Computer simulation model of multi-input multi-output converter using single-phase matrix converter

Mohd Shukri bin Mohd Ghazali[1], Rahimi Bin Baharom[1], Khairul Safuan Bin Muhammad[1], Dylan Dah-Chuan Lu[2]
[1]School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia
[2]School of Electrical and Data Engineering, University of Technology Sydney, Ultimo, Australia

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ABSTRACT

This paper presents a multi-input, multi-output power converter system using a single-phase matrix converter (SPMC) circuit topology. In particular, this technology is of vital importance in floating production such as offshore oil and gas platforms where space is crucial, therefore requiring a reduction in equipment size and weight. The proposed circuit topology only employed a single circuit to perform energy conversion of direct current (DC) to alternating current (AC), DC to DC, AC to DC, and AC to AC operations, thus can reduce the power losses resulting in high power density. As a result, it can promise technological advancement and convergence, hence, support the manufacturing sector transition to industry 4.0, and in line with the United Nation's sustainable development goals. The proposed converter model will be validated in terms of electrical circuit operations through the computer simulation (MATLAB/Simulink) software.

Corresponding Author:

Rahimi Baharom
Power Electronics Research Group (PERG), School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA
Jalan Ilmu 1/1, 40450 Shah Alam, Selangor Darul Ehsan Malaysia
Email: rahimi6579@gmail.com

1. INTRODUCTION

The rapidly evolving global manufacturing landscape calls because of the excellent quality and reliability of the power supply. Industrial applications require that voltage supplied to electrical loads maintain good regulation capability while being cheaper and efficient [1]. It is estimated that 90% of electrical energy is processed through power converters before their final use [2]. This trend reflects the increased use of power electronic converters systems for supplying loads with clean and dependable power [3]–[5]. The increased power density of converters is the current trend in power electronics, particularly for applications in information technology, where fast advancements in integrated circuit technology have resulted in more compact devices with higher power consumption [6]. Multiple-input converters have high regard for multiple renewable energy sources used in smart grid systems, especially for distributed generators as explained in [7] and define as a type of device that has been proposed to give simple circuit topologies, low manufacturing cost, high reliability, centralized control, and small size [8], [9]. Researches in [10]–[13] has introduced the systematic techniques for creating and synthesizing multi-input converters (MICs) that are configured with dc voltage sources at their input ports to accommodate energy sources such as solar panels photovoltaic (PV) and wind turbines. The output of the existing MICs has been controlled to produce either AC or DC and has been classified as direct current (DC) to alternating current (AC) MICs and DC–DC MICs.

The invented DC–DC MICs as developed in [14]–[17] consists of three multi-input. These converters' architectures are based on DC boost converters, and have several advantages such as reducing circuit complexities and fewer power switches used. Another structure of multi-input DC–DC converters that has been presented in [18] uses the combination of DC-link voltages with the magnetic coupling of the half-bridge boost circuit. Hybrid DC–DC converters have been introduced in [19], [20], with the decoupling method control strategies to separately compensate the cross-coupled control loops. A systematic approach is proposed in [21] for the derivation of non-isolated three-port converter topologies. For high step-up applications, a three-input DC–DC converter incorporating battery powers and PV is proposed in [22].

Despite the successful development of MICs, several limitations remain. The typical multiple-input multiple-output (MIMO) converter utilizing four separate circuits topology and four separate microcontrollers to perform AC to DC, DC to AC, DC to AC, and AC to AC converters that will increase size, power loss, and complexity of the circuit, thus, do not in line with the current trend of converter development. To address these limitations, a novel MIMO converter with a single control circuit has been proposed. A novel MIMO converter circuit topology is introduced in this work to integrated the switching algorithms of the MIMO power converter system based on the single-phase matrix converter (SPMC) topology. The proposed topology features power density and reliability improvement, thus reducing the complexities of the circuit. This new circuit then will be validated in terms of electrical circuit operations through the computer (MATLAB/Simulink) simulation model.

The SPMC has been classified as a fully controllable converter topology. The circuit topology as shown in Figure 1 employed four bidirectional switches as illustrated in Figure 2 that have the capability to conduct current to flows in both directions. With suitable toggling of the matrix switches, the output voltage waveform can be formed, as long as the switches do not open the circuit of the current sources or short circuit the voltage sources.

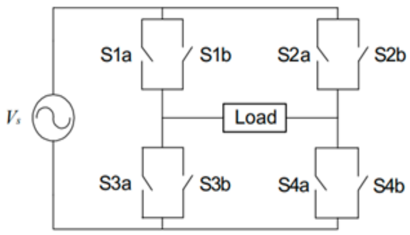

Figure 1. SPMC circuit topology

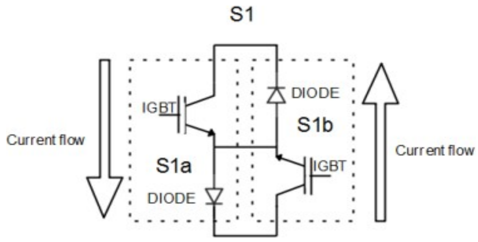

Figure 2. Bidirectional matrix converter switch

2. THE PROPOSED METHOD

The typical MIMO converter utilizing at least four separate circuits topology such as DC to DC, AC to DC, DC to AC, and AC to AC power converters. Apart from using the separate circuits, the typical DC chopper (DC to DC converter) also could not perform regulation of DC machines in four quadrants operations and would require the additional circuit to fulfill such control requirement. The use of separate circuit topologies for MIMO converter can contribute to very excessive power losses that may be linked to inefficiency problems. As a result, this could lead to a lower power density, thus, it is not in line with the power electronic converters technological roadmap that focuses on reducing the power losses, size, and volume. In this paper, the SPMC circuit is the heart or the creation of the proposed MIMO power converter system and focuses on the workability of the MIMO power converter system while switching losses and efficiency of the proposed topology will be discussed in future work. The proposed MIMO converter as shown in Figure 3 is valid for both AC and DC supplies and can be converted to either AC or DC with a single SPMC control circuit. A single circuit can perform all the power converter functions of the AC controller, DC chopper, inverter, and rectifier using a suitable controller and integrating the switching algorithm as tabulated in Table 1. In addition, the use of the proposed MIMO converter circuit can solve the limitation of a typical DC chopper circuit to regulate the DC machines in four quadrants operations without any additional circuits. The proposed MIMO power converter system features low power losses resulting in high power density. Thus, it promises technological advancement and convergence; hence, it is possible to support the manufacturing sector transition to industry 4.0 and the United Nation's sustainable development goals.

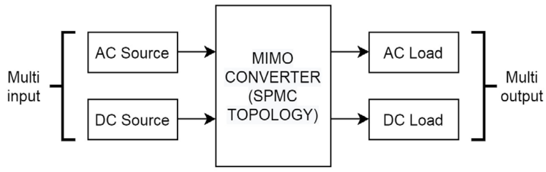

Figure 3. The proposed MIMO converter

Table 1. SPMC switching combination for different converter operation

Converter	PWM Switch	SPWM Switch	Commutation switch
Rectifier	S1a		S4a, S3b
	S3b		S2b, S1a
Inverter		S4a	S1a, S2b
		S3a	S1b, S2a
AC Regulator 12.5 Hz		S3a, S3b,	S1a, S1b
		S4a, S4b	S2a, S2b
AC Regulator 25 Hz		S3a, S3b,	S1a, S1b
		S4a, S4b	S2a, S2b
AC Regulator 50 Hz		S4a, S4b	S1a, S1b
			S2a, S2b
AC Regulator 100 Hz		S3a, S3b,	S1a, S1b
		S4a, S4b	S2a, S2b
AC Regulator 150 Hz		S3a, S3b,	S1a, S1b
		S4a, S4b	S2a, S2b
DC Chopper Q1	S4a		S1a, S2b
DC Chopper Q2	S3a		S1b, S4b
DC Chopper Q3	S3a		S1b, S2a
DC Chopper Q4	S4a		S2b, S3b

3. RESEARCH METHOD

In this paper, the MATLAB/Simulink software is used to design and develop the computer simulation model for the proposed MIMO power converter based on the parameters as tabulated in Table 2. The proposed computer simulation model consists of four main parts such as the controller and the SPMC topology circuits. This simulation model was used to construct all MIMO power converters discussed in this paper.

Table 2. Simulation parameters

Parameter	Value
Load (ohms)	50
Input voltage (V peak)	100
Input frequency (Hz)	50
Output frequency (Hz)	15, 25, 100, 150
Switching frequency (KHz)	5
Inductor (mH)	5

3.1. Controller model

The controller model is developed for the pulse width modulation (PWM) and the sinusoidal pulse width modulation (SPWM) signals. A high-frequency triangular carrier wave is compared to the desired reference waveform to create the PWM signal as shown in Figure 4. In this work, the 0.5 modulation signal is used to synthesize the output. A carrier signal is contrasted with a reference sinusoidal waveform to create the SPWM signal. For contrast, a triangular carrier wave with a pre-determined switching frequency was used. In this work, a reference sinusoidal signal of 0.9 sin (100 πt) is used to compare with the 5 kHz triangular carrier signal as shown in Figure 5.

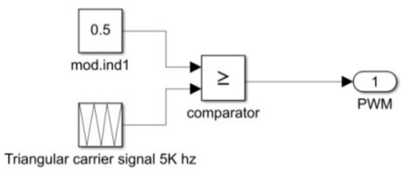

Figure 4. Simulation model of PWM signal

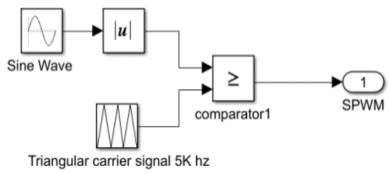

Figure 5. Simulation model of SPWM signal

3.2. Single-phase matrix converter topology circuit model

The SPMC circuit is developed by using four bidirectional switches; S1, S2, S3, and S4 as shown in Figure 6. These bidirectional switches are capable of conducting current in both directions. Each bidirectional switch used an insulated gate bipolar transistor (IGBT) with diode pairs which are connected in the common-emitter configuration as shown in Figure 7.

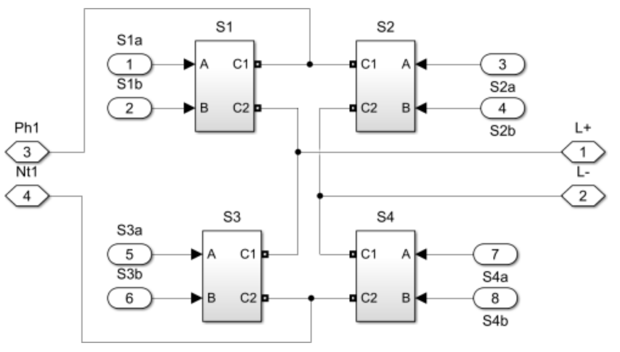

Figure 6. Simulation model for SPMC topology

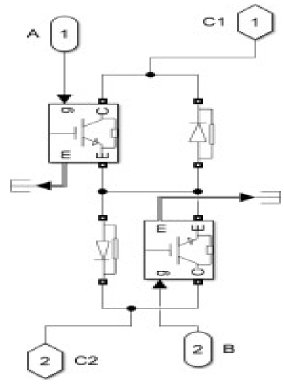

Figure 7. Bidirectional matrix converter switch

Figure 8 shows the simulation model for the SPMC circuit with the controller circuit. Figure 9 shows the details of the controller circuit construction for the rectifier operation. Based on Figure 9, the positive cycle is indicated by number 1 at the phase detector block set. The generated PWM signal is connected to the switch S1a, while the pair of switches S4a and S3b are maintained turned ON for the safe commutation switches. The negative cycle signal is indicated by number 2 at the phase detector block set. It is then multiplied with the generated PWM signal to control the switch of S3b. At this time, the pair of switches S2b and S1a are kept turned ON for the safe commutation switches.

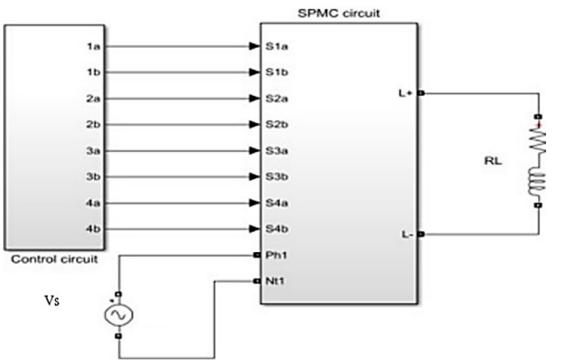

Figure 8. Simulation model of SPMC

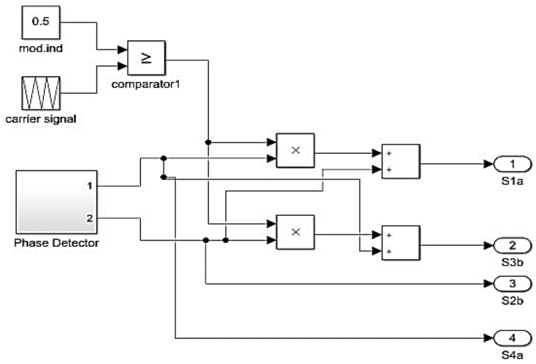

Figure 9. Controller circuit of rectifier with the controller circuit

The simulation model for the controller circuit of the inverter is as shown in Figure 10. The SPWM signal is used to control the switch S4a for the positive cycle operation. To apply the safe commutation technique, two switches, S1a and S2b, are turned ON to dissipate inductive energy when switch S4a is turned OFF. For negative cycle operation, the switch S3a is controlled by the SPWM signal, while the pair of switches S1b and S2a are turned ON for the safe commutation approach.

Figures 11 and 12 show the block diagram of the controller circuits describing the SPMC as an AC regulator. Based on Figure 7 during state 1, switches S1a and S2b are kept turned ON, while the SPWM signal controls the switch S4a. To change the frequency of the proposed AC regulator's output, the period of pulse generator 1 and pulse generator 3 are set to 0.08 s to produce a 12.5 Hz signal frequency. For pulse generator 2, the period is set to 0.02 s to produce the 50 Hz signal frequency. The AC regulator of 25 HZ, 100 Hz, and 150 HZ was simulated using the same circuit but different in period used for pulse generator 1 and pulse generator 3 as shown in Table 3. Figure 13 shows the control circuit for the DC chopper for quadrant 1 (Q1), the pair of switches S1a and S2b are maintained turned ON while the switch S4a is controlled by the PWM signal. Table 1 shows the switching algorithms for the computer simulation model of quadrant 1 (Q1) to quadrant 4 (Q4) operations.

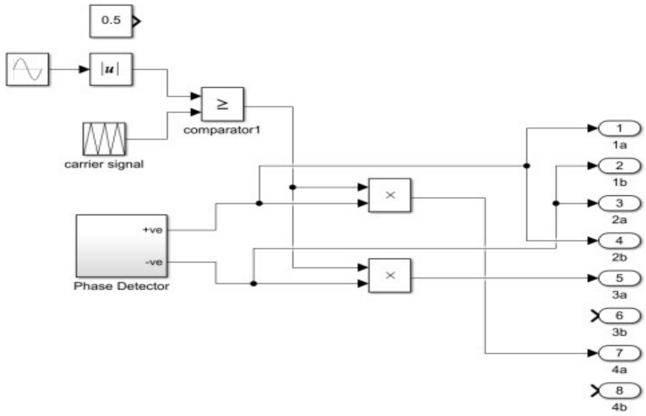

Figure 10. Controller circuit of inverter

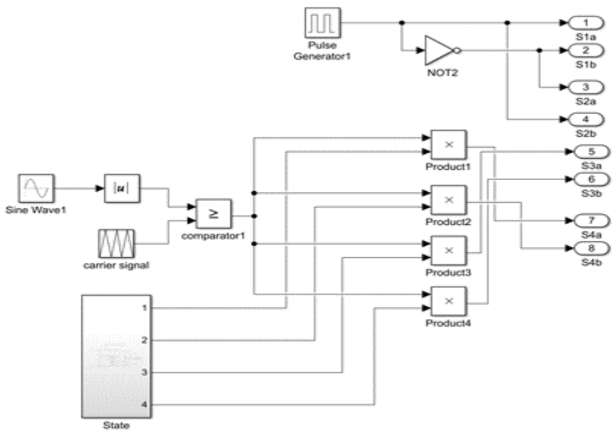

Figure 11. Control circuit AC regulator 12.5 HZ

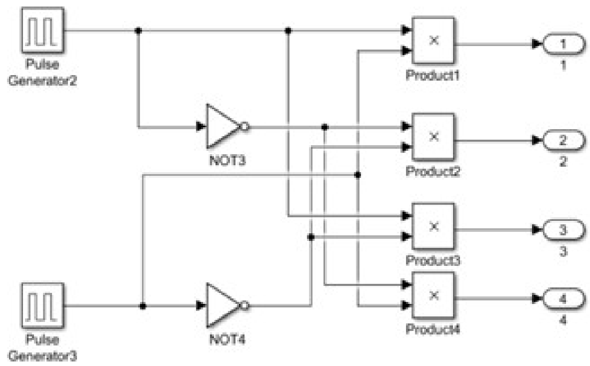

Figure 12. State circuit AC regulator 12.5 HZ

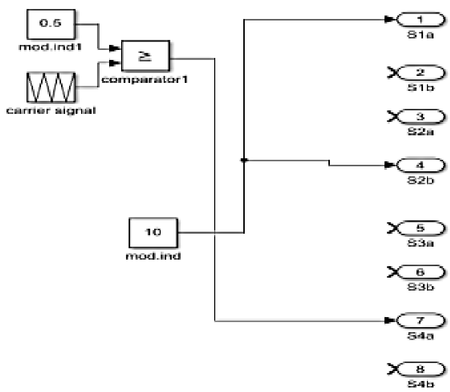

Figure 13. Control circuit for DC chopper for Q1

Table 3. The period for pulse generator 1 and 3

Output frequency (Hz)	Period pulse generator 1 and 3 (s)
12.5	0.08
25	0.04
100	0.01
150	0.0067

4. RESULTS AND DISCUSSION

Figures 14 and 15 demonstrate the conversion of the voltage waveforms obtained from the input AC voltage to the output DC form. There are no output voltage spikes, thus verify that the rectifier operation was successfully performed using the proposed circuit topology with the safe commutation strategy. The input and output voltage waveforms for the inverter operation are shown in Figures 16 and 17 respectively. Figure 16 shows the input voltage in DC form, which was successfully converted to the AC form in a square shape using the proposed converter as shown in Figure 17.

The results of the AC to AC conversion operation are shown in Figures 18 to 22 in terms of conversion from the input frequency of 50 Hz to the output frequencies of 12.5 Hz, 25 Hz, 50 Hz, 100 Hz, and 150 Hz. The inductive load spikes were successfully removed using the proposed safe commutation technique, confirming the workability and efficiency of the proposed safe commutation technique. The results for the operation of the four-quadrant DC chopper are presented in Figures 23 to 30. The load voltage and current waveforms in Figures 23 and 24 are in the positive polarized. Therefore, the proposed converter has been successfully performing the DC Chopper operation to fulfill the Q1 operation as mentioned in Table 1.

The operation of DC Chopper for Q2 has been successfully implemented as shown in Figures 25 and 26, where the output voltage is in the positive polarity, while the output current is in the negative polarity. The output voltage and current waveforms as shown in Figures 27 and 28 are both in the negative polarities, indicating that the proposed converter successfully conducted the DC Chopper operation for Q3. Figure 29 shows the output voltage waveform in negative polarity, while Figure 30 shows the output current waveform is in the positive polarity. These characteristics verify that the proposed converter has successfully performed the operation of DC Chopper for the Q4.

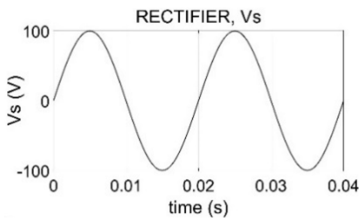

Figure 14. Supply voltage for rectifier

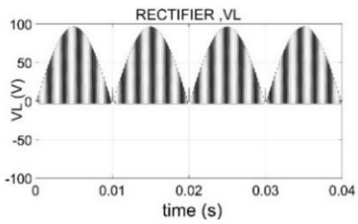

Figure 15. Load voltage for rectifier

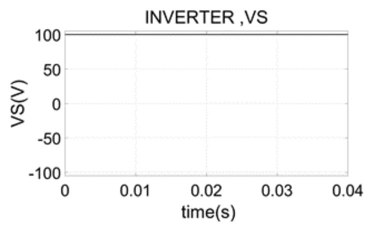

Figure 16. Supply voltage for inverter

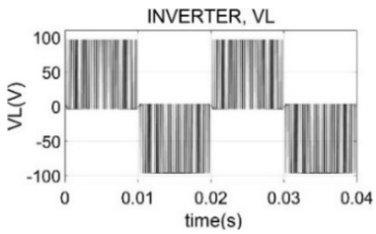

Figure 17. Load voltage for inverter

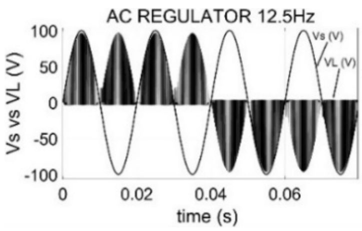

Figure 18. Supply vs load voltage for 12.5 Hz

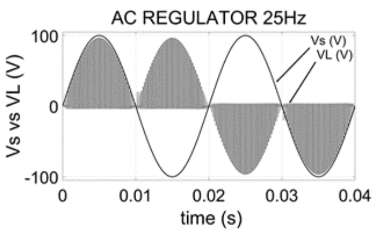

Figure 19. Supply vs load voltage for 25 Hz

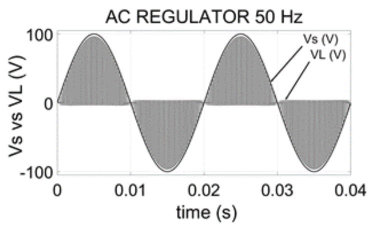

Figure 20. Supply vs load voltage for 50 Hz

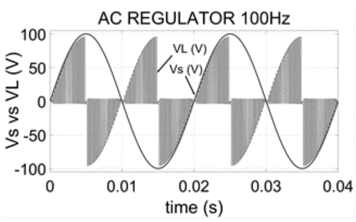

Figure 21. Supply vs load voltage for 100 Hz

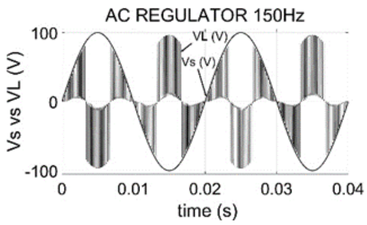

Figure 22. Supply vs load voltage for 150 Hz

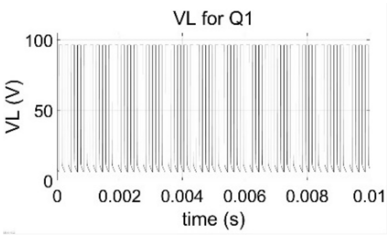

Figure 23. Load voltage for Q1 DC chopper

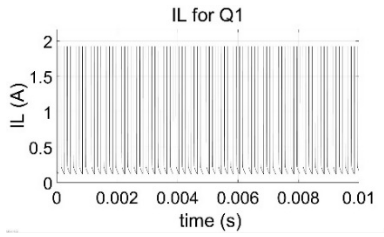

Figure 24. Load current for Q1 DC chopper

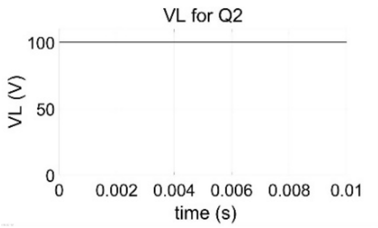

Figure 25. Output voltage for Q2 DC chopper

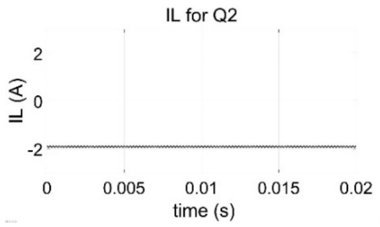

Figure 26. Output current for Q2 DC chopper

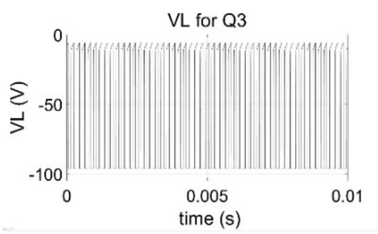

Figure 27. Output voltage for Q3 DC chopper

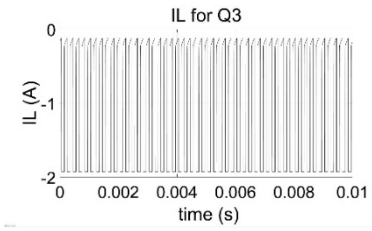

Figure 28. Output current for Q3 DC chopper

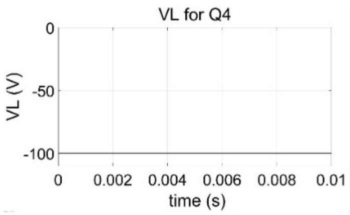

Figure 29. Output voltage for Q4 DC chopper

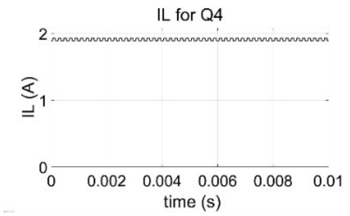

Figure 30. Output current for Q4 DC chopper

Based on the results from the computer simulation model, it has been verified that the proposed MIMO converter can be used to operate all four power converter which is as a direct AC-AC converter [23], DC chopper [24], rectifier [25], and inverter [26] operations. The output waveforms have been synthesized using the PWM or SPWM signals. Therefore, the proposed MIMO power converter can allow users to have selection input and loads either in AC or DC forms. The use of a single circuit topology to execute MIMO converters instead of at least four separate circuits to perform the AC regulator, DC chopper, rectifier, and inverter will result in lower electronic component usage and lower power losses, thus, resulting in higher power density. This is in line with the current trend in the power electronics converter roadmap to increase the converter power density, especially for information technology (IT) applications, where rapid advancements in integrated circuit technology have resulted in more compact systems with higher power consumption. As a result, these recent improvements can be seen as a solid base for potential improvements of power electronic converters system and in-line with the strategic thrusts 1 and 2 of shared prosperity vision 2030 to increased contribution of high technology subsector to the manufacturing sector [27].

5. CONCLUSION

This paper outlined and illustrated that the proposed MIMO power converter can operate as a rectifier, inverter, DC chopper, and AC regulator. The proposed safe commutation strategy was successful in eliminating the current spikes, indicating its practicality and effectiveness. Compared to the typical MIMO power converter, the proposed MIMO power converter systems feature reduced size, weight, cost, and efficiency improvements. This could lead to the increased of the power converter density that is in line with the current power converter trend and very helpful to the application of space constraints such as electric vehicles, oil, and gas offshore platforms. For future recommendations, the validation for this circuit should be done through the experimental test rig. As a suggestion to increase power density for MIMO power converter, future development should be developed with a single circuit and a single microcontroller to reduce the electronic component usage, size, cost, volume, and power loss of the converter.

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BIOGRAPHIES OF AUTHORS

Mohd Shukri bin Mohd Ghazali is a lecturer in Electrical Engineering Department at Politeknik Sultan Mizan Zainal Abidin, Terengganu, Malaysia. He received his degree in Electrical Engineering (Mechathronics) from Universiti Teknologi Malaysia in 2010. He has been a student M.Eng. in power electronics, from Universiti Teknologi MARA in 2020 until now. His research interests include the field of power electronics, single-phase matrix converter, and microcontroller applications. He can be contacted at email: shukri.projek@gmail.com.

Rahimi Bin Baharom is a lecturer in School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Malaysia since 2009; and He has been a senior lecturer since 2014. He received the B.Eng. degree in electrical engineering and the M.Eng. degree in power electronics, both from Universiti Teknologi MARA, Malaysia, in 2003 and 2008, respectively; and Ph.D. degree in power electronics also from Universiti Teknologi MARA, Malaysia in 2018. He is a senior member of IEEE and also a corporate member of the Board of Engineers Malaysia and the member of Malaysia Board of Technologists. His research interests include the field of power electronics, motor drives, industrial applications, and industrial electronics. He can be contacted at email: rahimi6579@gmail.com.

Khairul Safuan Bin Muhammad was born in Kuala Lumpur, Malaysia, in 1977. He received the B.Eng. (Hons.) degree in electrical engineering and the M.Sc. degree in power electronics from the Universiti Teknologi MARA, Shah Alam, Malaysia, in 2003 and 2007, respectively. He is also currently with the Faculty of Electrical Engineering, Universiti Teknologi MARA. His current research interests include power electronics circuits for efficient power conversion, renewable energy, and fault-tolerant converters. He can be contacted at email: Khairul-safuan@uitm.edu.my

Dylan Dah-Chuan Lu received the B.Eng. (Hons.) the Ph.D. degrees in electronic and information engineering from, the Hong Kong Polytechnic University, Hung Hom, Hong Kong, in 1999 and 2004, respectively. In 2003, he joined Power Lab, Ltd., as a Senior Design Engineer. His major responsibilities included project development and management, custom circuit design, and contribution of research in power electronics. In 2006, he joined the School of Electrical and Information Engineering, University of Sydney, Australia, as a Lecturer and became an Associate Professor in 2016. He was a visiting Associate Professor at the University of Hong Kong in 2013. Since July 2016, he has been with the School of Electrical, Mechanical and Mechatronic Engineering, University of Technology, Sydney, Australia, where he is currently an Associate Professor. His current research interests include power electronics circuits and control for efficient and reliable power conversion and applications such as renewable energy systems, microgrids, motor drive, and power quality improvement. He can be contacted at email: Dylan.Lu@uts.edu.au.