A New H-Bridge Multilevel Current-Source PWM Inverter with Inductor Cells

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Abstract-The paper proposes a new circuit configuration of a multilevel current-source inverter (CSI). In this new topology, a basic H-bridge CSI working as a main inverter is connected in parallel with inductor cells operated as auxiliary circuits. The inductor cell is composed by four unidirectional power switches with an inductor across the cell circuit. The inductor cells work generating the intermediate level currents to obtain a multilevel current waveform without additional external DC power sources. A simple PI controller is adopted to control the intermediate level currents of the multilevel output waveform. Five-level PWM inverter configuration, with a chopper based DC current source, is verified through computer simulations. Furthermore, an experimental prototype of a five-level CSI is setup and is tested. The results show that the circuit works properly to generate the multilevel output current waveform with low harmonic distortion by using small inductors, which proves feasibility of the proposed strategy.

Keywords: current-source inverter; H-bridge, inductor cell; multilevel

1. INTRODUCTION

Recent development of high-performance semiconductor power switches such as MOSFETs and IGBTs increases the research interest in high power converters such as multilevel voltage source inverters (VSI) and their dual circuits, multilevel current source inverters (CSI). Multilevel inverters have capability to deliver higher output power with lower dv/dt or lower di/dt and less distorted output waveforms resulting in reduction of EMI noise and size of an output filter [1].

In distributed generation application, as most renewable energy sources, such as photovoltaic systems, deliver DC power, the generated power must be converted to AC power and is fed into the grid through a grid connected inverter. Various international standards, like IEEE-1547, IEEE-929 and EN-61000-3-2, impose requirements on the inverter's output power quality, such as harmonic currents and total harmonics distortion (THD) of the output current [2]. Multilevel CSI is one of effective solutions to tackle such problem. Control of the grid connected CSI is comparatively simpler than its counterpart, VSI. A grid connected CSI can buffer the output from grid voltage fluctuation, generates a predetermined magnitude of current to the grid without AC current feedback loops, and can achieve a high power factor operation [2], [3]. Its output current is less affected by grid voltage, and it has inherent short circuit protection.

Some topologies of multilevel CSIs have been proposed by researchers and engineers. A conventional method to generate the multilevel output waveforms is by paralleling some three-level H-bridge CSIs [4]-[6]. However, the requirement of many isolated DC current sources is a problem introduced by this configuration. Another topology of the multilevel CSI is by applying multicell topology of CSI, which is the dual converter of flying capacitor multilevel VSI [7]-[9]. However, this topology has drawback with its bulky intermediate inductors and its control complexity for balancing control of the intermediate level currents. References [10] and [11] presented a novel common-emitter configuration of multilevel-CSI obtained by connecting two-level CSI modules with the three-level common-emitter CSI. This configuration has a great advantage because all of the power switches are connected at a common-emitter point. This topology needs only an isolated gate drive circuit to drive all power switches of the inverter, hence the complexity of the gate drive circuits can be moderated.

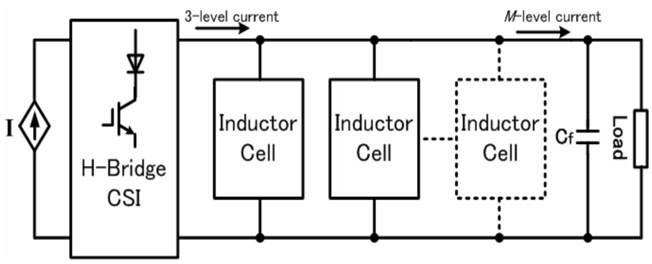


Fig. 1. Proposed configuration of multilevel CSI

This paper proposes a circuit configuration of a new multilevel CSI. In this new topology, a basic H-bridge CSI working as a main inverter circuit is connected in parallel with inductor cells. The inductor cells work generating the intermediate level currents of the output to obtain a multilevel current waveform without any additional external DC power sources. The operating performance of the proposed multilevel CSI is examined and tested through some computer simulations and experiments.

2. CIRCUIT TOPOLOGY AND OPERATION PRINCIPLE

2.1. Operation Principle of Proposed Multilevel CSI

Fig. 1 shows a schematic diagram of the proposed multilevel CSI. The newly proposed configuration of the multilevel CSI is obtained by connecting the H-bridge CSI with a single or more inductor cells. Fig. 2 shows a configuration of the proposed inductor cell circuit composed by four unidirectional controlled power switches Q_{C1}, Q_{C2}, Q_{C3} and Q_{C4}, and an inductor Lc connected across the cell circuit. A five-level CSI configuration is obtained by connecting a single inductor cell, a nine-level CSI configuration is achieved by connecting two inductor cells in parallel with the main three-level H-bridge CSI, and so forth. The relation between the level number of the output current waveform (*M*) and the number of the inductor-cells (*N*) can be formulated as expressed by the equation below:

$$M = 2^{(N+1)} + 1. \quad (1)$$

Fig. 3 shows the configurations of a five-level CSI using the proposed strategy. The switching states of this five-level CSI are listed in TABLE I. A single inductor cell is connected to the H-bridge CSI. The inductor-cells work generating intermediate level currents of a multilevel output waveform from the basic

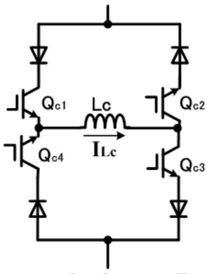


Fig. 2. Proposed inductor cell circuit

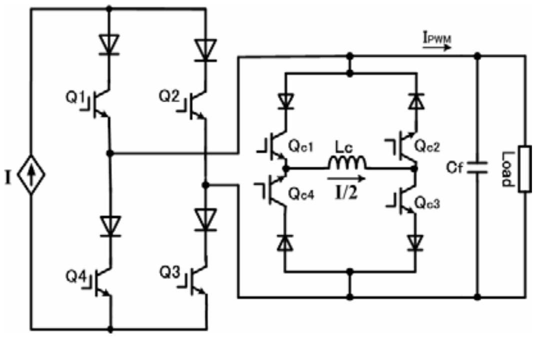
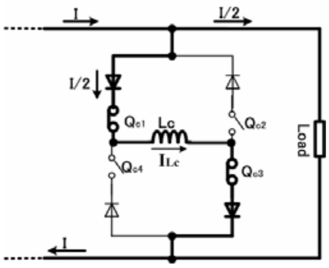
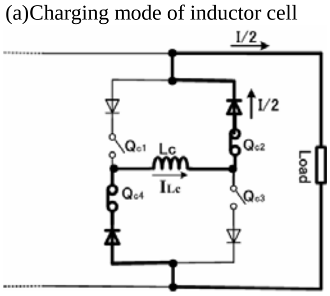


Fig. 3. Proposed five-level CSI



(a)Charging mode of inductor cell



(b) Discharging mode of inductor cell
Fig. 4. Operation modes of inductor cell

TABLE I
SWITCHING STATES OF FIVE-LEVEL CSI

Q_1	Q_2	Q_3	Q_4	Q_{c1}	Q_{c2}	Q_{c3}	Q_{c4}	**Output**
1	0	1	0	1	1	0	0	+I
1	0	1	0	0	0	1	1	+I
1	0	1	0	1	0	1	0	+I/2
1	0	0	1	0	1	0	1	+I/2
1	0	0	1	1	1	0	0	0
1	0	0	1	0	0	1	1	0
0	1	0	1	0	1	0	1	-I/2
1	0	0	1	1	0	1	0	-I/2
0	1	0	1	0	0	1	1	-I
0	1	0	1	1	1	0	0	-I

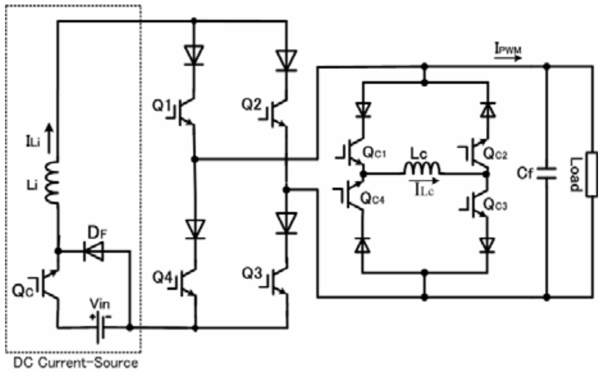


Fig. 5. Five-level CSI with chopper based DC current source

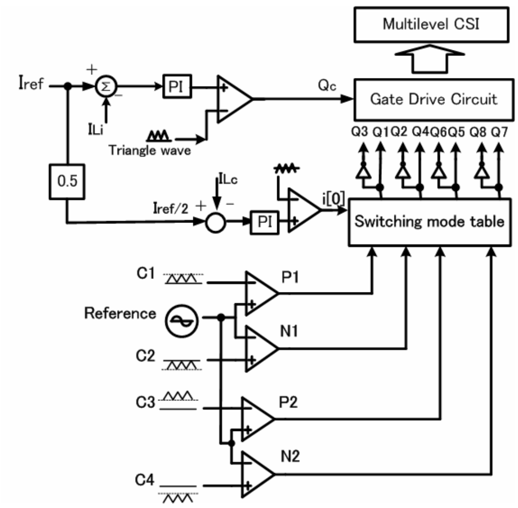


Fig. 6. Control diagram of proposed five-level CSI

three-level current of H-bridge CSI. It utilizes charging and discharging operation modes of the inductor. Fig. 4 shows the operation modes of the inductor cell during a positive cycle operation of the five-level CSI. Charging operation mode of the inductor Lc is conducted when the switches Q_{C1} and Q_{C3} are turned on, while Q_{C2} and Q_{C4} are turned off. A current I_{Lc}=I/2 flows through the power switches Q_{C1} and Q_{C3} which energizes the inductor Lc. Discharging operation mode is achieved by turning on the switches Q_{C2} and Q_{C4} and by turning off Q_{C1} and Q_{C3}. The stored energy in the inductor is discharged to the load as a current I/2. Similar operation modes occurred for the negative cycle of the output current waveform. For *M*-level CSI, if the DC current-source of the main H-bridge CSI is assumed to have an amplitude I, the current flowing through the N^{th} inductor cell $I_{LC(i)}$ is expressed as

$$I_{Lc(i)} = \frac{I}{2^i}\text{ , i=1, 2,…, N.} \tag{2}$$

The output current levels of the five-level CSI are +I, +I/2, 0, -I/2, and -I current levels. For nine-level CSI, the output are +I, +3I/4, +I/2, +I/4, 0, -I/4, -I/2, -3I/4, and -I current levels.

2.2. DC Current Source

In the proposed multilevel CSI, the DC current source is indispensable. In order to test the proposed circuit, the DC current source is obtained by employing a chopper with a smoothing inductor connected with the main three-level H-bridge inverter.

The chopper consists of a controlled switch that regulates the DC current flowing through the smoothing inductor Li. A free-wheeling diode is used to keep continuous current flowing through the smoothing inductor I_{Li}. The chopper works as a regulated DC current source. Fig. 5 shows a circuit configuration of the proposed five-level CSI with the chopper based dc current source. The power source (Vin) may be batteries, PV modules, a fuel-cell or a rectifier. A simple proportional integral (PI) regulator is applied to control the DC current flowing through the smoothing inductor, which determines the amplitude of the PWM output current waveform I_{PWM} simultaneously.

2.3. PWM Technique and Inductor-Cell Control

In order to achieve a low distortion of the output current waveform, a pulse width modulation (PWM) technique is applied. In this paper, a level-shifted multi-carrier based sinusoidal PWM technique is employed to generate gate signals for the CSI power switches and to obtain the PWM current waveforms. A schematic control diagram including the current controller of the chopper and the inductor cell for the five-level CSI is shown in Fig. 6.

The control circuit of the inductor cell functions to control the operation modes, i.e. charging and discharging modes, of the inductor cell Lc. The current flowing through the inductor cell I_{Lc} is kept constant. It generates the intermediate level currents based on the output waveform of the H-bridge CSI. A PI regulator is applied to zero the error between the detected current flowing through the inductor cell and the reference current which is half of the main dc current and to obtain stable and balanced intermediate level currents. The output of the PI regulator is modulated by a triangular carrier to generate the control signal i[0] determining the operation modes of the inductor cell. The frequency of the triangular carrier waveform determines the switching frequency of the inductor cell's power switches which also regulates the charging and the discharging modes of the inductor-cell.

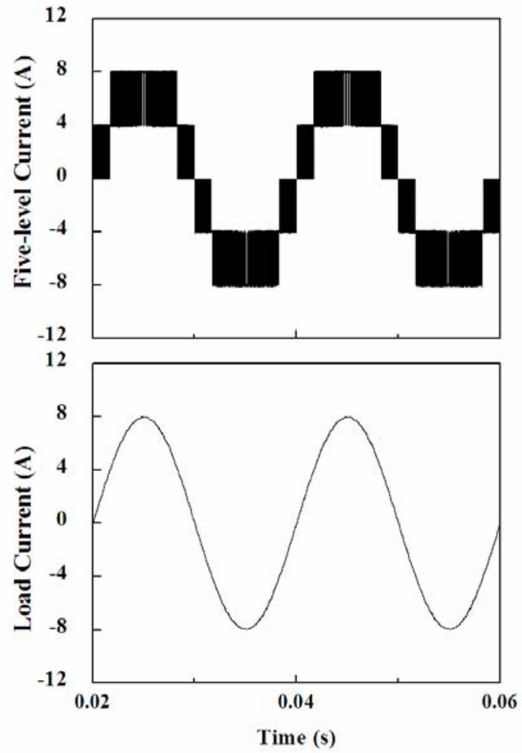
In case of the nine-level CSI, the control circuit of the second inductor cell is similar to the first inductor cell mentioned above. The difference is only the reference value of the second inductor cell current, which is quarter of the main DC current source amplitude. Therefore, for *M* level CSI, if the DC current source of the main H-bridge CSI is assumed to have amplitude I, the current flowing through the N^{th} inductor cell I_{Lc} is expressed as in (2).

3. SIMULATION RESULTS

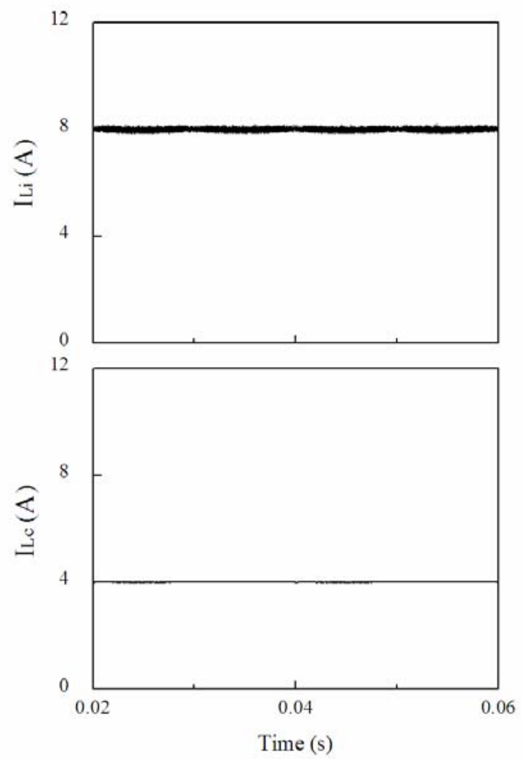
In order to test the proper operation of the proposed multilevel CSI topology, a five-level CSI configuration with a chopper based dc current source as shown in Fig. 5 was tested by using computer simulation with a PSIM software. The test parameters are listed in TABLE II. Fig. 7(a) shows the computer simulation result of the proposed five-level CSI, where the five-level PWM current and the load current waveforms are presented. Fig. 7(b) shows the smoothing inductor current and the inductor cell current waveforms. As can be seen in the result, the amplitude of the inductor cell current is properly controlled at 50 % of the 8-A smoothing inductor current.

TABLE II
TEST PARAMETERS

Smoothing inductor and inductor cell	1 mH and 5 mH
Power source voltage	160 V
Inverter switching frequency	22 kHz
Filter capacitor C*f*	5 μF
Load	R = 6.2 Ω, L =1.2 mH
Output current frequency	60 Hz



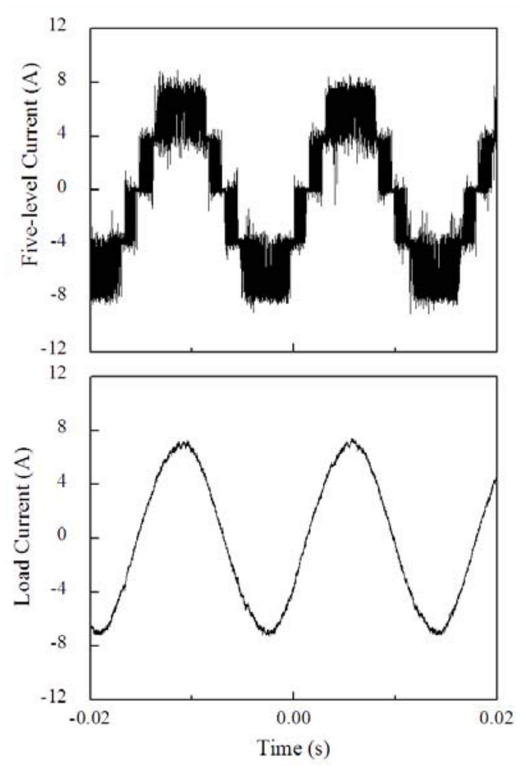
(a) Five-level and load current waveforms



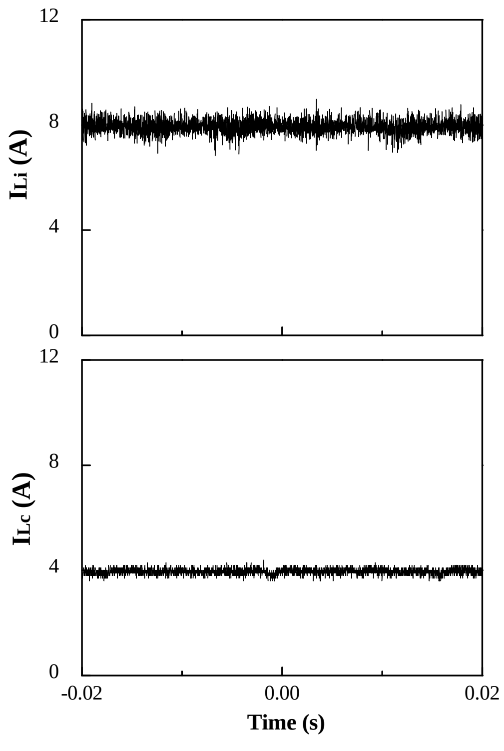
(b) Smoothing inductor current I_{Li} and inductor cell current I_{Lc} waveforms
Fig. 7. Simulation result of the proposed five-level CSI

4. EXPERIMENTAL TEST RESULTS

In order to verify and to prove feasibility of the proposed multilevel CSI configuration, a laboratory prototype of the five-level CSI was constructed with IXFK90N30 power MOSFETs in series with DSEI120-06A fast recovery diodes. The control circuits were designed with mixed-signal electronics using analog Op-Amps and EPROMs. The opto-isolator based gate drive



(a) Five-level and load current waveforms



(b) Smoothing inductor current I_{Li} and inductor cell current I_{Lc} waveforms
Fig. 8. Experimental test result of five-level CSI

circuits are used in the prototype. The implemented circuit specifications are identical with the computer simulation parameters in TABLE II. Fig. 8(a) shows the experimental waveforms of the five-level CSI, i.e., an 8-A, 60-Hz five-level PWM output current and a load current waveforms with modulation index 0.9. Fig. 8(b) shows the current waveforms flowing through the smoothing inductor and inductor cell. The inverter worked properly generating a five-level output current waveform. In addition, a low distorted sinusoidal load current waveform is also obtained after filtering by a small 5-μF filter capacitor. All of the experimental waveforms agree with those of the computer simulation results. The measured THD value of the five-level PWM current is 2.93%.

5. CONCLUSION

In this paper a new configuration of a multilevel CSI, which employs inductor cells as auxiliary circuits, has been proposed. The inductor cells are connected in parallel with the main H-bridge CSI to generate multilevel output current waveforms without additional external DC power sources. A chopper based dc current source is also introduced in order to reduce the size of the smoothing inductor. The simulation and experimental results show that using the proposed multilevel CSI a low distortion of output current can be obtained by using small inductors.

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