Three-Level Single-Phase Current-Source AC/DC/AC Conversion System with Reduced Switching Device Counts

Eka Rakhman Priandana*, Toshihiko Noguchi (Shizuoka University)

This paper proposes a new circuit configuration of a three-level single-phase AC/DC/AC conversion system with reduced switching device counts. The circuit incorporates a three-level single-phase half-bridge current-source PWM inverter and a three-level single-phase half-bridge current-source PWM rectifier. The inverter circuit part is constructed from duality principle of the conventional voltage-source PWM inverter, while the rectifier circuit part is built by means of mirroring and reversing process of the inverter part. By combining them into one circuit with two reactors as the energy buffers, the converter can not only convert the voltage and frequency, but also can reduce the total harmonic distortion with reduced reactor size, compared with a two-level one according to the circuit simulations.

Keywords: three-level, half-bridge, current-source PWM inverter, current-source PWM rectifier, duality principle, mirroring, reversing, total harmonic distortion, circuit simulation

1. Introduction

In general, AC-to-AC conversion systems are classified to four types: AC/DC/AC conversion systems (i.e., with a rectifier, a DC link and an inverter), cyclo-converters, indirect matrix converters, and direct matrix converters. Despite having lower efficiency due to the two-step conversion, the AC/DC/AC conversion systems with the DC link have the simplest arbitrarily switching control feature and is the most applicable in industry(1).

The voltage-source AC/DC/AC conversion systems have been widely developed in order to convert the line voltage and frequency from one to different one. Unfortunately, this kind of converter will encounter problem while supplying heavy inductive loads such as AC motors. The converter does not have robust self-protection from short circuit load and has high dv/dt or di/dt transient behavior. Meanwhile, the current-source types are less applied due to two main disadvantages: high conduction losses and low power density. Nonetheless, its advantages such as having natural protection from short circuit and low dv/dt or di/dt cannot be omitted(2).

The fundamental of single-phase half-bridge current-source AC-to-AC converters as shown in Fig. 1 has been proposed by the authors in order to give an alternative solution for power electronics, especially while supplying high inductive loads(3). Technically, the converter consists of half-bridge current-source rectifier and half-bridge current-source inverter. The output rms voltage is controlled by adjusting the DC current. Q1 and Q2 switches are driven by pulse-width modulation (PWM) generator which is its reference regulated by the output voltage error, the DC current error, and the input sinusoidal waveform. Meanwhile, Q3 and Q4 are driven by independent PWM generator with fixed modulation index. Near unity modulation index would be applied if converting to lower voltage is desired. Otherwise, lowering the modulation index will increase the output voltage.

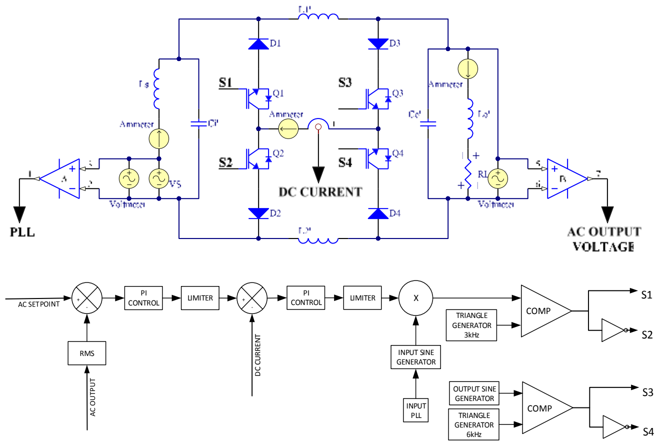


Fig. 1. Single-phase half-bridge current-source AC/DC/AC conversion system and its controller.

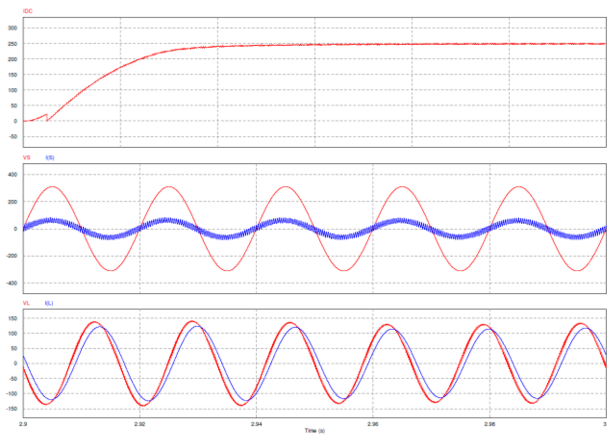


Fig. 2. Simulated waveforms of AC/DC/AC conversion from 220V/50Hz to 100V/60Hz.

Fig. 2 shows the simulation result when the circuit converts 220V/50Hz to 100V/60Hz. The top waveform is a DC link current, the middle one is enlargement waveforms of the source voltage and the source current, and the bottom one is enlargement of the load voltage and the load current. It is shown that the input current contains relatively high harmonics that may damage the power source although it has unity power factor. This problem can be addressed by increasing its power quality.

The development of high-performance semiconductor devices increases the research interest in high power converters such as multilevel converters because they have capability to produce higher output power with low-voltage rating devices, lower switching losses, and higher power quality with less harmonic distortion compared with the conventional two-level converters. Many power semiconductor devices utilization in the multilevel converter circuit increase circuit complexity such as control and gate drive circuits, as well as conduction losses. Therefore, half-bridge configuration is the most efficient approach to reduce the device counts utilization to a half [4].

This paper proposes a novel circuit configuration of the multilevel half-bridge current-source AC/DC/AC converters along with its control system. The circuit incorporates a three-level single-phase half-bridge current-source PWM inverter and three-level single-phase half-bridge current-source PWM rectifier into one circuit with two reactors as the energy buffers. Prior to the simulation result discussion, the operation principle of the conversion system will be explained, including a duality principle of the multilevel converter configuration that gives higher power quality contribution to this research.

2. Circuit Configuration and Operation Principle

2.1 The Three-Level Current-Source Converter Circuit

The multilevel configuration of the current-source converter is derived from the conventional voltage-source converter. Fig. 3 shows a circuit configuration of a fundamental three-level current-source inverter (CSI) proposed by Suroso and Noguchi [5]. This circuit was derived from the single-phase half-bridge three-level voltage-source inverter (VSI) by converting it with duality principle. The DC voltage-sources, the anti-parallel diodes and transistors, and the inductive load are replaced with DC current-sources, series-connected diodes and transistors, and a capacitive load (a parallel connected C-R), respectively.

Instead of two switches, three-level CSI employs four switches where each switch is driven so that its output will generate three states of the current waveform. Table 1 explains the switching states regarding to the output current [4].

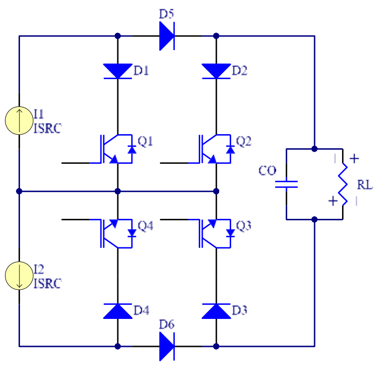


Fig. 3. Basic configuration of three-level current-source inverter (CSI).

Fig. 4 shows the output current waveforms of the three-level current-source inverter that shown in Fig. 3. The upper waveform is the current before filtering by a capacitor, meanwhile the bottom one is the load current. It is shown that the current conforms to Table 1 that has three states: + I, 0, and – I. This circuit will be utilized as reference to construct the three-level current-source rectifier.

2.2 Mirroring and Reversing

In the voltage topology, the rectifier and the inverter have similar circuit configuration. In order to apply inverter as rectifier, the AC phase reference must be shifted to –180 degree, so that the

Table 1. Switching states of three-level CSI.

Q1	Q2	Q3	Q4	Output
0	0	1	1	+ I
1	0	0	1	0
1	1	0	0	– I

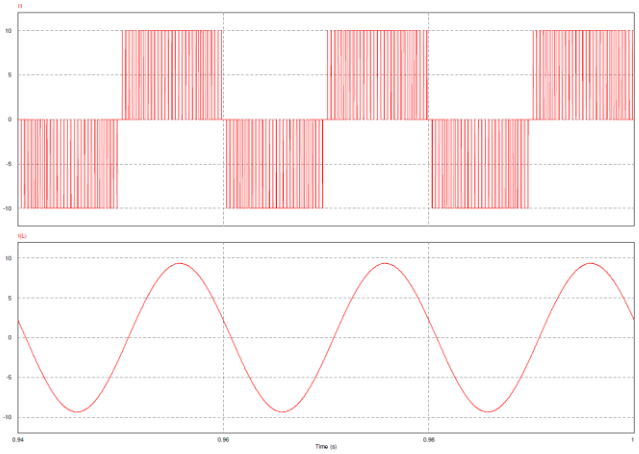
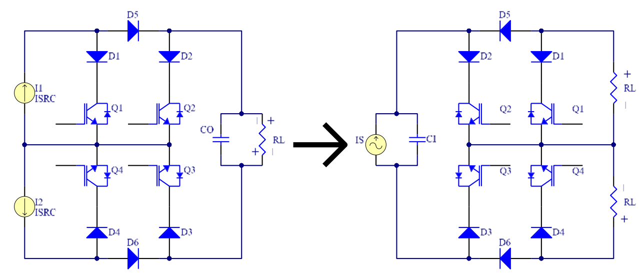
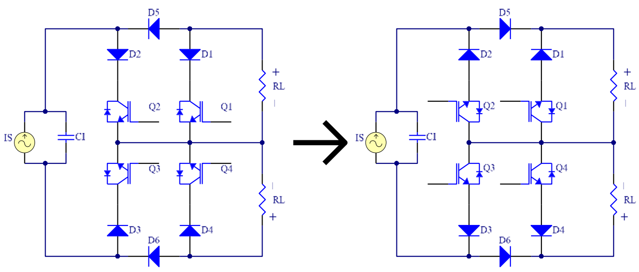


Fig. 4. Output current waveforms of three-level CSI.



(a) Mirroring process.



(b) Reversing process.

Fig. 5. Mirroring and reversing processes of CSI in order to construct CSR.

current flows reversely from AC side to DC side [6]. On the other hand, in the current topology, only shifting the phase reference is not sufficient, but mirroring the inverter circuit and reversing its components are necessary.

Fig. 5 explains how to construct the three-level half-bridge current-source rectifier (CSR) from the corresponding CSI. In the mirroring process, the load is converted to the source and vice versa. Whereas in the reversing process, all devices are connected in the opposite direction, compared with the CSI circuit. By combining them into one circuit with the additional reactors as the energy buffers, it will become the three-level single-phase AC/DC/AC conversion system. Fig. 6 shows the resultant proposed circuit.

2.3 Operation Principle of Rectifier Part

The operation principle of the proposed circuit is divided into two parts, i.e., the rectifier side and the inverter side. Since the operation principle of the inverter side has been explained in Table 1, the following discussion will focus on the rectifier side.

Since the source current is AC sinusoidal, the principle will be explained in two current directions. When the source current flows in the forward direction, Q1 and Q2 are turned off and the others are turned on, the reactor L1 is charged meanwhile the reactor L2 holds the current. If Q1 and Q4 are turned on and the others are turned off, both reactors will hold the current. If Q1 and Q2 are turned on and the others are turned off, the reactor L1 will hold the current meanwhile the reactor L2 will be discharged. Fig. 7 describes the above operation principles.

On the other hand, when the source current flows in the reverse direction on the next half period, what happens is the opposite operation explained above. Table 2 summaries the operation principle of the rectifier side.

2.4 Control System and PWM Generation

Fig. 8 describes the control system of the converter and how PWM signals are generated for each switching device. Q1 – Q4 are driven by the PWM generator which receives its reference from calculation of the output voltage error, the DC current error, and the 180-degree-shifted input sinusoidal waveform. Meanwhile, Q5 – Q8 are driven by the independent PWM generator with a fixed modulation index. If the buck mode operation is desired, near unity modulation index for the inverter part may be used. Otherwise, lower modulation index than unity must be applied.

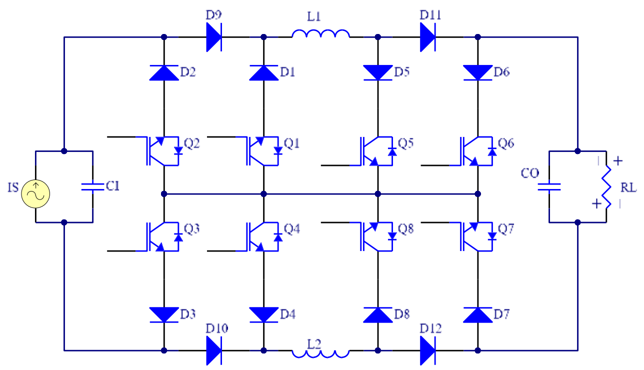


Fig. 6. Proposed three-level single-phase current-source AC/DC/AC conversion system.

The proposed control system looks to have a similar configuration with Fig. 1. The difference is only in the reference comparator that needs two comparators as a consequence of using the three-level switching configuration.

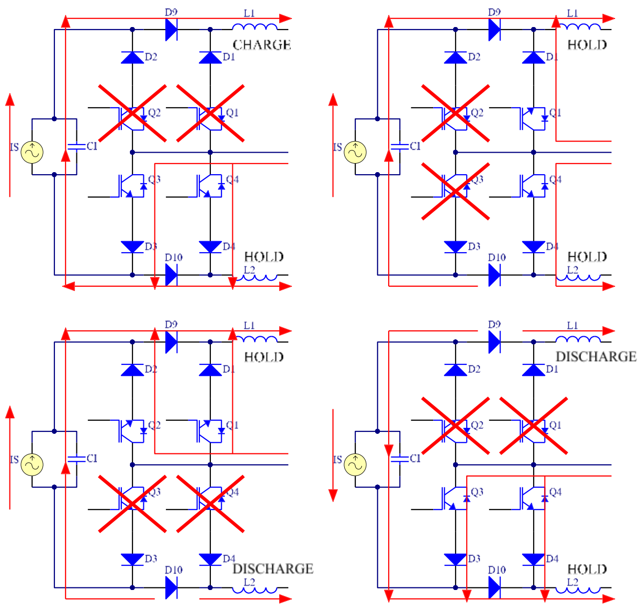


Fig. 7. Three-level current-source rectifier (CSR) operation principle.

Table 2. Switching states of three-level CSR.

Current Source	Q1	Q2	Q3	Q4	L1 State	L2 State
Forward	0	0	1	1	Charge	Hold
Forward	1	0	0	1	Hold	Hold
Forward	1	1	0	0	Hold	Discharge
Reverse	0	0	1	1	Discharge	Hold
Reverse	1	0	0	1	Hold	Hold
Reverse	1	1	0	0	Hold	Charge

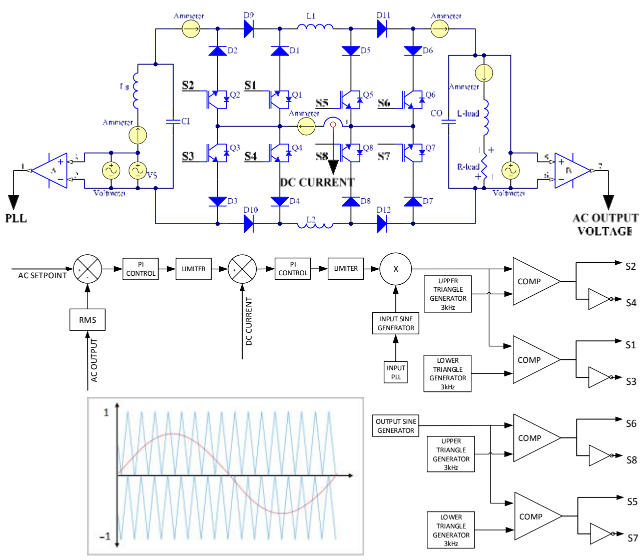


Fig. 8. Proposed converter control system and PWM generation.

3. Simulation Results

Some simulations were conducted in order to verify the performance of the proposed converter. Prior to the simulations, several circuit parameters Fig. 8 were determined as listed in Table 3. Fig. 9 shows the result of simulation waveforms that consist of the DC link current, the enlargement of the input switched current, the enlargement of the source voltage and current, the enlargement of the output switched current, and the enlargement of the load voltage and current.

It is shown in Fig. 9 that the source current has better waveform than the source current in Fig. 2 and still demonstrates the unity power factor. Table 4 reports the comparison between the two-level and the three-level configurations, where the input THD-I was successfully reduced to 13.7 %. These results proved that the multilevel configuration effectively improves the power quality of the converter without sacrificing the power factor.

The merit of the proposed converter is not only increasing the converter power quality, but also reducing the utilized reactors to a quarter. Previous research reported that the employed reactor size was 100 mH for the two-level configuration, but the investigated converter in this study uses only 25 mH each [3]. Due to smaller reactor size, the consequent output THD-V and THD-I are slightly increased but are not significant. The converter efficiency also slightly decreased due to higher semiconductor counts utilization, which causes higher conduction losses.

Table 3. Simulation parameters.

Parameters	Values
Source voltage	220 V / 50 Hz
Set point	100 V / 60 Hz
Loads	1.07 Ω / 0.98 mH
Modulation index	0.6
Carrier frequency	3000 Hz
Filter capacitors	Input: 100 uF / ESR 1 mΩ Output: 680 uF / ESR 1 mΩ
Series inductor	1 mH / ESR 1 mΩ
Reactors	25 mH / ESR 1 mΩ

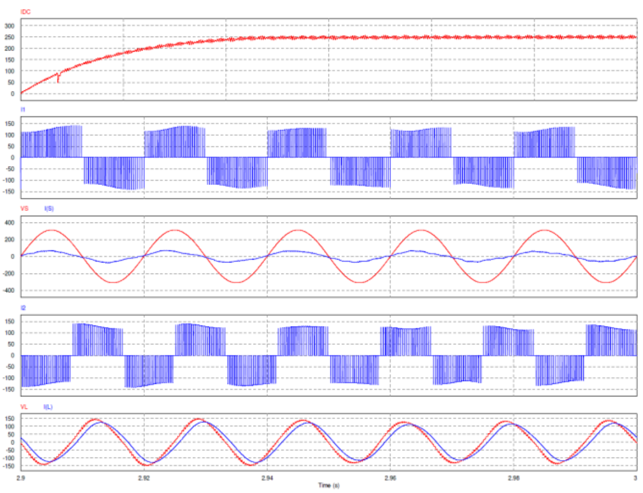


Fig. 9. 220V/50Hz to 100V/60Hz conversion simulation result.

Table 4. Recorded simulation data.

Measured quantities	Two-level		Three-level	
	Input	Output	Input	Output
Voltage	220 V	95.1 V	220 V	95.1 V
THD-V	0.09 %	3.39 %	0.09 %	4.09 %
Current	44.8 A	84.0 A	43.3 A	84.0 A
THD-I	34.8 %	1.27 %	13.7 %	1.75 %
Reactor size	100 mH		25 mH	
DC-link current	249.8 A		249.8 A	
Efficiency	79.8 %		78.9 %	

4. Conclusion

The three-level single-phase current-source AC/DC/AC conversion system with reduced switching device counts has been presented with some simulation results. The multilevel configuration application does not only improve the converter power quality and the power factor, but also reduces the reactor size utilization. In order to verify the simulation results, the proposed circuit prototype is currently under development for experimental tests.

References

(1) J. W. Kolar et. al., "The essence of three-phase AC/AC converter systems", Proceedings of the 13th Power Electronics and Motion Control Conference (EPE-PEMC'08), Poznan, Poland, pp. 27 – 42, Sept. 1 - 3, 2008.

(2) L. A. Costa et. al., "Single-phase AC-DC-AC current source converter with reduced DC-link oscillation," 2017 IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, 2017, pp. 480-487.

(3) E. R. Priandana and T. Noguchi, "Single-phase current-source AC/DC/AC conversion system with reduced switching device counts", The 2018 Annual Meeting of The IEEJ.

(4) Suroso and T. Noguchi, "New generalized multilevel current-source PWM inverter with no-isolated switching devices," 2009 International Conference on Power Electronics and Drive Systems (PEDS), Taipei, 2009, pp. 314-319.

(5) Suroso and T. Noguchi, 'Three-level current-source PWM inverter with no isolated switching devices for photovoltaic conditioner', IEE J Trans. Ind. Appl., 2009, 129, pp. 505–510.

(6) M. P. Akter, et. al., "Modified model predictive control of a bidirectional AC–DC converter based on lyapunov function for energy storage systems," in IEEE Transactions on Industrial Electronics, vol. 63, no. 2, pp. 704-715, Feb. 2016.