Simulation of AC/AC Converter using Single Phase Matrix Converter for Wave Energy Converter

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***Abstract*—Matrix converter applications in the power electronics field eliminate the common practice of reactive power storage in the system. Due to its universal converter applicability, the Single Phase Matrix Converter (SPMC) is among the most widely used matrix converter configurations. Operating as a universal converter means that the SPMC can be used as a frequency changer, an inverter, a rectifier, and a chopper. The SPMC topology consists of four bidirectional switches that allow reverse blocking and bidirectional current flow. This paper presents the implementation of SPMC as an AC/AC converter with passive load conditions. The output of SPMC is synthesized using the Sinusoidal Pulse Width Modulation (SPWM) technique to calculate the switch duty ratio. The modelling and simulation of SPMC are carried out using MATLAB/Simulink software, and the results are discussed. Further testing was conducted with the input generated from a point absorber wave energy converter simulated in ANSYS to validate the ability of the SPMC as an AC/AC converter model.**

Keywords—AC/AC converter, matrix converter, single phase matrix converter, power electronics converter, wave energy converter.

I. INTRODUCTION

Wave energy harvesting thrived, particularly for being clean, sustainable, and extracted from inexhaustible resources. Wave energy is harvested through a series of conversions starting from wave energy converter (WEC) devices responsible for extracting energy contained in the wave. This energy is then channeled through a power conversion system before reaching the grid. As a result, the WEC devices and their power conversion systems are interrelated.

In the early development of WEC systems, power conversion system were often studied separately [1]. As commercialization progressed, this integration became necessary. The WEC systems are often unique and designed to suit the prospective location of deployment. In addition, the energy harvested from renewable energy resources is typically weather dependent. As a result, the voltage amplitude and frequency generated from wave resources are usually unstable and vary continuously. Hence, a suitable power conversion system for the WEC output voltage and frequency is significant to match the load side requirements.

The advancement of semiconductors in high power applications is becoming significant, particularly for power converter applications [2]. Generally, power converters can be categorized into four types: AC/AC converters, AC/DC converters, DC/DC converters, and DC/AC converters. The type of power converters used in a system is determined by considering the conditions of the system where a suitable converter would be placed according to its applicability.

A complete WEC system combined with its power conversion system usually utilizes a combination of a wave harvesting device, a rotary type generator, an AC/DC converter, a DC link capacitor, or a DC/DC converter, followed by a DC/AC converter. The combination of AC/DC/AC converters used in these WEC research [3]–[22], is due to the fact that the generator used in most WEC devices is a rotary-type generator with a fixed output frequency. However, in a point absorber WEC system in which a linear generator is used, the energy produced can have a varying frequency. This is due to the nature of linear generator operation, which heaves upwards and downwards following the motion of ocean waves. Therefore, the application of an AC/AC converter in this case can help generate a stable output frequency for the WEC system.

Applications of AC/AC converter in the power electronics field eliminate the common practice in rectifier-inverter (AC/DC/AC) systems, which requires the installation of reactive power storage [23]. This practice is due to direct conversion from an AC input into an AC output through a combination of high-power switches controlled by a high-frequency modulation technique. Today, matrix converters and cycloconverters are among the most widely used AC/AC converters in industrial operations. The Single Phase Matrix Converter (SPMC) was first introduced by Zuckerberger [23]. The author was first motivated due to minimal converter applications and realized that SPMC could be implemented at high power traction. Later, SPMC is studied in terms of its potential as a universal converter [24]–[30]. As a universal converter, SPMC could be used as a frequency changer (AC/AC) [31]–[36], inverter (DC/AC) [37], rectifier (AC/DC) [38] or chopper (DC/DC) [39] with specific switching sequences.

This paper presents the implementation of the SPMC topology as an AC/AC converter with passive load conditions. The high-frequency switches responsible for controlling the on and off operation of the SPMC are IGBT switches. The output of SPMC is synthesized using the Sinusoidal Pulse Width Modulation (SPWM) technique. Commutation problems during switch turn off are addressed by pairing two switches with PWM switches when turned on at a certain time interval. This pairing will eliminate the remaining residual energy in the system, and the combination is documented in Table I and II, respectively. Further testing was conducted with the input generated from a point absorber WEC simulated in ANSYS to validate the ability of the SPMC AC/AC converter model.

II. METHODOLOGY

In this section, the overall methodology process involved in modelling SPMC are discussed theoretically, including the basic topology, modulation theory, commutation problems, switching strategies and application as an AC/AC converter before the simulation of SPMC are discussed.

A. Single Phase Matrix Converter

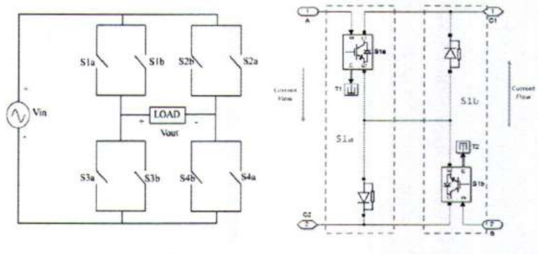
The SPMC topology in Fig. 1 consists of four pairs of bidirectional switches (IGBT) in a common emitter anti-parallel configuration. The relationship of SPMC input and output voltages are given by Equation (1), (2), and (3) with reference to [23]:

$$v_i(t) = \sqrt{2}v_i \sin \omega_i t \tag{1}$$

$$v_o(t) = \sqrt{2}v_o \sin \omega_o t \tag{2}$$

$$v_o(t) = Ri_o + L\frac{di_o}{dt} \tag{3}$$

Where i and o denotes the input and output, respectively.



(a) (b)

Fig. 1. (a) SPMC topology, and (b) Bidirectional switches in common emitter configuration.

B. The Modulation Technique and Commutation Solution

The SPWM technique is used in this work by synthesizing the output of SPMC. The principle operation of SPWM is by comparing a high frequency triangular signal with a low frequency sinusoidal reference signal, as in Fig. 2. The two states of comparison would define the high level and low level of the PWM output signal. When the triangular wave is lower than the sine wave, the PWM output signal would be high, or '1' and '0' would indicate as low when the triangular wave is higher than the sine wave. These switching edges would trigger at each intersection between the two signals. Each intersection between these two signals created a sequence of pulses that used to trigger the switching state, 'ON' and 'OFF', of the IGBTs, as illustrated in Fig. 2. Fig. 3 illustrates an example of the SPWM switching model used to control the operation of IGBTs in the SPMC topology.

Theoretically, the switching of IGBTs occurs instantaneously. However, the inductive load will create a short circuit through the collector current due to the inductor characteristics and bidirectional switch configuration during IGBT turn off [31], [32]. To overcome this problem, a sequence of switching is introduced to pair with SPWM switching. This sequence would introduce a delay, *td*, enough for any residual energy to dissipate from the system before the next IGBT are turn on, thus solving the commutation problem. A recommendation of commutation strategies is shown in Fig. 4 with reference to data tabulated in Table I and Table II.

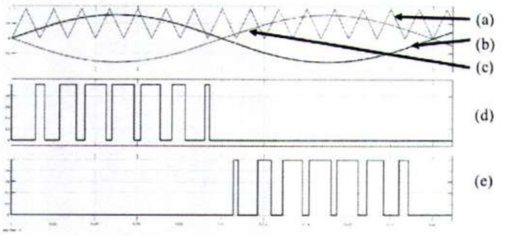


Fig. 2. The SPWM switching principle; (a) triangular signal, (b) reference signal 1, (c) reference signal 2, (d) SPWM output signal for reference signal 1, and (e) SPWM output signal for reference signal 2.

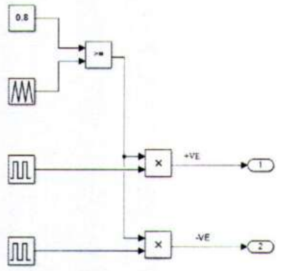


Fig. 3. Example of PWM generator for SPMC switching.

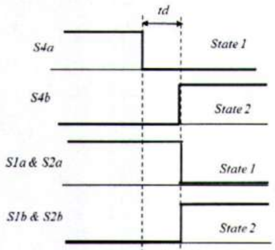
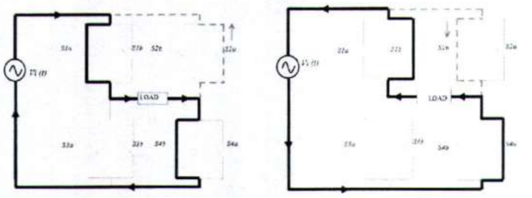


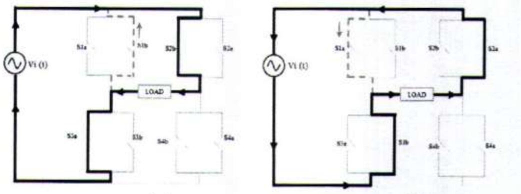
Fig. 4. Commutation strategies timing recommendation.

C. SPMC Switching Strategies and Commutation Solution

An example of a switching state of each switch for AC input is illustrated in Fig. 5. These switching states determine the directions of current flow in every interval with reference to the synthesized output. The switching pattern of one cycle, as tabulated in Table I, is shown in Fig. 6. The bidirectional switches allow both directional currents to flow during the negative cycle, as illustrated in Fig. 5(b) and Fig. 5(d). Details of these switching rules could be found in [40].



(a) (b)



(c) (d)

Fig. 5. Examples of IGBT switching state when receiving AC input, (a) State 1 in positive cycle, (b) State 2 in negative cycle of AC input, (c) State 3 in positive cycle and (d) State 4 in negative cycle of AC input.

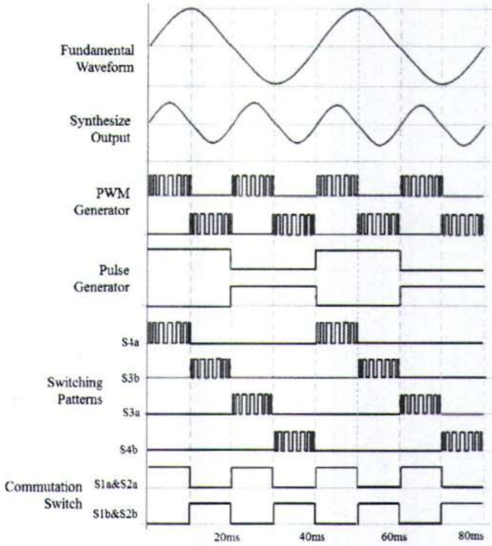


Fig. 6. Switching pattern for 100 Hz AC/AC converter.

TABLE I. SEQUENCE OF SWITCHING CONTROL FOR SPMC OPERATING AS AN AC/AC CONVERTER

Input Freq.	Output Freq.	Time Interval	State	PWM Switch	Commutation Switch
50	25	1	1	S4a	S1a & S2a
		2	4	S3a	S2a & S1a
		3	3	S3b	S2b & S1b
		4	2	S4b	S1b & S2b
	50	1	1	S4a	S1a & S2a
		2	2	S4b	S1b & S2b
	100	1	1	S4a	S1a & S2a
		2	3	S3b	S2b & S1b
		3	4	S3a	S2a & S1a
		4	2	S4b	S1b & S2b
	150	1	1	S4a	S1a & S2a
		2	3	S3b	S2b & S1b
		3	1	S4a	S1a & S2a
		4	2	S4b	S1b & S2b
		5	4	S3a	S2a & S1a
		6	2	S4b	S1b & S2b

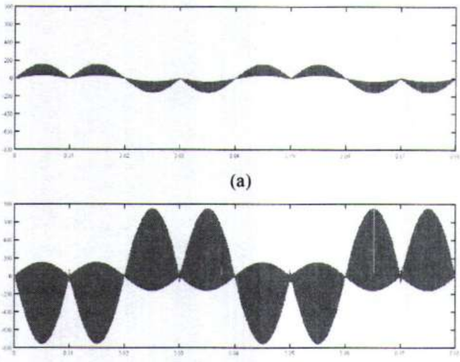
III. RESULT AND DISCUSSION

Several output frequencies are evaluated with reference to Table I in order to determine the SPMC's suitability as a frequency changer. The following parameters are used in the Matlab/Simulink software for all simulations;

TABLE II. SPMC SIMULATED PARAMETERS

Input voltage	110 Vrms
Load	R=100 Ω and L=4 mH
Modulation Index, ma	0.8
Switching Frequency, fs	15 kHz

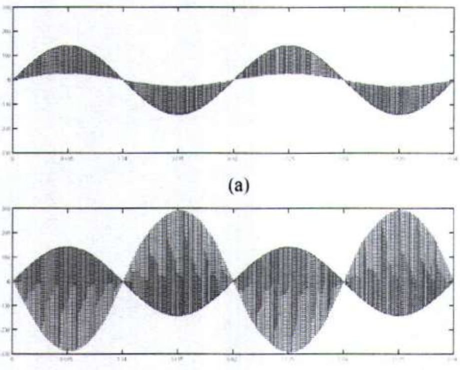
Fig. 9 to 12 exhibit SPMC simulation models and related findings when simulated as an AC/AC converter.



(a)

(b)

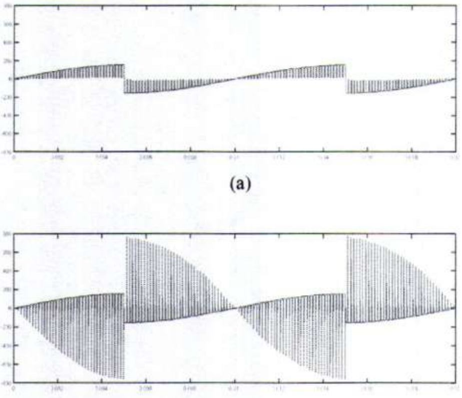
Fig. 9. Simulation results of SPMC at 25 Hz, (a) R & (b) RL load.



(a)

(b)

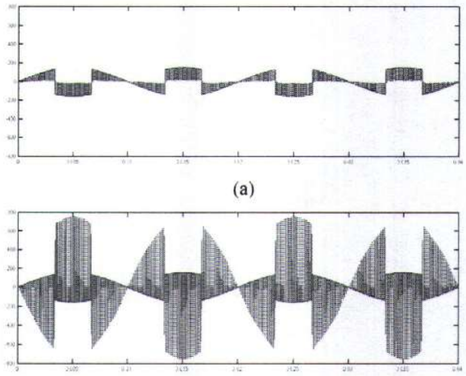
Fig. 10. Simulation results of SPMC at 50 Hz, (a) R & (b) RL load.



(a)

(b)

Fig. 11. Simulation results of SPMC at 100 Hz, (a) R & (b) RL load.



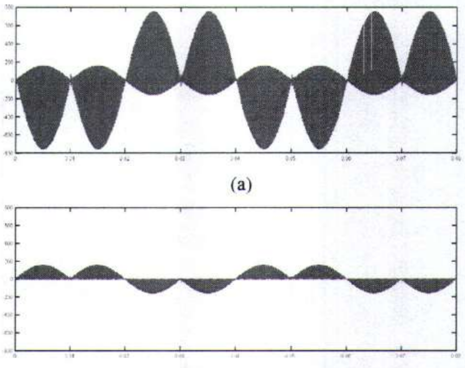
(a)

(b)

Fig. 12. Simulation results of SPMC at 150 Hz, (a) R & (b) RL load.

When RL load is employed instead of R load, the evidence of residual energy existence in the system can be seen in Fig. 9 to 12. Therefore, the commutation schemes will ensure that any remaining energy in the inductor is removed before the next switch is activated. This is used in practice to safeguard the system against spikes and inrush current development.

The commutation approach is implemented by inserting a delay, td, which is about 97μs in [40]. This will provide the IGBT ample time to completely turn off before conducting current in the forward state for the following sequence, as shown in Fig. 4. Fig. 13 shows the simulation results of SPMC with commutation techniques for 25 Hz with RL load.

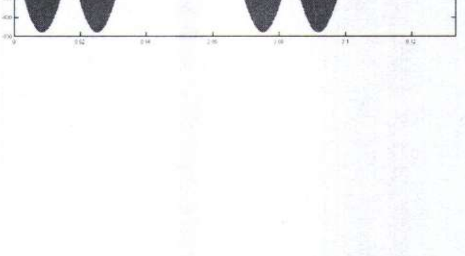


(a)

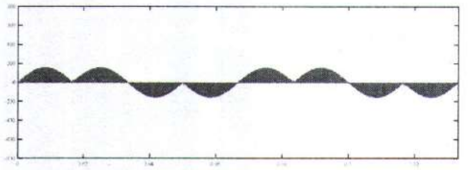
(b)

Fig. 13. SPMC outputs for RL load at 25 Hz, (a) without & (b) with commutation strategy.

Further testing was done with the commutation strategy to test for varied input signal values. Fig. 14 shows the simulation results of a 30 Hz input signal to a 15 Hz output. This experiment was carried out to demonstrate that SPMC could deal with a wide range of input signals.



(a)



(b)

Fig. 14. SPMC outputs for RL load at 15 Hz, (a) without commutation strategy and (b) with commutation strategy.

To validate the model, testing was done with the input generated from a point absorber WEC simulated in ANSYS software published in [41]. The induced voltage generated from the point absorber WEC is the slotted design in the kV range, which have the output frequency of approximately of 6.67 Hz. Therefore, for the purpose of comparison, a 150 V sine wave with input frequency of 6.67 Hz and output frequency of 50 Hz is generated as in Fig. 15. With reference to Fig. 16, this input data is then fed into the model by using a signal builder block available in Matlab/Simulink. The signal builder block will allow the excel formatted data to be imported into Matlab/Simulink in a signal form. This amplitude of this signal is then scaled down to 1/10 of the original output block and then fed into a controlled voltage source as the input source for the converter. The output of the AC/AC converter from the WEC signal is displayed in Fig.17. From Fig.17, the output of the AC/AC converter is proven able to generate an acceptable output based on the input given and, in this case, the induced voltage generated from the point absorber WEC simulation.

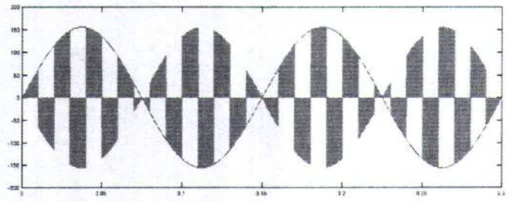


Fig. 15. The AC/AC converter input and output voltages using SPMC for input frequency of 6.67 Hz to 50 Hz output frequency.

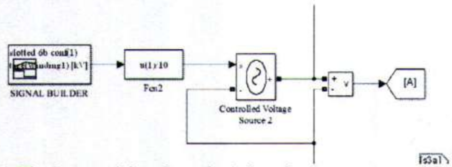


Fig. 16. The imported data from the induced voltage generated from the point absorber WEC.

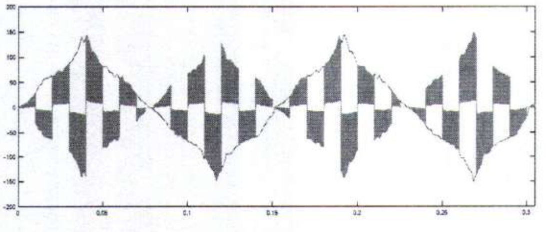


Fig. 17. The input and output voltages of the AC/AC converter for the point absorber WEC are of the slotted design as in [20].

Fig. 18 displays the plot for Iout versus time. By Equation (2) and (3), considering the initial load conditions where R is kept constant at 100 Ω and the value of L is gradually increased from L = 0 H, L = 100 mH, L = 400 mH, L = 1 mH, L = 4mH, to L = 1 H. L values are being varied to show that passive element have an impact on the overall system. From Fig. 18, this system is suitable for an L range of between 1 and 4 mH before the system starts to be unstable.

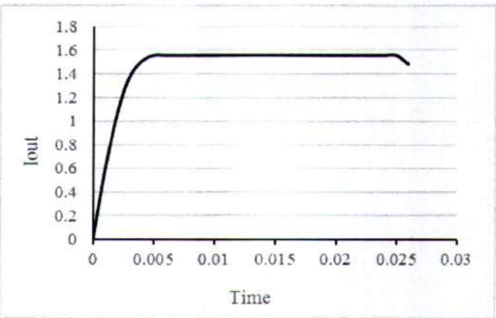


Fig. 18 Plot for Iout versus time

IV. CONCLUSION

An AC/AC converter using SPMC topology was demonstrated in this paper for both R and RL loads. The output signals were changed to 25 Hz, 50 Hz, 100 Hz, and 150 Hz for additional testing. The findings demonstrate that realizing SPMC as a universal converter is possible. In comparison to the system without the commutation strategy, a safe commutation approach was tested for a 25 Hz RL load and showed that residual energy and spikes at the output signals were eliminated. To demonstrate that this converter may be utilized for other input frequencies, a 30 Hz input signal was used as the SPMC input signal. The model was validated with the input generated from a point absorber WEC model simulated in ANSYS. The outputs from the SPMC AC/AC converter showed acceptable results, thus proving the converter's versatility. However, a wide variety of input frequencies and voltage amplitudes can be expected when using the SPMC for AC/AC converter for wave energy converter applications. The usage of a linear generator to harvest wave energy in upward and downward heaving action, for example, will collect a diverse set of data that may be unstable and change over time. Although SPMC's AC/AC converter capability has been demonstrated for a variety of input signals, current research is limited to a single input frequency. By using this system, for a multiple frequency input signal, the output is not acceptable due to the PWM signal setting being required to be adjusted for every frequency according to the specified output. Further research should investigate a control system that allows the SPMC for AC/AC converter to take a variety of input signals suited for wave energy harvesting, particularly when a linear generator is utilized in the upward and downward heaving motions or other comparable simulations.

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