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NEW H-BRIDGE BASED MULTILEVEL CSI USING INDUCTOR-CELL AND CURRENT-MODULE METHODS

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Abstract

This paper presents application of a new method to develop a novel multilevel inverter circuit with new features. The new method was developed by employing inductor-cells and current modules. The method was applied to H-bridge current-source inverter to produce a nine-level AC current waveform. Compared to the inductor-cell method, the new strategy was able to lessen the number of controlled power switches required to made inverter circuits. Hence, a simpler inverter can be constructed. Compared to current module method, the count of DC current sources can be reduced. Some experiments by using computer simulations and laboratory prototype were performed to test the working principle of the new inverter circuits. The test results indicated that the new inverter circuit functioned well in generating a multilevel AC current waveform.

Keywords: Current module, Inductor cell, Power inverter.

1. Introduction

In AC motor drive applications, current source power inverter (CSI) gives advantages than its dual circuit, voltage source power inverter (VSI). A current source power inverter is capable to generate a better AC current [1-5]. It also generates a less stress voltage because of its sinusoidal voltage wave [6-13]. This kind of inverter is more immune to short circuit faults because of its inductors [14-20]. Moreover, in application of renewable power generation such as grid-tied photovoltaic power conversion system, this inverter has boost-up voltage capability [21-24]. Hence no need to add additional circuits nor power transformer to level-up its output voltage.

Inductor-cell method has been introduced by Suroso and Noguchi [25, 26] to produce multilevel current waveform. It makes use of charging and discharging stages of inductor cells. An inductor cell is assembled by four uni-directional current power switches, and an inductor with attached current sensor on it. A nine level current was produced by employing two inductor-cells to an H-bridge inverter [27]. Total twelve controlled power switches, two inductors, two current sensors, and a single current source were required. The total components of inverter circuit can introduce another problem. Inverter circuit with many controlled switches will need more complex driving circuits.

Suroso and Noguchi [28] developed and discussed another method to produce multilevel AC current. It applied DC current modules to H-bridge inverter in order to produce multilevel AC output current. To output a nine level AC current, four DC current sources, seven unidirectional current controlled switches, and three diodes were necessary. It has advantages related to its less controlled switches number. However, this circuit needs more DC current sources than the inductor-cell one. Inverter circuit with many DC current sources will require more power inductor number. In addition, Suroso et al. [29] presented and discussed a different nine-level CSI circuit. This inverter utilized a basic three-level common emitter CSI connected with inductor cell circuit. To generate a nine level AC current, four DC current sources were required. Consequently, the four inductors of DC current sources cause more power losses and add the total weight of inverter system. Gnanasambandam et al. [30] presented another nine-level current source inverter and its control strategy to operate inverter in fundamental switching frequency. It was basically four H-bridge CSIs operated in parallel with isolated DC power sources. In this method, a single phase nine-level inverter requires six-teen power switches.

In this paper, a combination of the previous two methods, i.e. inductor-cells and current modules methods is proposed to develop a new inverter circuit. The method employs inductor-cells and DC current modules to the main H-bridge current source inverter to output multilevel AC current. A novel nine level inverter circuit was created by using the new methods. New features such as capability in reducing the controlled switches count can be achieved by using new inverter circuit. Some computer simulation and laboratory experiment tests were performed to investigate principle work of the new inverter circuit.

2. Proposed Method

Figure 1 shows a conventional configuration of nine-level inverter circuits using inductor cell method applied to H-bridge inverter. Two inductor-cell circuits were employed to construct inverter circuits. It has twelve uni-directional control switches, two power inductors, and a single DC current source. In case of gate drive circuit number, it requires twelve drive circuits with five isolated gate drive power circuits. Moreover, Fig. 2 presents another conventional structure of nine-level inverter circuits constructed utilizing DC current modules applied to H-bridge inverter. The circuit needs seven unidirectional control switches, three diodes and four DC current sources. To drive the power switches, seven driving circuits are required with three isolated gate driving circuits. Hence, the driving circuit of this inverter is simpler than the circuits applying inductor cell method. The number of control switches is also fewer. However, this inverter requires four DC current sources. It will cause more complex DC current source circuits as inputs of inverter.

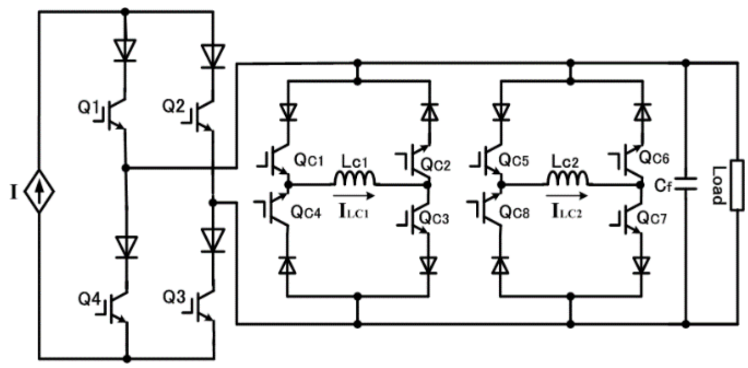


Fig. 1. Conventional nine-level inverter with inductor cells [27].

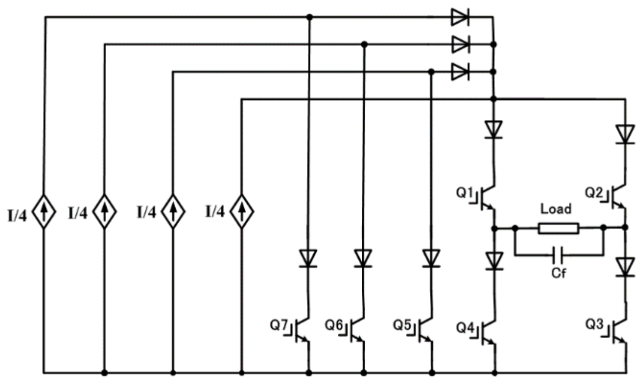


Fig. 2. Conventional nine level inverter with current modules [28].

Applying combination of both methods, a new circuit is developed as shown in Fig. 3. It consists of an inductor cell, a DC current module, and H-bridge inverter. It has nine unidirectional control switches, single diode, a power inductor, and two DC current sources. This circuit is also capable of generating a nine-level AC current. Compared with inductor cell method, this circuit is able in reducing the total of control switches, and power inductors. Moreover, compared with the DC current module method, it reduces the number of DC current sources as presented in Table 1.

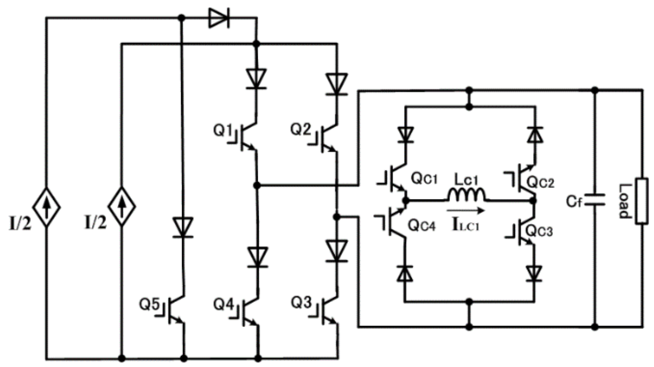


Fig. 3. New nine-level inverter circuit.

Table 1. Comparison of component number.

Methods	Inductor-cell method	Current-module method	Proposed method
DC current sources	1	4	2
Power switches	12	7	9
Diodes	0	3	1
Isolated gate drive circuits	9	3	6
Inductors	2	0	1

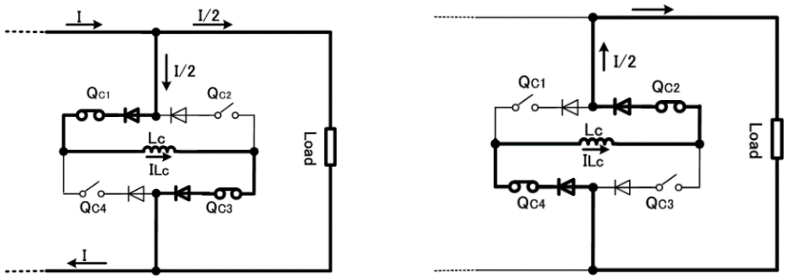
Operation modes of the new inverter circuit is detailed in Table 2. ON state of power switches is indicated by "1", while OFF state is indicated by "0". Employing switching combination of power switches, a nine level AC current waveform was generated. The magnitudes of output current levels consist of +I, +3I/4, +2I/4, +I/4, 0, -I/4, -2I/4, -3I/4, and –I currents. In this case, I is the magnitude of AC current generated by inverter. The inductor cell circuit works to create current levels thru charging and discharging operations of its inductor as depicted in Fig. 4. Energizing operation state of inductor cell (L_c) is performed if power switches Q_{C1} and Q_{C3} are turned on, whilst power switches Q_{C2} and Q_{C4} are turned off. A constant current 2I/4 passes though the power switches Q_{C1} and Q_{C3} which charges the inductor cell (L_c) to its stored energy capacity W_c. The kept energy in the inductor is formulated as:

$$W_c = \frac{1}{2} L_c I_{Lc}^{\ 2} \tag{1}$$

where L_c is the inductor cell size, and I_{Lc} is the current of inductor cell [26]. This energy will be utilized to obtain staircase currents of multilevel AC current waveform.

Table 2. Operation states of inverter's power switches.

Q_1	Q_2	Q_3	Q_4	Q_5	Q_{C1}	Q_{C2}	Q_{C3}	Q_{C4}	I_{out}
1	0	1	0	0	1	1	0	0	+I
1	0	1	0	1	0	1	0	1	3I/4
1	0	1	0	1	0	0	1	1	2I/4
1	0	0	1	1	1	0	1	0	I/4
1	0	1	0	1	1	1	0	0	0
0	1	0	1	1	0	1	0	1	-I/4
0	1	0	1	1	0	0	1	1	-2I/4
0	1	0	1	1	1	0	1	0	-3I/4
0	1	0	1	0	1	1	0	0	-I



(a) Energizing operation. **(b) De-energizing operation.**

Fig. 4. Operation modes of the inductor cell circuits [26, 27].

In this proposed inverter, in order to adjust the current flowing through inductor cell, a proportional integral (PI) current controller was employed as shown in Fig. 5. Error signal of controller regulates operation modes of inductor cell circuits, i.e. energizing or de-energizing mode. This will keep a steady inductor cell current required to generate less harmonics of AC current [26, 27]. Furthermore, a pulse width modulation (PWM) strategy using triangular carrier signals, and sinusoidal reference wave was implemented to output PWM pattern of output current. Eight carrier signals with same phase but different offset values plus a single sinusoidal signal were required as shown in Fig. 6.

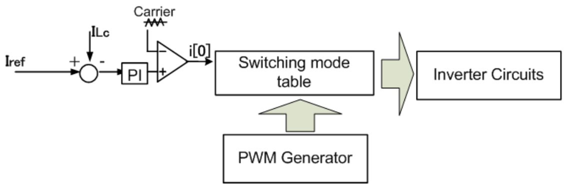


Fig. 5. Control system of inverter circuit.

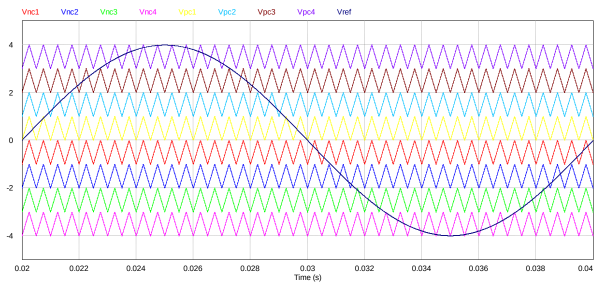


Fig. 6. Modulation technique [29].

3. Test Results and Analysis

3.1. Test parameters

The proposed method was tested thru computer simulations and laboratory prototype. Table 3 is the specification of inverter system. The power switches worked at 22 kHz, which is the frequency of carrier signals of PWM modulation technique. It was chosen to evade noise caused by switching operation, and to minimize the size of inverter's output filter where in this research was 3 µF. The inverter will output current with main frequency 50 Hz which is the sinusoidal reference frequency of modulation. The voltage of input power was 120 volts. The chosen inductor size for the DC current generator and inductor cell was the same as 1 mH. This inductance value is commercially available in the market. Its price is also relatively cheap and light in weight. The power switches of inverter's laboratory prototype were realized by using high speed power MOSFET FK30SM-6 in series with ultrafast recovery power diode HFA16PB120.

Table 3. Test parameters of the circuits.

Switching speed	22 kHz
Fundamental frequency	50 Hz
Load	L= 1 mH, R= 12 ohm
Filter	3 uF
DC input	120 volts
Inductor	1 mH

3.2. Output current waveforms

Figure 7 shows the nine-level PWM current (I_{9level}), and load current (I_{Load}) delivered by inverter system with frequency 50 Hz. The peak current of nine level current is 10 amperes. Current waveform in the capacitor filter (I_{Cf}) can also be observed in this figure. As can be seen, the harmonics current flown thru the filter capacitor. The load current is the nine-level current minus the capacitor current. As a result of this, a pure sinusoidal current was delivered to the load.

Moreover, the DC current sources I_{L1} and I_{L2}, and the inductor cell current (I_{Lc}) are depicted in Fig. 8. In this operation, the inductor cell current was set as half of DC current source, i.e. I_{L1}= 5 A, I_{L2}= 5 A and I_{Lc}=2.5 A. Closely constant DC currents were achieved by using inductor 1 mH. The sum of the current I_{L1} and I_{L2} will be the magnitude of nine level current waveform. While the current I_{Lc} will form staircase currents as described in Table 2. Figure 9 presents experimental test results of the inverter prototype. The magnitude of the PWM current was 8 A with modulation index 0.95. A PWM multilevel current, and sinusoidal load current were experimentally confirmed.

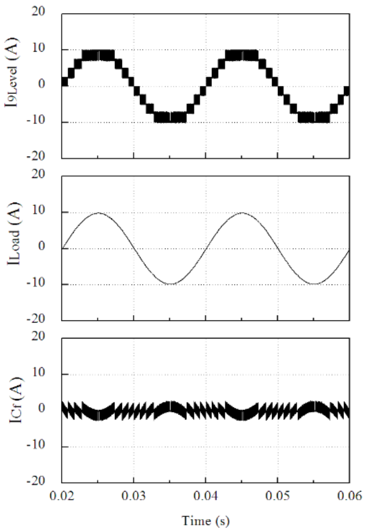


Fig. 7. Inverter's current waveforms.

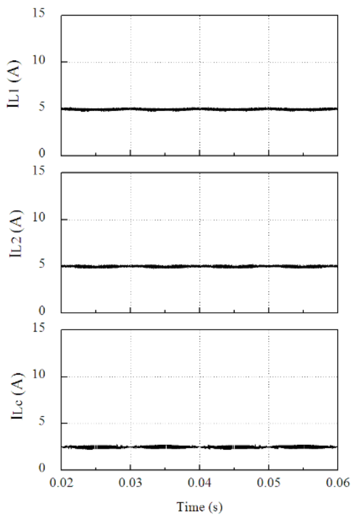


Fig. 8. Inductor's currents.

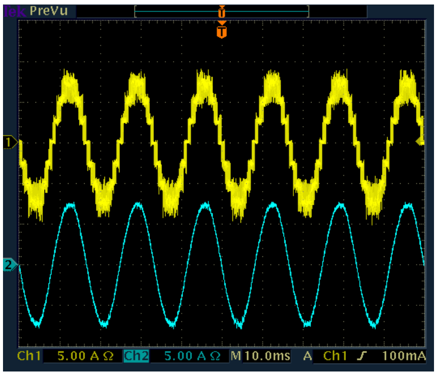


Fig. 9. Experimental test results of PWM and load current waveforms.

3.3. Harmonics and transient analysis

In order to investigate the quality of inverter output current, harmonics analysis was carried out. The harmonics spectra of nine-level current are depicted in Fig. 10. It includes the harmonics bands of switching frequency, around 22 kHz and 44 kHz. These harmonics components will flow thru filter capacitor installed at output terminal of inverter as previously depicted in Fig. 7. The low frequency harmonics constituents of the nine-level PWM current is presented in Fig. 11. The highest harmonic was the 5th order, of which its magnitude was only about 0.4%. The 3rd and 7th harmonics were around 0.07% and 0.2%, respectively.

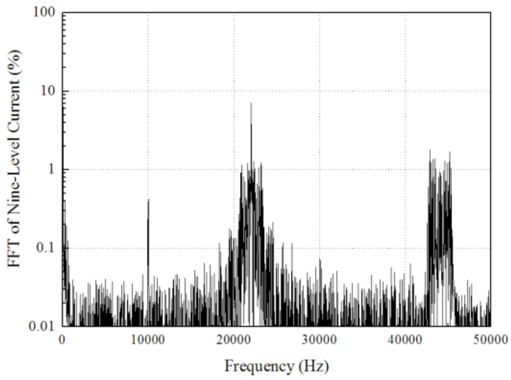


Fig. 10. Harmonics of nine-level current.

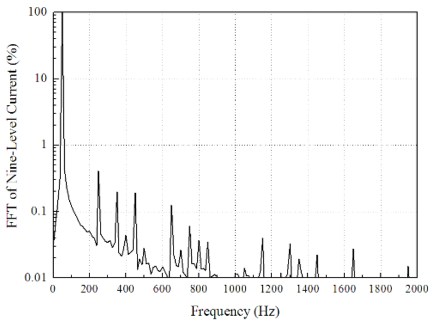


Fig. 11. Low harmonics of nine level current.

Harmonics profile of load current is shown in Fig. 12, of which magnitude of all harmonics components were less than 0.2%. The 5th harmonic order was still the highest magnitude, around 0.19%. Applying 3 μF filter capacitor at the output terminal of inverter, a closely pure sinusoidal current was confirmed. The measured harmonic distortion (THD) value of this current was 0.48 %.

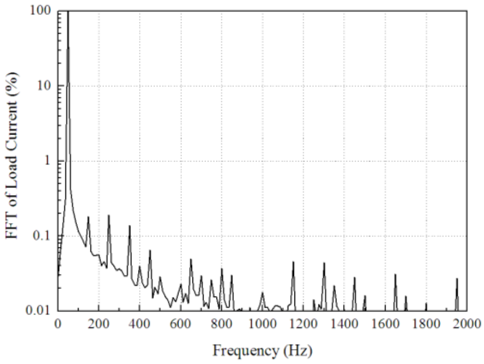


Fig. 12. Harmonics of load current.

In order to assess the performance of the current controller, transient test of inverter circuit was carried out. Test result waveforms of inverter during transient condition is shown in Fig. 13. In this test, the DC input current was changed from 2.5 A to 5 A as depicted in this figure. It will also change the inductor-cell and load currents of inverter. The result shown that the inverter circuit worked properly even the load current was changed 100% from 5 A to 10 A. The inductor cell current varied from 1.25 A to 2.5 A. There was no overshoot of the DC input inductors and inductor cell currents. It confirmed that the controller has functioned well in keeping constant and stable DC input and inductor cell currents.

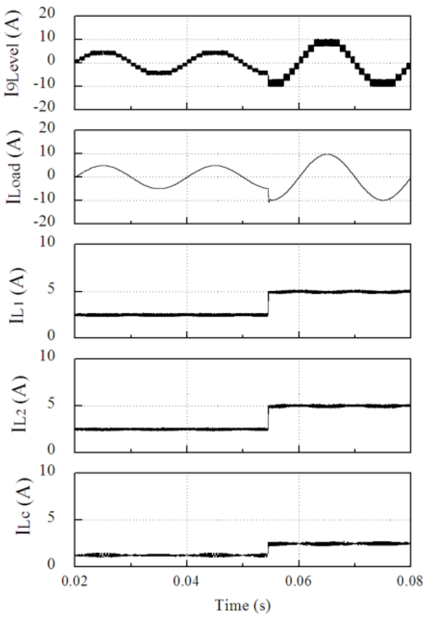


Fig. 13. Transient test results.

4. Conclusions

Inverter having less harmonics with minimum component number is a challenging in the development of inverter circuits. Conventionally, increasing level number of output waveform will need more components to build the inverter circuits. A new method has been developed by combining two different methods, i.e. inductor-cell and DC current module methods. The new method was applied to create new circuit of multilevel inverter. The developed inverter can be a new alternative to produce multilevel output current with less harmonics components, and fewer component number. Compared with inductor cell method, this circuit was able in reducing the total of control switches, and power inductors. Moreover, compared with the DC current module method, it reduced the number of DC current sources. The new inverter circuits worked properly generating a multilevel AC current waveform.

Acknowledgments

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Nomenclatures

I_{Ln}	DC current source, A
L_C	Inductor cell, mH
I_{Lc}	Current of inductor cell, A
I_{ref}	Reference current, A
W_c	Energy capacity, J

Abbreviations

AC	Alternating Current
CSI	Current Source Inverter
DC	Direct Current
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
PI	Proportional Integral
PWM	Pulse Width Modulation
THD	Total Harmonics Distortion
VSI	Voltage Source Inverter

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