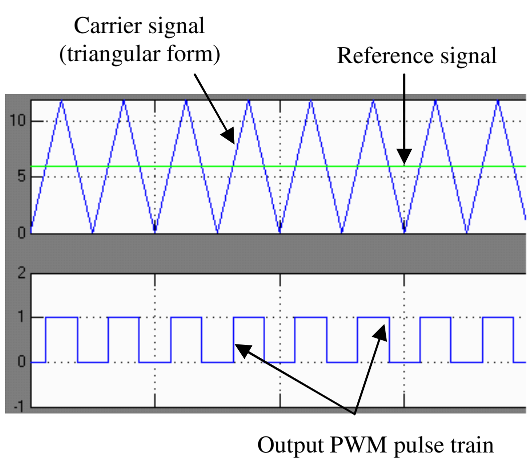

Figure 11: Sampling waveform of MPWM

8. CIRCUIT DIAGRAM OF SPMC IN MATLAB/SIMULINK

The following circuit is designed to act as an AC-DC single phase matrix converter as simulated in MATLAB/Simulink.

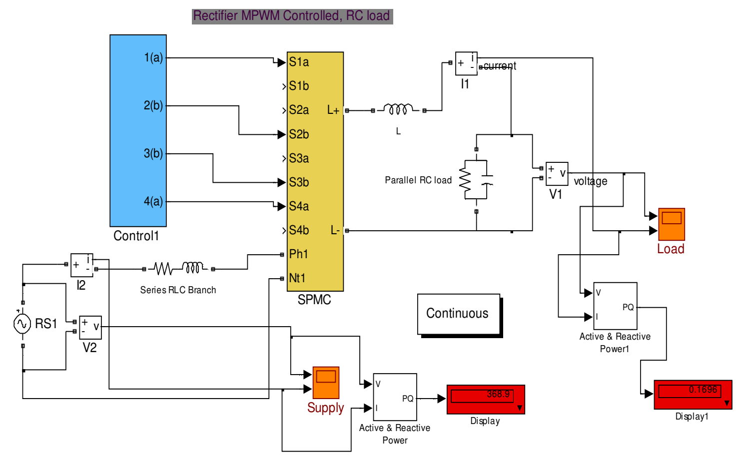

Figure 12: RC-load of SPMC as Rectifier

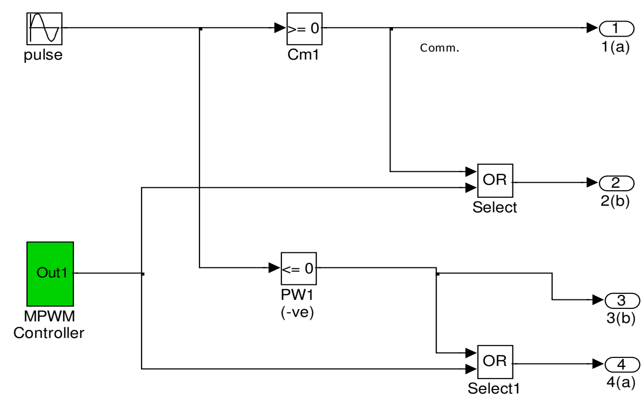

Figure 13: Controller in SPMC

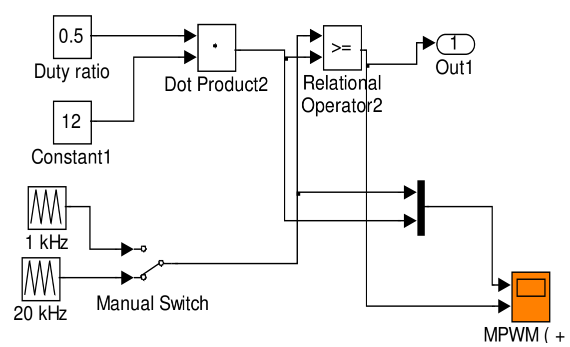

Figure 14: MPWM controller

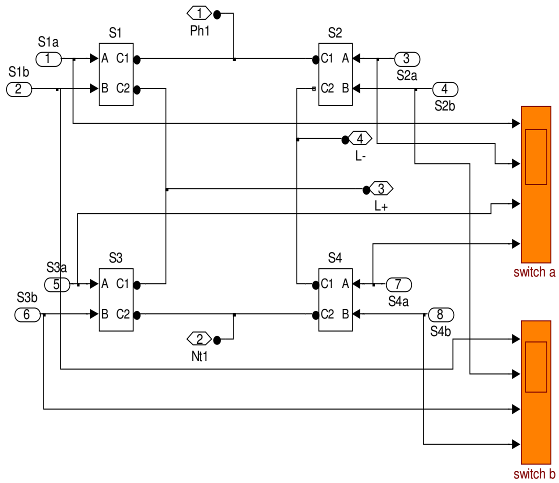

Figure 16: SPMC switches arrangement

9. RESULTS AND DISCUSSION

The single phase matrix converter is designed to convert AC to DC signal with the implementation of MPWM to synthesize the output. Losses in this circuit can be analyzed by simply follow the equation: $P_{losses} = P_{in} - P_{out}$. The following result has shown that by using RC-load as in Fig.19, losses can be reduced with respect to frequency increment. With the used of RL and R as the load, the losses showed an incremental value as tabulated in Fig.17 and Fig.18.

Frequency (kHz)	P_{in}	P_{out}	P_{losses}
1	53.56	0.8079	52.75
2	55.22	0.7453	54.47
3	56.06	0.7757	55.28
4	56.66	0.8404	55.82
5	56.7	0.8079	55.89
10	57.32	0.8472	56.47
12	57.45	0.8478	56.6
15	57.6	0.8423	56.76
17	57.73	0.8467	56.88
20	57.92	0.8538	57.07

Table 3: Losses in R-load implementation

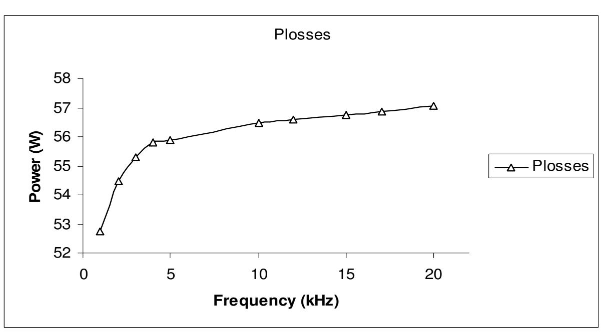

Figure 17: Graph for power losses in R load.

Frequency (kHz)	P_{in}	P_{out}	P_{losses}
1	26.09	0.4512	25.64
2	28.64	0.3656	28.27
3	29.83	0.3977	29.43
4	30.39	0.4135	29.98
5	30.64	0.3871	30.25
10	31.28	0.4082	30.87
12	31.41	0.4066	31
15	31.58	0.4005	31.18
17	31.69	0.4022	31.29
20	31.85	0.4049	31.45

Table 4: Losses in RL-load implementation

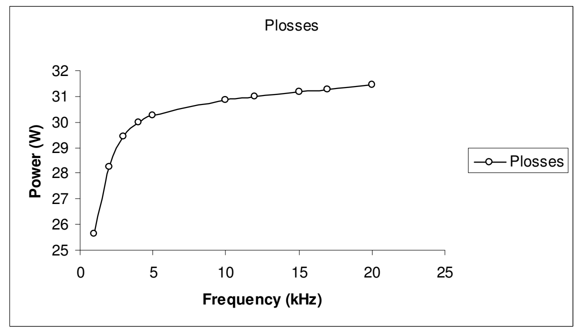

Figure 18: Graph for power losses in RL-load.

Frequency (kHz)	P_{in}	P_{out}	P_{losses}
1	121	0.9697	120.0303
2	111.6	0.5192	111.0808
3	103.7	0.5206	103.1794
4	96.76	0.5078	96.2522
5	89.96	0.388	89.572
10	68.75	0.2109	68.5391
12	63.27	0.1709	63.0991
15	56.96	0.131	56.829
17	53.56	0.1114	53.4486
20	49.49	0.0918	49.3982

Table 5: Losses in RC-load implementation

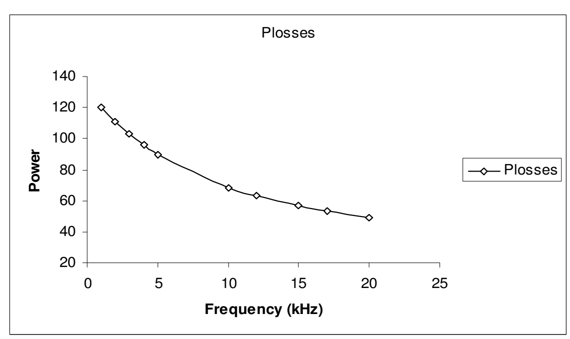

Figure 19: Graph for power losses in RC-load.

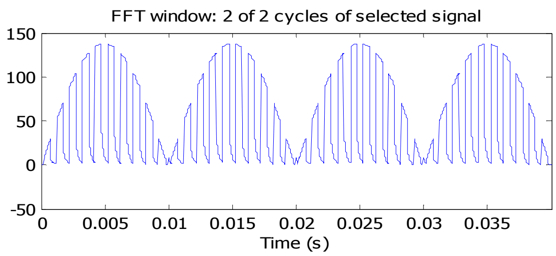

Figure 20: Output voltage at R-load at switching frequency of 1 kHz.

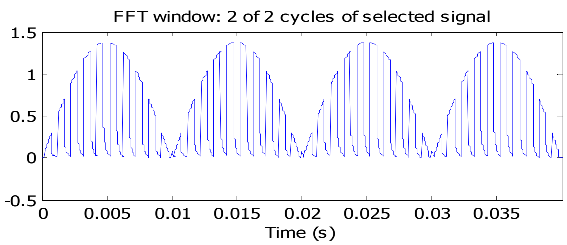

Figure 21: Output current at R-load at switching frequency of 1 kHz.

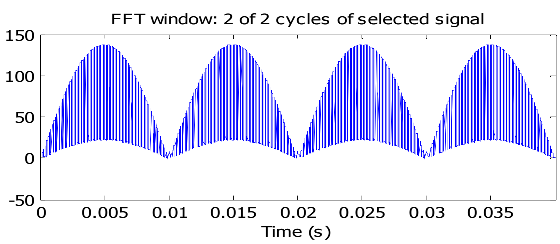

Figure 22: Output voltage at R-load at switching frequency of 20 kHz.

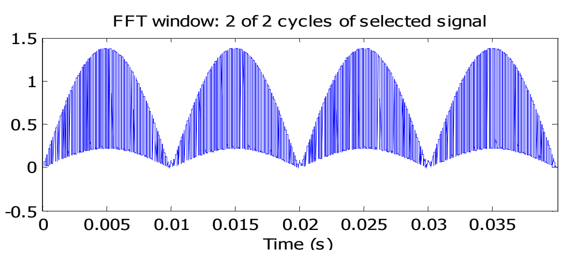

Figure 23: Output current at R-load at switching frequency of 20 kHz.

The output by using R-load in the circuit showed rectified waveform as illustrated in Fig.20 – Fig.23. The output waveform at 20 kHz demonstrated a full area of waveform because the use of the frequency is large. Compared to 1 kHz implementation, the waveform showed some gap. The larger the frequencies, the more the PWM waveform will oscillate and the smaller the gap thus provide a better output.

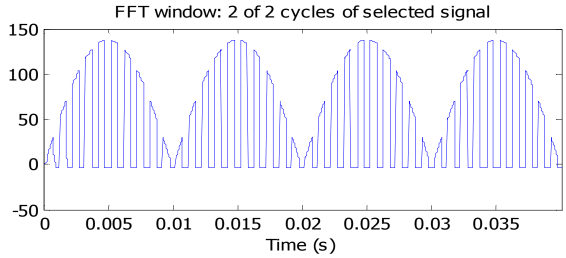

Figure 24: Output voltage at RL-load at switching frequency of 1 kHz.

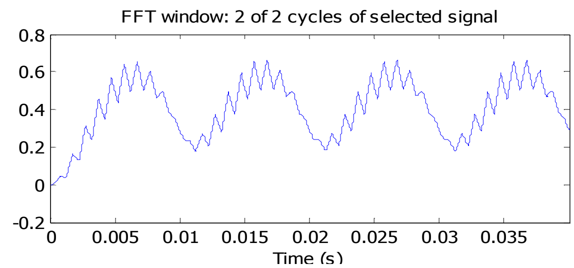

Figure 25: Output current at RL-load at switching frequency of 1 kHz.

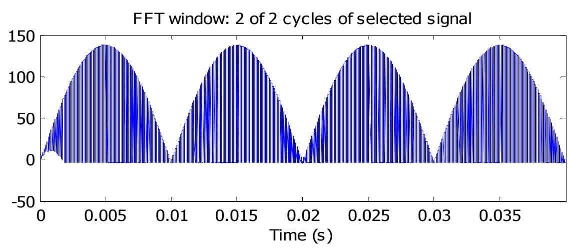

Figure 26: Output voltage at RL-load at switching frequency of 20 kHz.

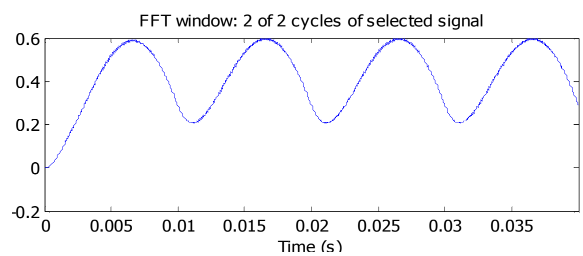

Figure 27: Output current at RL-load at switching frequency of 20 kHz.

The output voltage by using RL-load in the circuit showed full-wave rectified waveform as illustrated in Fig.24 – Fig.27. By introducing an inductor to the load, there were spikes presented, as in Fig.28, but the implementation of the commutation strategy has resulted in spike being eliminated. The output waveform of 20 kHz is smoother than the output waveform of 1 kHz because of the fast switching on-off thus caused the gap become smaller.

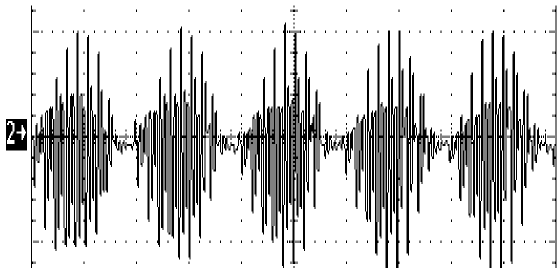

Figure 28: Output voltage of RL load without commutation

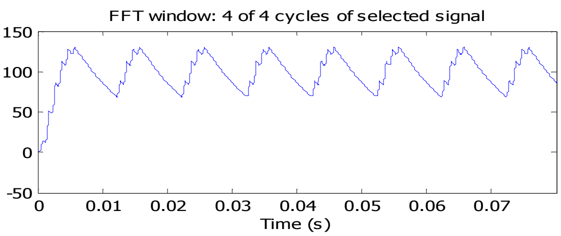

Figure 29: Output voltage at RC-load at switching frequency of 1 kHz.

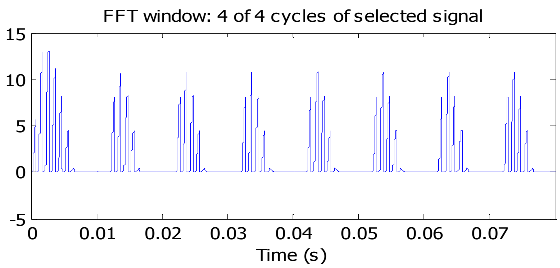

Figure 30: Output current at RC-load at switching frequency of 1 kHz.

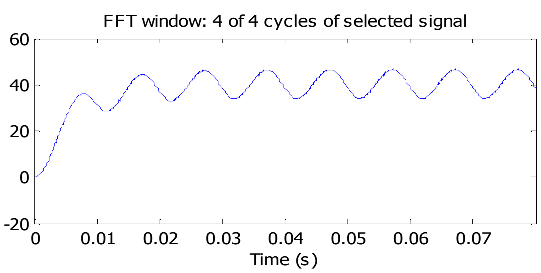

Figure 31: Output voltage at RC-load at switching frequency of 20 kHz.

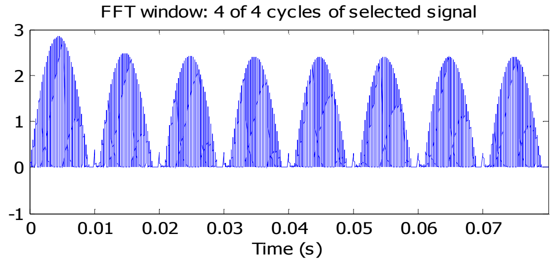

Figure 32: Output current at RC-load at switching frequency of 20 kHz.

The output voltage of RC-load in the circuit showed the ripple of the waveform tends to oscillate constantly at the certain value of voltage. By introducing a capacitor caused the change in voltage but not in current, the higher the frequency switching, the more PWM waveform will oscillate and caused the gap smaller. This is shown in Fig.29 – Fig.32 above.

10. CONCLUSIONS

The SPMC topology has been presented to operate as a controlled rectifier by suitable switching schemes, where IGBTs are used for the main power switching device. Inherent commutation problems that lead to switching spikes have been presented with safe commutation algorithm being proposed. Further simulations were carried-out to develop active current wave-shaping technique in order to ensure that the supply current waveform is continuous, sinusoidal and in phase with the supply voltage. Power losses were studied to indicate the differences using different load. Satisfactory results has been accomplished to indicate that the SPMC could be efficiently be used for controlled rectifier application. It can also be concluded that the amount of AC voltage mixed with the rectifier's DC output is called ripple voltage. in most cases, since "pure" DC is the desired goal, ripple voltage is undesirable. If the power levels are not too great, filtering network may be employed to reduce the amount of ripple in the output voltage. The output at RC-load due to frequency value of 20 kHz has shown an improved DC signal. By using R-load and RL-load, the output waveform of a DC signal can also be achieved but nevertheless, the losses seemed to increase. In the work presented, the SPMC proves to be a versatile topology that has been shown to operate as a controlled rectifier extending the capabilities beyond the direct AC-AC converter, inverter and four quadrant DC chopper operations.

11. REFERENCES

[1] Venturini M., “A New Sine Wave in Sine Wave Out, Conversion Technique Which Eliminates Reactive Elements,” Proceedings Powercon 7, pp.E3_1-E3_15, 1980.

[2] Gyugyi,L and Pelly,B.R, “Static Power Chargers, Theory, Performence and Application,“ John Wiley & Son Inc, 1976

[3] Zuckerberger, A.; Weinstock, D.; Alexandrovitz, A.; “Single Phase Matrix Converter’’, IEE Proc.Electric Power App, Vol.144(4), Jul 1997, pp235-240.

[4] Siti Zaliha Mohammad Noor, Mustafar Kamal Hamzah & Ahmad Farid Abidin, “Modelling and Simulation of a DC Chopper Using Single Phase Matrix Converter Topology” IEEE Sixth International Conference PEDS 2005, Kuala Lumpur, Malaysia.

[5] Zahiruddin Idris, Mustafar Kamal Hamzah & Ahmad Maliki Omar “Implementation of Single-Phase Matrix Converter as a Direct AC-AC Converter Synthesized Using Sinusoidal Pulse Width Modulation with Passive Load Condition”, IEEE Sixth International Conference PEDS 2005, Kuala Lumpur, Malaysia

[6] Ward Reid, “Power Quality Issues-Standards and Guidelines”, IEEE Pulp and Industry Technical Conference, Jun 1994.

[7] Squez, C. Aquilar, R. O. Caceres, I. Barbi and J. A. Gallegos, “A Novel Uninterruptible Power Supply System with Active Power Factor Correction,” IEEE Transaction on Power Electronics, Vol. 17, No. 3, May 2002.

[8] N. Burany, “Safe control of four-quadrant switches,” in *Conf. Rec. IEEE-IAS Annu Meeting*, 1989, pp. 1190–1194.