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Studies on Switching Algorithms for Uninterruptible Power Supply (UPS) System Using SPMC

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Abstract: The demand for availability, stability, reliability, and high quality of power supply has increased nowadays. This is particularly critical in the data centers, financial institutions, and cloud computing division, where data is the most important aspect of computer usage. The loss of data due to power failure can contribute to significant economic losses. Therefore, this paper aims to present a study on switching algorithms for the UPS system using Single-Phase Matrix Converter (SPMC) circuit topology. It features low power losses resulting in high power density. The proposed switching algorithms are derived via a proposed UPS function which takes both rectifier and the inverter operations using only one SPMC circuit topology into account. Besides, in the proposed control scheme, the safe-commutation strategy is developed to solve the commutation problem due to the inductive load disturbance. A step response function is used to investigate the transition between the proposed switching algorithms for rectifier and inverter operations, where the rectifier operation representing the normal operation that receives the supply from the grid system. For the power outage condition, the switching algorithms will shift to perform an inverter operation and provide the supply from the standby charged battery. Finally, the computer simulation model using MATLAB/Simulink results verify the effectiveness of the proposed switching algorithms.

Keywords: Uninterruptible Power Supply (UPS), AC-DC Converter, DC-AC Converter, Single-Phase Matrix Converter (SPMC)

Abstrak (Malay): *Kajian ini bertujuan untuk membentangkan kajian tentang algoritma pensuisan untuk sistem UPS menggunakan topologi Single Phase Matrix Converter (SPMC). Algoritma pensuisan yang dicadangkan diperoleh melalui fungsi UPS yang mengambil kira kedua-dua penerus dan operasi penyongsang menggunakan hanya satu topologi litar SPMC. Selain itu, dalam strategi kawalan, strategi pertukaran dibangunkan untuk menyelesaikan masalah tukar ganti akibat gangguan beban. Apabila keadaan terputus bekalan kuasa, algoritma pensuisan akan beralih untuk melakukan operasi penyongsang dan menyediakan bekalan daripada bateri. Model simulasi menggunakan MATLAB/Simulink digunakan bagi mengesahkan keberkesanan algoritma penukaran.*

Kata kunci: *Uninterruptible Power Supply (UPS), AC-DC Converter, DC-AC Converter, Single-Phase Matrix Converter (SPMC)*

1. Introduction

The transformation of the manufacturing industry could create a path for the manufacturing sector to align with the recent fourth Industry Revolution (IR 4.0), and as a result, would enable to support Malaysia's commitment to fulfilling Goal 9 and Goal 12 of the United Nation's Sustainable Development Goals (SDGs) (Ministry of International Trade and Industry, 2018). This is in line with the 7th Core of the Eleventh Malaysia Plan (RMK-11) Blueprint that highlights infrastructure strengthening via effective sourcing and energy delivery to ensure energy sustainability (Affair, 2015). The increased use of Uninterruptible Power Supply (UPS) has recently been sparked due to the revolution of the global manufacturing sector that requires high power quality and high-power reliability that would enable to prevent any power disruption, especially for a critical load (Beleiu et al., 2018). Despite power system reliability, the high-quality power supply is also important to cater to sensitive equipment that couldn't optimize their operation and could affect device destruction and

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malfunction due to the harmonics penetration (Gerber et al., 2022).

Figure 1 shows the conventional UPS circuit topology. This circuit topology consists of a separated rectifier circuit that is used to convert input AC voltage into DC form to charge the standby battery, an inverter circuit to convert DC supply from the standby battery during power outage condition, and a manual bypass switch. The rectifier or charger normally uses a bridge-diode in implementation using a typical switch without affording any control function (Kim et al., 2020) Due to the use of two separate circuit topologies to perform rectifier and inverter operations, the traditional UPS system is bulky, hence, reduce the power density (Okasili et al., 2022).

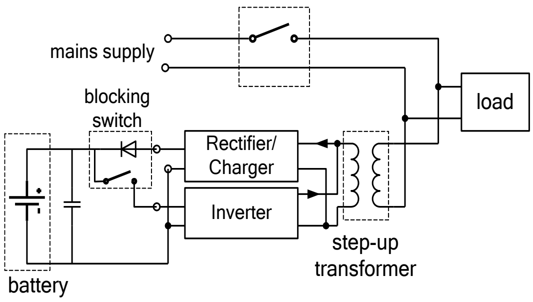

Figure 1: Typical static UPS system

Prior studies have also established a standard rectifier and inverter converters using SPMC topology. This fully controllable rectifier has been designed for charging operation with the output synthesized using a suitable switching algorithm (Renjini G, 2015) . The DC to single phase AC matrix converter has been presented schematically with switching patterns (Noor et al., 2007). Boost DC–AC inverter naturally generates in a single stage an AC voltage whose peak value can be lower or greater than the DC input voltage. Thus far, the limitations that the fundamental studies have solved are described by the following:

a) Provide alternative topology for fully controlled rectifier and inverter converters using SPMC with various loads studies such as pure resistive (R), and inductive (RL).
b) Control algorithms for rectifier and inverter operation using SPMC with safe commutation strategies to eliminate voltage and current spikes that may cause devices damage.

Despite being successful, several limitations remain. This poses an issue for integration of rectifier and inverter models to develop UPS system. Based on previous limitation work, have been established a standard rectifier and inverter converter using SPMC topology, but no integration of rectifier and inverter as a UPS system by using proper control algorithms. To solve this, an improved version of UPS system could be developed, based on up-scaling the typical UPS model. The SPMC will perform all the three functions of inverter, rectifier and blocking switch. By suitable control, added feature could be implemented in the form of safe-commutation strategy operation for inductive load. Since the SPMC capable of conducting current in forward and reverse directions, it is also possible that the DC side becomes the generating source and the AC side becomes the receptacle in the UPS system. In this way the SPMC can function either as a Voltage Source Inverter (VSI) or a Current Source Inverter (CSI) supplying various shapes of alternating current to the AC supply system.

Therefore, this paper aims to present the switching algorithms of the proposed UPS system that combines rectifier and inverter circuits using a single SPMC circuit topology. Its features the low power losses resulting in high power density, thus, can solve serious concern for floating offshore oil and gas platforms by minimizing the size of UPS system. As a result, such new enhancements can be used as a good foundation of future UPS 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. The proposed UPS system will be beneficial to the industries related to data, financial and cloud computing managements, where the stability of the power supply is very crucial to protect the data. The large-scale power outage accident in northeastern Brazil in 2011 recorded USD$60 million loss. Therefore, it could be expected that the developed UPS system with compact and high-power density could help to minimize losses due to power failure particularly for the critical loads, thus, promises technologies advancement and convergence, hence, enable the manufacturing sector to move into Industry 4.0 and along the way contribute to fulfilling Malaysia's commitment to support the United Nation's Sustainable Development Goals(Ministry of International Trade and Industry, 2018).

2. Proposed Converter and Principle of Operation

The proposed single-phase UPS system is shown in Figure 2. It is composed of a single SPMC circuit topology that operates based on the open-loop controller. This controller provides switching algorithms for both rectifier and inverter operations that are triggered during normal power supply (rectifier mode) and during a power outage (inverter mode). The benefits of a proposed single-phase UPS system are preserved, such as a smaller number of power devices and low power losses. Nonetheless, the main important feature of the proposed single-phase UPS system is the fact that the whole system uses only a single circuit topology to perform both rectifier and inverter operations. This attribute to the high-power density power converter system, which is in-line with the power electronics technological roadmap to reduce the losses, size, volume, and cost that is presented in the Figure of Merit (FOM) as illustrated in Figure 3.

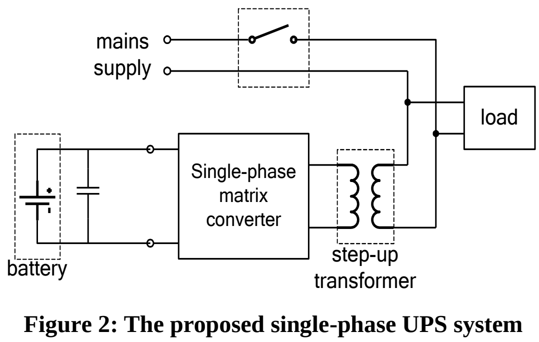

Figure 2: The proposed single-phase UPS system

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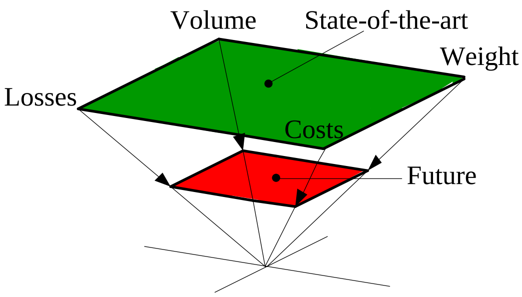

Figure 3: The Figure of Merit (FOM)

2.1 DC-AC operation

Figure 4 shows the operational stages when the proposed single-phase UPS system operates as a DC-AC converter. The first operational stage occurs when the pair of switches S1a and S4a turn ON, as shown in Figure 4 (a). During this time interval, the supply current from the positive DC source of inverter will flow to the load through switch S1a, then, return back to the negative DC source of inverter through switch S4a. At this time, the DC source (standby battery) transfers energy to the AC load, performing an inverter operation for the positive half-cycle. This circuit configuration has duration δTs, where δ corresponds to duty cycle of the pair of switches S1a and S4a.

The second operational stages starts when the pair of switches S1a and S4a turn OFF, and the pair of switches S2a and S3a turn ON instantaneous and simultaneously as shown in Figure 4 (b). In this stage, the energy in DC source is transferred to the AC load through switch S2a and return back to the negative terminal through switch S3a. Again, the DC source transfers energy to the AC load, performing an inverter operation for the negative half-cycle. This circuit has duration (1-δ)Ts where δ corresponds to duty cycle of the pair of switches S2a and S3a.

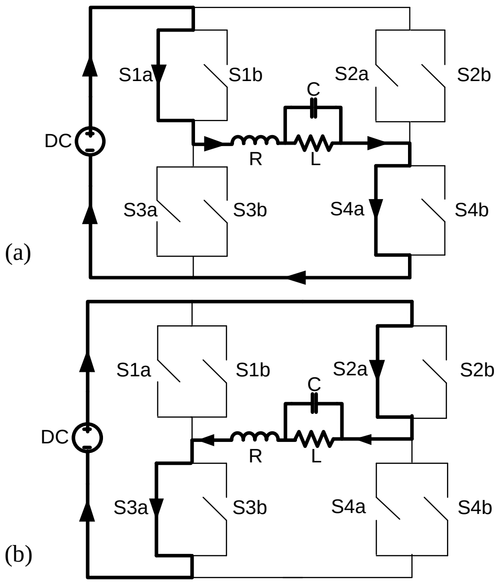

Figure 4: The operational stages of DC-AC converter (a) Positive cycle operation, (b) Negative cycle operation

From the DC-AC operation stages, the input DC voltage can be converted into an AC form using SPMC with proper control of switches based on the switching algorithms as tabulated in Table 1. A desired output AC voltage can be obtained using a purely resistive load. However, with an inductive load, the commutation problem might be happened due to the short-circuit path during switches transition, thus, voltage spikes are induced. This can cause damage to the converter power switches because the resulting voltage spike is usually twice or more than the supply voltage value and depends on the value of an inductor.

Table 1: Switching Algorithm for DC-AC Operation

Switches	Positive cycle	Negative cycle
S1a	SPWM	OFF
S1b	OFF	OFF
S2a	OFF	SPWM
S2b	OFF	OFF
S3a	OFF	SPWM
S3b	OFF	OFF
S4a	SPWM	OFF
S4b	OFF	OFF

To solve the commutation problem, a safe-commutation strategy has been developed by creating the dissipation path for the energy stored in an inductor to fully dissipate during the switch's dissipations process. Table 2 shows the switching algorithms for the DC-AC operation stages with a safe-commutation strategy. With proper control of the SPMC switches, the stored energy in the inductor can be dissipated, hence, eliminated the induced voltage spikes. This method does not require any addition of electronic components such as snubber capacitors as have been proposed by other researchers. This method features cost reduction and can reduce the power losses resulting from the addition of electronic components.

Table 2: Switching Algorithm for DC-AC Operation with Safe-Commutation Strategy

Switches	Positive cycle	Negative cycle
S1a	ON	OFF
S1b	OFF	ON
S2a	OFF	ON
S2b	OFF	OFF
S3a	OFF	SPWM
S3b	ON	OFF
S4a	SPWM	OFF
S4b	OFF	OFF

Figure 5 illustrates the operational stages for the DC-AC converter with a safe-commutation strategy. The first operational stage occurs when the pair of switches S1a and S2b turn ON, as shown in Figure 5 (a). During this time interval, a free-wheel path is created to allow the inductor energy to fully dissipated before the next switches transitions process, thus eliminating the voltage spikes. The supply current from the positive DC source of the inverter will flow to the load through switch S1a, then, return back to the negative DC source of the inverter through switch S4a (SPWM). At this time, the DC source (standby battery) transfers energy to the AC load, performing an inverter operation for the positive half-cycle as illustrated in Figure 5 (b).

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The third operational stage starts when the pair of switches S21b and S2a turn ON as shown in Figure 5 (c). In this stage, the stored energy in the load inductor dissipated through the pair of switches, thus, the created free-wheel path allows the inductor energy to fully dissipated. In the fourth stage as illustrated in Figure 5 (d), the energy in the DC source is transferred to the AC load through switch S2a and return back to the negative terminal through switch S3a (SPWM). Again, the DC source transfers energy to the AC load, performing an inverter operation for the negative half-cycle.

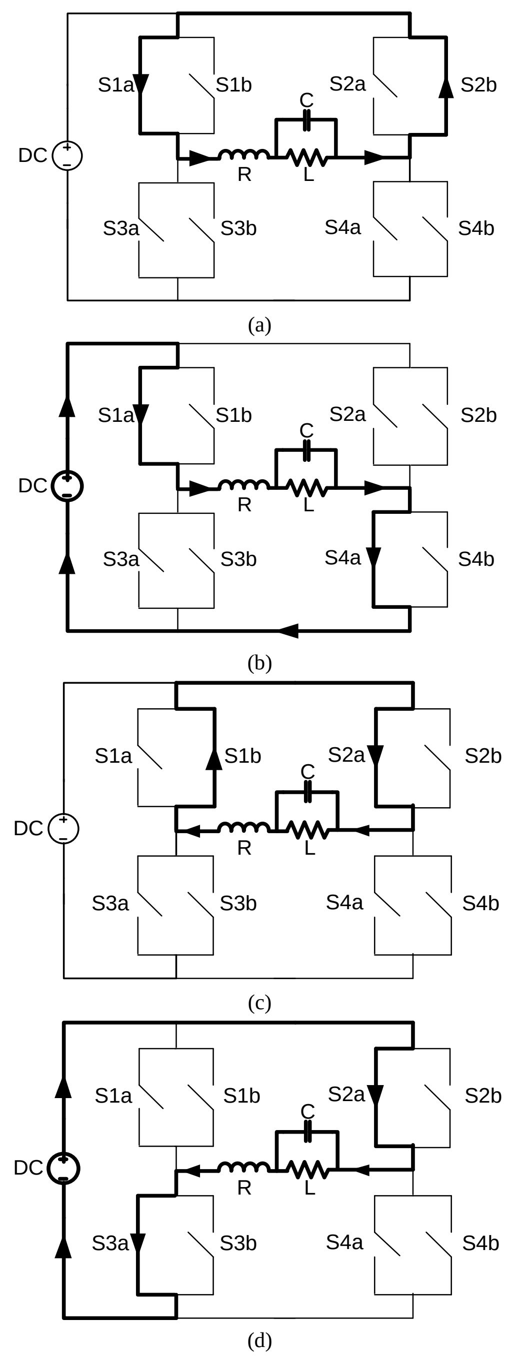

Figure 5: Operational stages of DC-AC converter with safe-commutation strategy (a) Stage 1, (b) Stage 2, (c) Stage 3, and (d) Stage 4

2.2. AC-DC Operation

The schematic diagram of the controlled AC–DC operation using SPMC is shown in Figure 6. In this operation, the same circuit of the DC–AC converter as discussed in the previous subsection is used. The main differences between the DC–AC and the AC–DC operations are the input source and the output of the converter. As shown in Figure 6, the input AC-side structure of the AC–DC converter is at the AC load side of the DC-AC converter. On the one hand, the DC-side of the AC–DC converter is at the DC source side of the DC-AC converter. With the proposed switching algorithms for the AC-DC operation, a single circuit of SPMC that has been used to operate as a DC-AC converter, now, can be used to perform the AC-DC operation without any additional circuit, thus, improving the power density of the converter system and reducing the total power losses of the proposed UPS system.

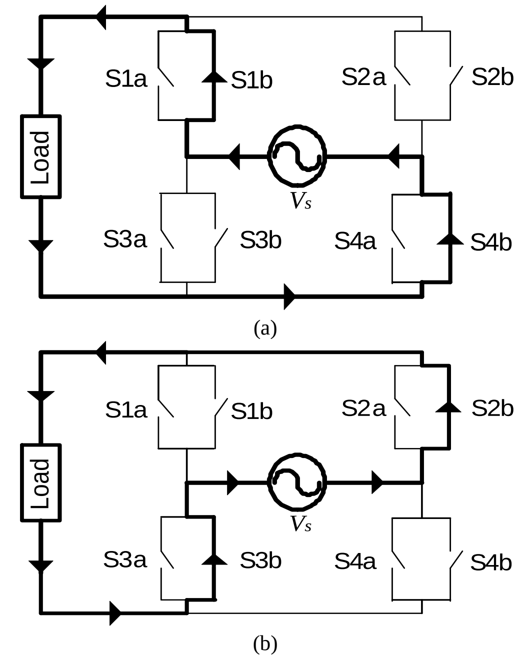

Figure 6: Operational stages of AC-DC converter (a) Positive cycle operation, (b) Negative cycle operation.

Figure 6 shows the sequence of conduction of each rectifying component of the SPMC circuit when a Pulse Width Modulation (PWM) control is applied according to the switching algorithms as tabulated in Table 3. To describe the operation of this circuit, the operation in a positive half-cycle of the source voltage is discussed. Let the pair of switches, S1b, and S4b be conducting and the output capacitor, CO, is left charged in the polarity indicated in the figure to a voltage VO. When S1b is triggered, the current from the source voltage, VS has flowed across the load, R, via switch S4b as illustrated in Figure 6(a).

At initial, the VS reaches zero at t = 0.00s, the positive half-cycle of the source voltage operation is applied. Figure 6(a) illustrated the operation of the AC-DC converter for the positive half-cycle of the source voltage. During this stage, VS gives energy to the capacitive load, RC, and provides the voltage across it via the pair of switches S1b and S4b. Fig(b) illustrated after t = 0.01s, the pair of switches S1b and S34b

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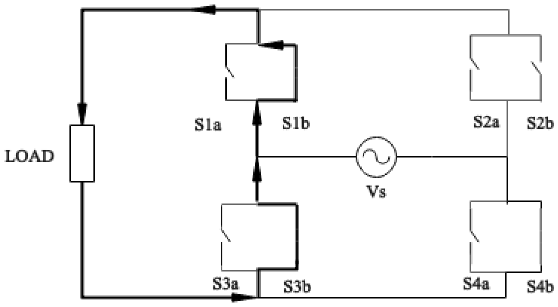
turned OFF and the load current circulates through S2b and S3b, since these switches turned ON again for the negative half-cycle of the source voltage operation.

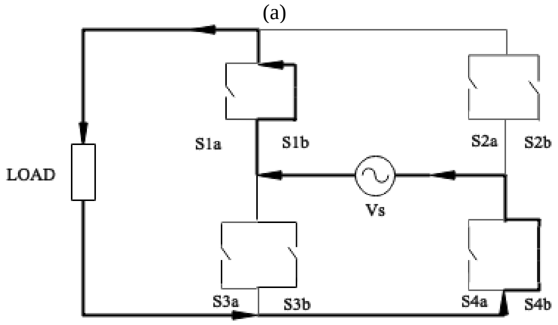
Table 3: Switching Algorithm for AC-DC Operation

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

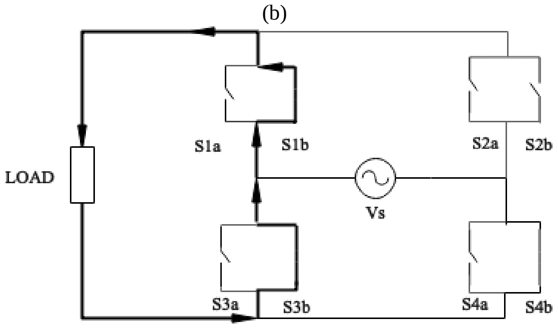
Figure 7 illustrates the operational stages for the AC-DC converter with a safe-commutation strategy. To facilitate the description of the circuit operation, it is divided into four stages of operations. The first operational stage occurs when the pair of switches S1b and S3b turn ON, as shown in Figure 7 (a). During this time interval, the commutation path of inductive energy from the RL load is created to allow the stored energy to fully dissipated through this path.



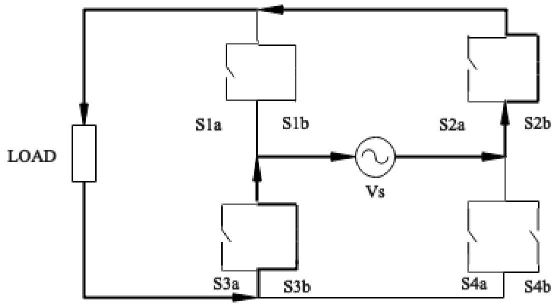
(a)



(b)



(c)



(d)

Figure. 7 Operational stages of AC-DC converter with safe-commutation strategy (a) Stage 1, (b) Stage 2, (c) Stage 3, and (d) Stage 4

In the second stage of operation, the supply current from the AC source of the rectifier will flow to the DC load through switch S1b, then return to the negative AC source of the rectifier through switch S4b. At this time, the AC source transfers energy to the DC load, performing a rectifier operation for the positive half-cycle as illustrated in Figure 7 (b). The third operational stage starts when the pair of switches S1b and S3b turn ON as shown in Figure 7 (c). In this operational stage, the created free-wheel path allows the inductive energy to fully dissipated before the next switches transitions process, thus eliminating the voltage spikes.

The AC source transfers energy to the DC load, performing the rectifier operation for the negative half-cycle. When the pair of switches S2b and S3b turn ON, the energy from the AC source is transferred to the DC load as illustrated in Figure 7 (d) to represent the fourth operational stage. Details of switching algorithms for the AC-DC operation with a safe-commutation strategy are tabulated in Table 4.

Table 4: Switching Algorithm for AC-DC Operation with Safe-Commutation Strategy

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

Figure 8 shows the PWM generator for the safe-commutation technique to produce a PWM output signal by comparing the carrier signal (repeating sequence block) which produces sawtooth waveform to the constant that represents a straight-line reference signal through a relational operator. Then the PWM output signal is multiplied with the output signal of the phase detector as in Figure 9 to produce a positive and negative pulse waveform. The block 'more than zero' represents the 'ON' pulse for a positive cycle while block 'less than zero' represents the 'ON' pulse for a negative cycle operation. The 'Add' block is added to the PWM generator circuit in order to integrate the PWM signal and the output signal from the phase detector. The PWM pulse signal induced to the S4b for a positive cycle and S3b for a negative cycle.

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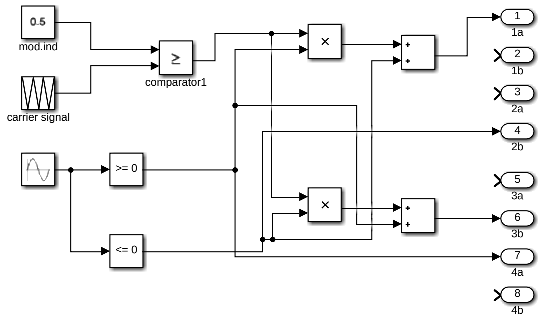

Figure 8: PWM Generator with safe-commutation

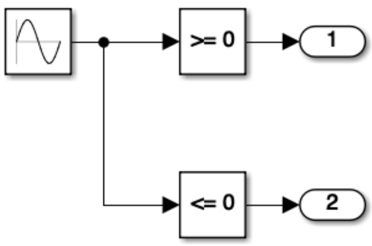

Figure 9: Phase Detector Circuit

3. Control Strategy and System Modeling of UPS

Figure 10 shows the circuit topology of the proposed UPS system. The proposed circuit topology system consists of only one power converter; thus, it provides a simple UPS system circuit topology as compared to the conventional system that consists of at least two separate circuits. For this circuit topology that utilizes the SPMC, a suitable switching algorithm is developed to control the SPMC switches to operate as a rectifier during normal operation and as an inverter during an interruption or power outage, thus removing the need for two separate circuits of the rectifier and the inverter.

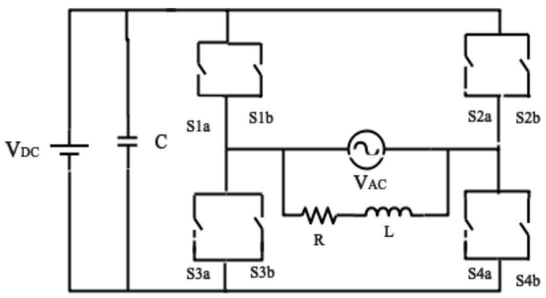

Figure 10: The circuit topology of the proposed UPS system

A computer simulation model of the proposed UPS system is simulated using MATLAB/Simulink. In this work, the switching algorithm for both rectifier and inverter operations as discussed in the previous subsection is integrated for the proposed UPS system. The schematic circuit model of the proposed UPS system is shown in Figure 11. A step response block set is used to simulate the transition time between rectifier and inverter operations to investigate the operation of the proposed UPS system during normal and power outage conditions. The transition times of the step response is set as 0 to 0.02s for the rectifier operation, whilst, from 0.02 to 0.04s for the inverter operation.

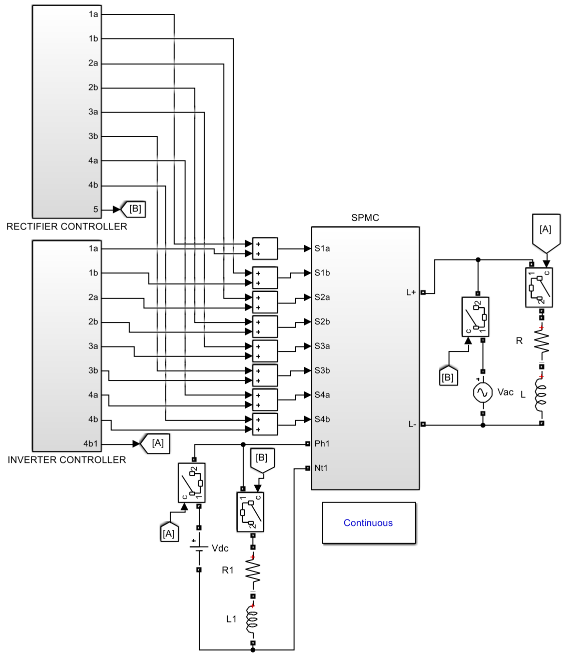

Figure 11: The schematic circuit model of the proposed UPS system using MATLAB/Simulink.

4. Results and Discussion

To verify the operation of the proposed UPS system, a computer simulation circuit is modeled, having various parameters as tabulated in Table 5. In MATLAB/Simulink model, the voltage and current sensors (measurement) are employed to sample the magnitudes of both input and output voltage waveforms. In this work, the operation of the proposed UPS system is investigated during all the possible operating conditions; normal (rectifier operation), and power outage (inverter operation). Figure 12 and Figure 13 shows the typical UPS signal without control algorithms. At Figure 12, show the input signal of typical UPS system in initial with rectifier operation at 0s to 0.04s while inverter operation at 0.04s to 0.06s. At Figure 13 show the output signal of typical UPS signal with initially rectifier operation at 0s to 0.04s and inverter operation at 0.04s to 0.06s.

Table 5: Computer Simulation Model Circuit Parameters

Parameters	Values
Supply voltage	100 Vpk-pk
Line frequency	50 Hz
Switching frequency	5 kHz
R load	50 Ohm
L load	5 mH

Nevertheless, the proposed system is initially working in the rectifier mode of operation from 0 to 0.02s, which is set using a step-response block set in MATLAB/Simulink. However, after a particular time of 0.02s to 0.04s, the utility becomes in an outage condition, and the inverter starts to operate to shift the load completely to the utility. Here, the supply from the grid goes under the faulty condition, and the

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standby DC battery source will take place to provide an uninterruptible power supply to the AC load.

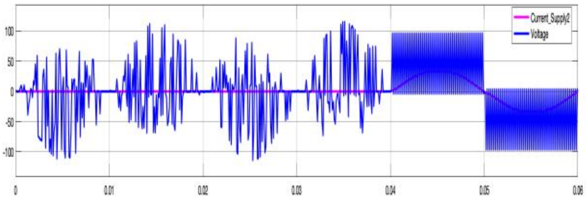

Figure 12: Typical UPS Input Signal - The input voltage waveform of the rectifier operation (0s to 0.04s) and the output voltage waveform of an inverter operation (0.04s to 0.06s) of for the typical UPS without control algorithms using MATLAB/Simulink.

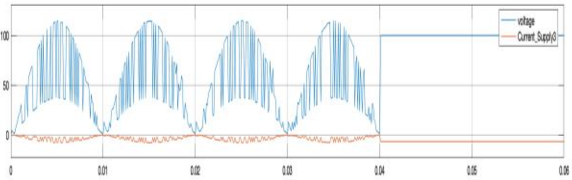

Figure 13: Typical UPS Output Signal - The output voltage waveform of the rectifier operation (0s to 0.04s) and the input voltage waveform of an inverter operation (0.04s to 0.06s) for the typical UPS without control algorithms using MATLAB/Simulink.

The computer simulation results at Figure 14 show the input signal while Figure15 show the output signal of proposed UPS system. The performance of the proposed UPS system is working according to the operating conditions and switching algorithms as presented in the previous subsection.

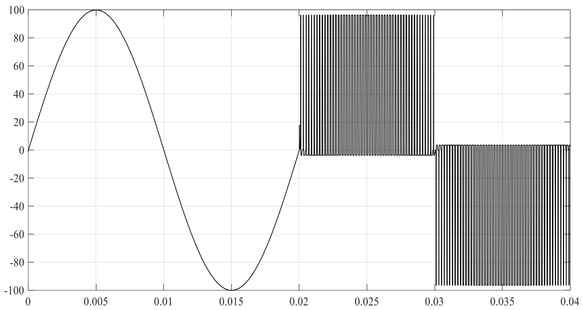

Figure 14: Proposed UPS Input Signal - The input voltage waveform of the rectifier operation (0s to 0.02s) and the output voltage waveform of an inverter operation (0.02s to 0.04s) of the proposed UPS system using MATLAB/Simulink.

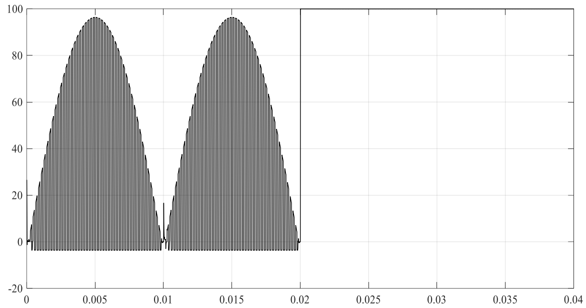

Figure 15: Proposed UPS Output Signal - The output voltage waveform of the rectifier operation (0s to 0.02s) and the input voltage waveform of an inverter operation (0.02s to 0.04s) for the proposed UPS system using MATLAB/Simulink.

5. Conclusion

In this paper, a single-phase UPS system using a single circuit topology based on SPMC was proposed. The rectifier and inverter operations of the proposed UPS system were able to be implemented using a single SPMC circuit topology, thus, it provides an alternative to the conventional circuit topology that uses at least two separate circuits. Table 6 shows the comparison on power quality based on Total Harmonic Distortions (THD) level for typical UPS without control algorithm and proposed UPS System. The THD level for typical UPS without control algorithms is 267.31% while the proposed UPS system is 2.86%. As a result, this attribute to the high-power density power converter system, which is in-line with the power electronics technological roadmap. The operation of the proposed UPS system with a new integrated switching algorithm was verified during all the possible operating conditions i.e., normal and power outage. From the results, it is concluded that the operation of the proposed single-phase UPS system is not only seamless, but it also requires less number of power devices and could lead to low power losses.

Table 6: Comparison Power Quality based on THD Result

Operation	Load	Strategies	THD
Typical UPS	RL	w/out Control Algorithms	267.31%
Proposed UPS	RL	Control Algorithms	2.86%

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