Multilevel Current-Source Inverters using Inductor-Cells and DC-Current Modules: A Comparative Discussion

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Abstract This paper presents a comparison discussion of new multilevel current-source inverters (CSIs) created from the basic H-bridge CSI. The first topology is obtained by connecting the inductor-cells in parallel with the main H-bridge CSI. The inductor-cells with its intermediate inductor work generating the intermediate current levels of multilevel waveform without any additional external power sources. The second configuration is achieved by superimposing the output of the DC-current modules to the H-bridge CSI. This strategy can reduce the number of power switching devices and simplify the gate drive circuits of the inverter. Furthermore, the superimposing technique can achieve lower inductor loss than the inductor-cell strategy. Several experimental results are presented in the paper, which demonstrates the features of each topology in generating multilevel output current with low harmonics distortion and with small size of inductors.

Keywords-current-source inverter; multilevel; inductor-cell; DC-current module

1. Introduction

Generally speaking, the multilevel inverter topologies can be classified into two types; voltage-source inverters (VSI) and its dual circuit, i.e., current-source inverters (CSI). Multilevel inverters have capability to deliver multilevel AC waveform with low-voltage or low-current rating devices, less distorted output waveforms, lower d*v*/dt or lower d*i*/dt, and resulting in reduction of voltage or current stress in the switching devices, reduction of EMI noise and reduction of the output filter size, if compared with the conventional two-level inverters[1], [2]. In distributed power generation, multilevel CSIs have some interesting features as power interface between the renewable energy systems and power grid. 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 [3]. These requirements can be easily achieved by using multilevel CSI. Moreover, 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. Moreover, it has inherent short circuit protection [4].

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 H-Bridge CSIs as shown in Fig. 1 [2]. However, the requirement of many isolated DC current sources is a problem introduced by this configuration. Fig. 2 shows another topology of multilevel CSI called as the multilevel multi-cell CSI [5]. This topology has drawback with its huge intermediate inductors and its control complexity for balancing control of the intermediate level currents. Some control methods have been proposed for balancing control of the intermediate level currents in [6] and [7], but very large in size of the intermediate inductors (>100 mH) are still used. These bulky inductors will be costly and cause low efficiency to the inverter. Reference [2] presented the configuration of multilevel single-rating inductor CSI which can be regarded as a modified configuration of multilevel paralleled H-bridge CSI with intermediate-inductors.

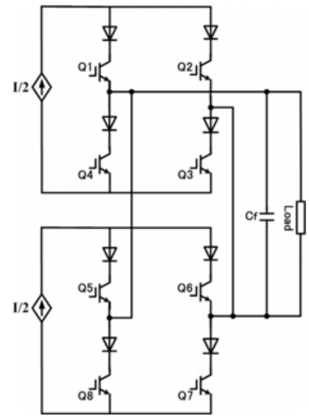


Fig. 1. Five-level paralleled H-Bridge CSI

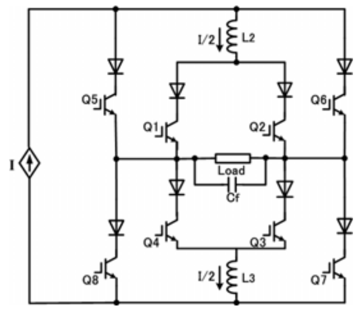


Fig. 2. Five-level multi-cell CSI

This paper discusses new circuit configurations of multilevel CSIs obtained from the basic H-bridge CSI. In the first topology, the H-bridge CSI working as a main inverter circuit is connected in parallel with the 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 second topology is created by connecting a single or more DC-current modules to the H-bridge CSI. The operating performance and the features of each multilevel CSI are analyzed and examined through some computer simulations, and experimentally using laboratory experimental prototypes.

2. Circuit Configuration and Principle Operation

2.1. Multilevel Inductor-Cell Type CSI

Fig. 3 shows the configuration of the proposed inductor-cell circuits composed by four controlled power switches QC1, QC2, QC3 and QC4 with series discrete diodes, and an intermediate inductor Lc connected across the bridge [8]. The newly proposed configuration of the multilevel CSI can be obtained by connecting the three-level H-bridge CSI as the main inverter with a single or more inductor-cells as shown in Fig. 4. A five-level CSI configuration is obtained by connecting only a single inductor-cell, a nine-level CSI configuration is achieved by connecting two inductor-cells in parallel with the main three-level CSI, and so forth. The relation between the level number of the output current waveform and the number of the inductor-cells can be expressed as the equation below:

$$M = 2^{(N+1)} + 1, \tag{1}$$

where M is the level number of the output current, and N is the number of the inductor-cells. The inductor-cell is used to generate a multilevel output current from the basic three-level current waveform by controlling the charging, and discharging operation modes of the intermediate inductor, Lc. If the amplitude of the DC current source in a M-level CSI is I, the current flowing through the N^{th} inductor-cell I_{LcN} is expressed as

$$I_{LcN} = \frac{I}{2^N}, \tag{2}$$

Fig. 5 shows the configuration of a five-level CSI composed by the H-bridge CSI and a single inductor-cell. Table 1 lists the switching states for five-level output current waveform generation. Furthermore, Fig. 6 shows the operation modes of the inductor-cell during a positive cycle operation of the five-level CSI.

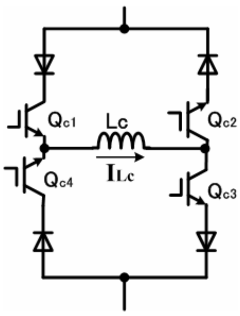


Fig. 3. Proposed inductor-cell circuits

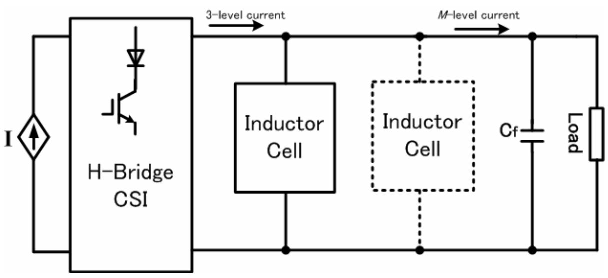


Fig. 4. Proposed *M*-level inductor-cell type CSI

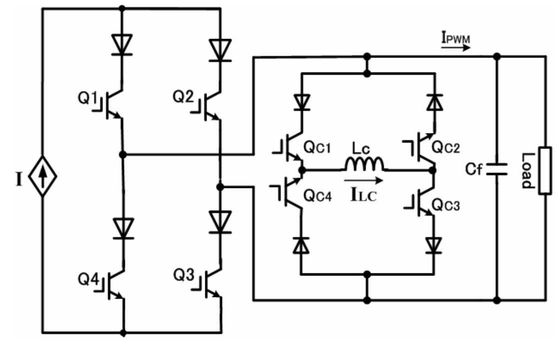
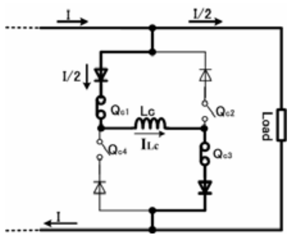


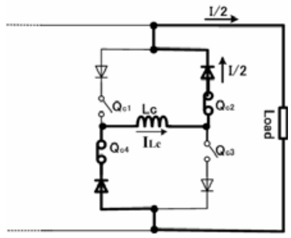
Fig.5. Five-level inductor-cell type CSI

Table 1 Switching states

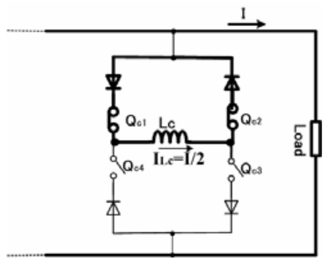
Q_1	Q_2	Q_3	Q_4	Q_{C1}	Q_{C2}	Q_{C3}	Q_{C4}	Output current
1	0	1	0	1	1	0	0	*+I*
1	0	1	0	0	0	1	1	*+I*
1	0	1	0	1	0	1	0	*+I/2*
1	0	0	1	0	1	0	1	*+I/2*
1	0	0	1	1	1	0	0	*0*
0	1	1	0	0	0	1	1	*0*
0	1	0	1	0	1	0	1	*-I/2*
0	1	1	0	1	0	1	0	*-I/2*
0	1	0	1	0	0	1	1	*-I*
0	1	0	1	1	1	0	0	*-I*



(a) Charging mode



(b) Discharging mode



(c) Circulating current mode

Fig. 6. Operation modes of inductor-cell

In the five-level H-bridge with inductor-cell CSI, in order to generate intermediate level currents +I/2 and –I/2, a constant current I/2 is kept constant flowing through the inductor-cell. It is achieved using the alternating charging and discharging operation modes of the inductor as shown in Fig. 6. In the nine-level CSI configuration with two inductor-cells, the current flowing through the second inductor-cell is regulated to be I/4, as expressed in (2).

2.2. Multilevel DC-Current Module Type CSI

Fig. 7 shows the basic circuit configuration of a DC-current module, and its output waveform [9]. The circuit is composed by a single DC current source, a controlled power switch Q with a series diode, and a blocking diode, Dc. Another new configuration of the multilevel CSI can be obtained by connecting the three-level H-bridge CSI with a single or some DC-current modules as shown in Fig. 8. The output of the DC-current modules are superimposed to the three-level current waveform of the H-bridge CSI to generate a multilevel output current waveform. The level number of the output current waveform (*M*) that can be produced by using *D*-number of the DC-current modules connected to the H-bridge CSI can be obtained from the equation below:

$$M = 3 + 2D, \tag{3}$$

A five-level CSI is obtained by connecting a single DC-current module, a seven-level CSI configuration is achieved by connecting two DC-current modules with the H-Bridge CSI, and so forth.

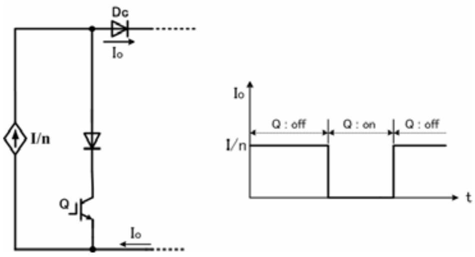


Fig. 7. Proposed DC-current module, and its typical output current waveform

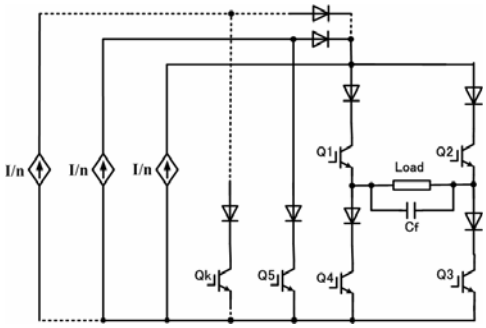


Fig. 8. Proposed *M*-level DC-current module type CSI

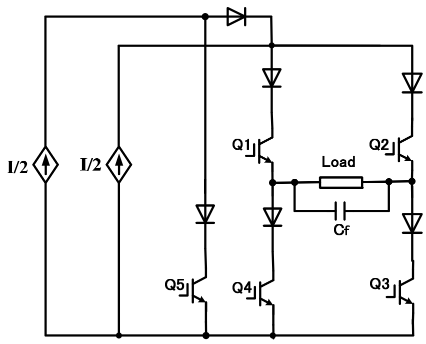


Fig. 9. Proposed five-level DC-current module type CSI

Table 2 Switching states of five-level CSI

Q_1	Q_2	Q_3	Q_4	Q_5	Output
1	0	1	0	0	*+I*
1	0	1	0	1	*+I/2*
1	0	0	1	1	*0*
0	1	0	1	1	*-I/2*
0	1	0	1	0	*-I*

As can be seen in the proposed *M*-level CSI in Fig. 8, the power switches Q3, Q4, and the power switches of the DC-current modules Q5 to Qk are connected at a common-emitter line or at the same potential level. Two isolated gate drive circuits are required to drive switches Q1 and Q2, and one more to drive Q3, Q4, Q5 and Qk. Hence, no matter how many DC-current modules are connected, the whole inverter circuit needs only three isolated gate drive circuits. Using this circuit topology, the number of the isolated gate drive power supplies can be simplified; hence, it can reduce the circuit components and the gate drive circuits complexity, such as isolation transformers; in case of isolated power supplies are used for each power switch; or the capacitors; in case of bootstrap technique is applied. Fig. 9 shows a configuration of the proposed five-level CSI composed by an H-bridge CSI and a single DC-current module. All of the DC current sources are assumed to have identical current amplitudes I/2, and the amplitude of the output current is I. Table 2 lists the operation modes for five-level output current generation.

2.3. DC Current Source Circuits

In this paper, the DC current sources required in the multilevel CSIs are obtained by employing chopper circuits with small inductors. The chopper circuit consists of a controlled switch $Q_{c,}$ controlling the DC currents flowing through the smoothing inductor, and assuring the intermediate levels balance of the multilevel output waveform. Free-wheeling diodes are used to keep continuous currents flowing through the inductors. Fig. 10 and Fig. 11 show the configurations of the five-level inductor-cell type and the five-level DC-current module type CSIs with chopper circuits as the DC current supplies, respectively. The inductors Li, L1, and L2 are the smoothing inductors used to generate the DC currents. In the multilevel DC-current module type CSI, by connecting more and more DC-current modules, the higher level number of the output current waveform with smaller current rating of the switching devices and smaller distortion of the output current waveform can be obtained. It should be noted that, only a single DC power source (Vin) is required to obtain the multiple DC current sources of the CSI. In real application, the DC power source can be PV arrays, fuel cell, battery or rectifier.

2.4. Current Control and PWM Modulation Strategy

The current control diagram of the chopper circuits and inductor-cell of the five-level inductor-cell type CSI is presented in Fig. 12. Proportional integral (PI) regulators are independently applied to control the currents flowing through the smoothing inductor Li and and inductor-cell Lc, which determine the amplitude of the PWM output current waveform (Ipwm) and the intermediate current levels, simultaneously. Making the smoothing and the intermediate inductor currents follow their reference current (Iref) is the objective of these current regulators. The switching gate signals of the chopper switch are generated by comparing the error signal of the detected steady state currents flowing through the smoothing inductor, ILi and a triangular waveform after passing through the PI regulator. This signal is used to control the duty cycles of the chopper switch to obtain a stable DC current. This control circuit is similar for all chopper circuits accompanying the DC-current modules in the multilevel DC-current module type CSI.

In order to obtain a better output current waveform, a pulse width modulation (PWM) technique is applied, instead of a staircase waveform operation. Staircase waveform can easily be obtained at the fundamental switching frequency, so the switching losses can be negligibly low. However more distortion of the output waveform is generated and a larger filter is needed. In this paper, a level-shifted

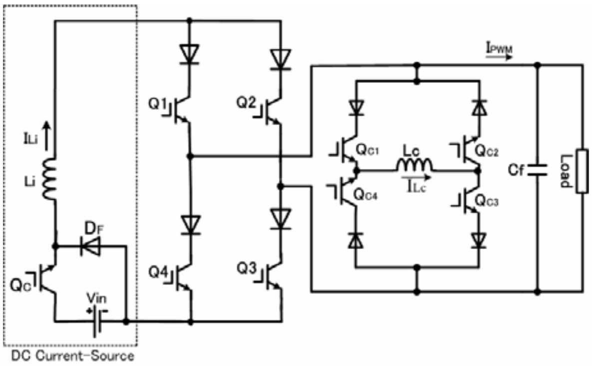


Fig. 10. Experimental circuit of five-level inductor-cell type CSI

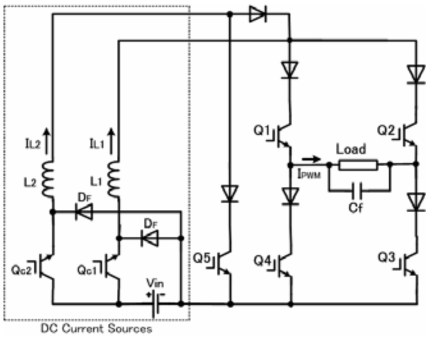


Fig. 11. Five-level DC-current module type CSI with chopper based DC current-sources

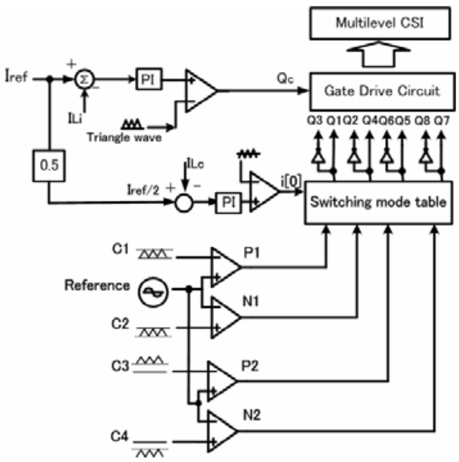


Fig. 12. Control diagram of five-level inductor-cell type CSI

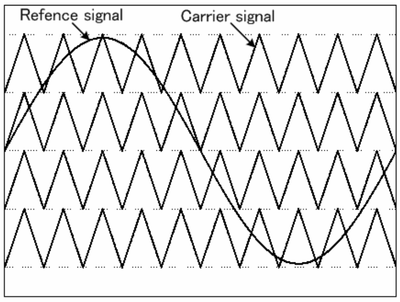


Fig. 13. Multi-carrier based sinusoidal PWM

multi-carrier based sinusoidal PWM technique is employed to generate the gating signals of the inverter's power switches to obtain the PWM current waveforms as shown in Fig. 13. All carrier waveforms are in phase with the identical frequency. The frequency of the reference sinusoidal waveform determines the fundamental frequency of the output current waveform, while the frequency of triangular carrier waves gives the switching frequency of the power switches.

2.5. Conduction Loss of Inductors

The conduction loss of huge inductors in the multilevel CSI is one of the main loss components which cause the efficiency of the CSI lower than the multilevel VSI topology. In the *M*-level CSI with *D*-number of DC-current modules, if the amplitude of the *M*-level output current is I, the current flowing through the smoothing inductor I_{lD} is expressed as

$$I_{lD} = \frac{I}{(D+1)}, \tag{4}$$

If the smoothing inductor has resistance R_l, the inductor's conduction loss (P_{lc}) caused by this current is expressed as

$$P_{lc} = \left(\frac{I}{D+1}\right)^2 R_l \tag{5}$$

The total conduction loss due to the inductors in an *M*-level DC-current module type CSI (P_{lc-M}) can be calculated as

$$P_{lc-M} == \frac{I^2 R_l}{D+1} \tag{6}$$

In the five-level DC-current module type CSI, the current flowing through the smoothing inductors is half the amplitude of the five-level output current. In the seven-level CSI configuration, the amplitude of the smoothing inductor currents is one third of the amplitude of seven-level current, and so forth. The higher the level-number of the output current leads smaller currents flowing through the smoothing inductors as expressed in (4). Therefore, it reduces the total conduction losses (P_{lc-M}) caused by the smoothing inductors as shown in Fig. 14. In this figure, the inductor's losses are normalized to the inductor's loss of the H-bridge CSI. The total inductor's conduction loss of the five-level CSI (P_{lc-5}) is half the inductor's conduction loss of the three-level H-bridge CSI (P_{lc-3}). The total inductor's conduction loss of seven-level CSI (P_{lc-7}) is one third of the inductor's conduction loss of the H-bridge CSI, and so forth. However, in the case of the multilevel inductor-cell type CSI, the inductor-cell circuits with its intermediate inductors will give the extra losses to the inverter. This condition is also the same as the multilevel multi-cell CSI configuration shown in Fig. 2.

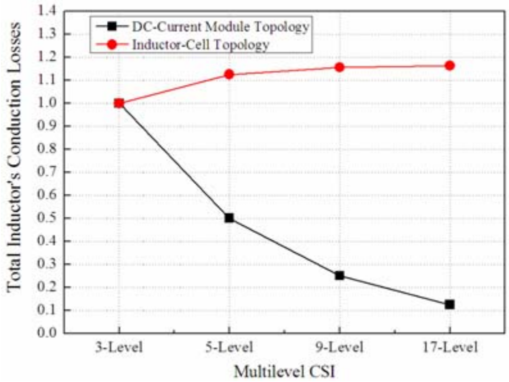


Fig. 14. Conduction loss characteristics of the inductors

Table 3 Comparison of component number

Multilevel CSI Types	Paralleled H-Bridge CSI Topology	DC-Current Module Topology	Inductor-Cell Topology
Power switches	10	7	9
Diodes	10	8	9
Inductors	2	2	2
Isolated gate drive circuits	6	5	5
DC current source	2	2	1
DC power source	2	1	1

In addition, Table 3 lists a comparison of the component number required to implement the five-level paralleled H-bridge CSI, five-level inductor-cell topology, and five-level with DC-current modules CSI. In this table it is assumed that all of the topologies use chopper circuits as DC current generation. The number of the components includes the devices required in the chopper circuits. As can be seen in the table, the five-level CSI with DC current modules requires the minimum number of the power switches and diodes even the chopper circuit components are included. The inductor-cell type CSI needs a single DC current source only, if ideal DC current sources are used.

3. Experimental Test Results

In order to verify and to prove feasibility of the proposed multilevel CSI configuration experimentally, laboratory prototypes of the five-level inductor-cell and the five-level DC-current module CSI topologies were constructed with IXFK90N30 power MOSFETs in series with DSEI120-06A fast recovery diodes. The five-level inverter circuit configurations shown in Fig. 10 and Fig. 11 were tested with a single 160 V DC power source. The switching and the fundamental output current frequencies are 22 kHz and 60 Hz, respectively. The inverter was connected to an inductive load, i.e. R = 6 Ω, L = 1.2 mH with a 5-μF filter capacitor. The smoothing inductors and the inductor-cell are 1 mH and 5 mH, respectively. Fig. 15 shows the experimental waveforms of the five-level inductor-cell type CSI showing the five-level PWM output current, the load current, smoothing inductor current and the inductor-cell current waveforms. This figure also shows the start-up transient waveforms of the inverter. No additional DC power source was connected to the inductor-cell circuits during the startup transient test. The inverter works properly generating a five-level output current waveform. The inductor-cell current has been driven to the balanced condition of 50% of the 8-A DC current source. As can be seen in the figure, a low distorted sinusoidal load current waveform is also obtained after filtering by a small 5-μF filter capacitor. Moreover, Fig. 16 shows the experimental waveforms of the five-level DC-current module type CSI presenting the five-level current, load current and the smoothing inductor currents I_{L1} and I_{L2}. Fig. 17 and Fig. 18 show the efficiency characteristics of the five-level CSIs with inductor-cell and DC-current module at a constant output current, respectively. The maximum efficiency of the five-level inductor-cell type CSI prototype is 90.8%, and 93.4% for the five-level DC-current module type CSI, which is higher than the inductor-cell type as predicted in the previous sections. Fig. 19 and Fig. 20 present the harmonics spectra of the five-level PWM current generated by the five-level CSI using inductor-cell and DC-current module topologies with THD values 2.93% and 2.6%, respectively

4. Conclusions

In this paper new configurations of multilevel CSI using inductor-cells and DC-current modules have been presented, and the validity has been verified experimentally. The proposed multilevel inductor-cell type CSI topology can reduce the number of the isolated DC current sources as required in the multilevel paralleled H-bridge CSI configuration. The configuration of the multilevel DC-current module type CSI can achieve lower inductor's conduction loss than the multilevel inductor-cell type CSI. The inductor-cells added to the main three-level CSI will give extra losses to the inverter. Chopper circuits working as DC current sources are also discussed which are able to reduce the inductor size down, and to assure stable DC current sources required in the multilevel CSI with simple PI regulators.

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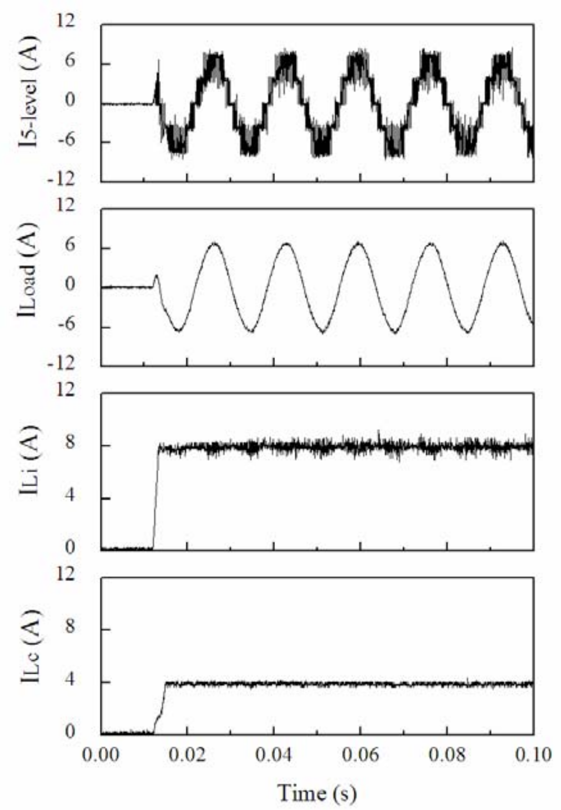

Fig. 15. Experimental waveforms of startup transient for five-level inductor-cell type CSI

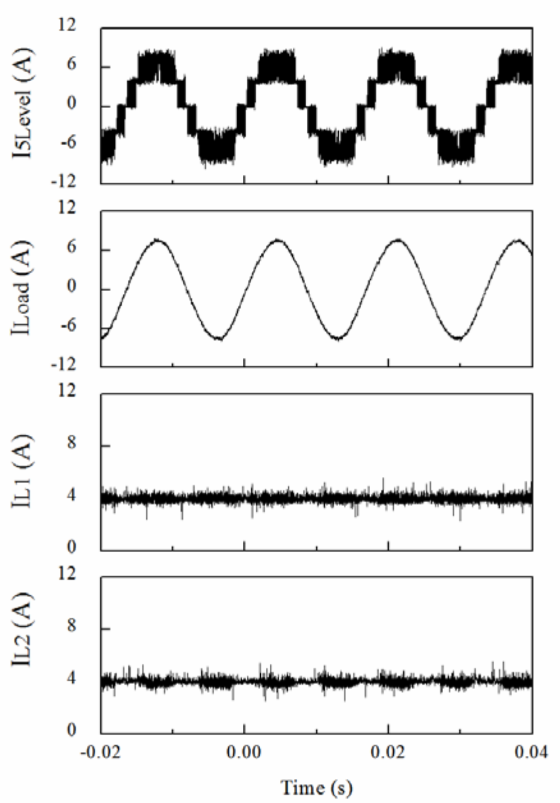

Fig. 16. Experimental waveforms of five-level DC-current module type CSI

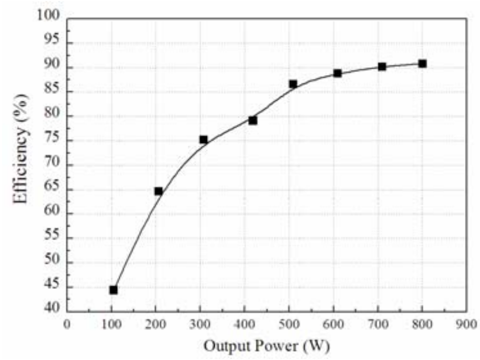

Fig. 17. Efficiency characteristics of five-level inductor-cell type CSI

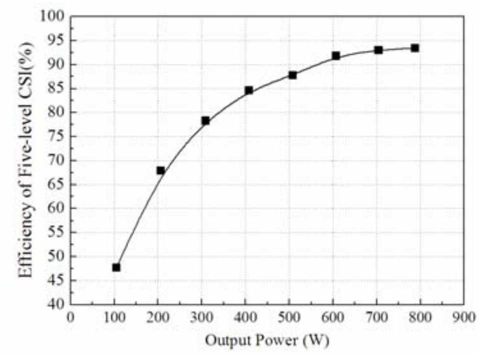

Fig. 18. Efficiency characteristics of five-level DC-current module type CSI

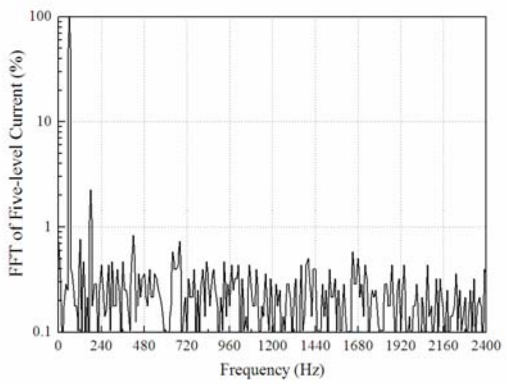

Fig. 19. FFT analysis result of five-level PWM current generated by five-level inductor-cell type CSI

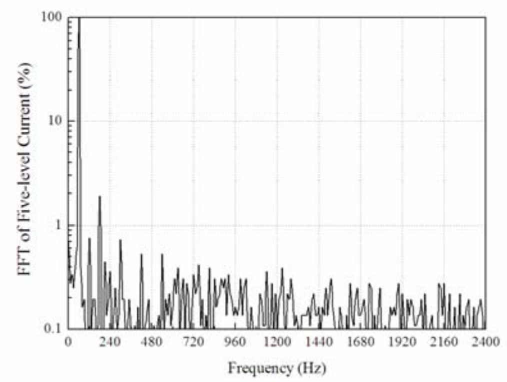

Fig. 20. FFT analysis result of five-level PWM current generated by five-level DC-current module type CSI