Review of Novel Multilevel Current-Source Inverters with H-Bridge and Common-Emitter Based Topologies

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***Abstract* -- This paper describes several approaches to create new configurations of multilevel current-source inverters from two kinds of basic main circuits, i.e., an H-bridge-based and a common-emitter-based topologies[1]. The first approach is an application of inductor cells connected in parallel with the main three-level current-source inverter. The inductor cells work to generate intermediate current levels for multilevel output waveform generation with no additional external power sources. The other approach is based on multiple superposition of non-isolated DC current-source modules onto the main three-level current-source inverter. Using these strategies, four of the new circuit topologies are obtained, which have simpler configurations and control algorithms. Several computer simulation and experimental results are presented in the paper to demonstrate proper operations of the proposed new topologies.**

***Index Terms*--DC-AC power conversion, duality, harmonic distortion, inverters, multilevel, switching circuits, topology**

I. INTRODUCTION

In general, renewable energy sources, energy storages and distributed power generation devices such as photovoltaic power systems, batteries and fuel cells basically supply DC power; hence, the generated surplus power is usually fed into the utility power grid through DC/AC power converters (inverters). On the other hand, various global standards like IEEE-1547, IEEE-929 and EN-61000-3-2 impose strict requirements on the output power quality of the grid-connected inverters, i.e., harmonics and total harmonic distortion (THD) of the output currents [1]. Current-source inverters incorporating multilevel techniques are likely to be an effective solution to satisfy such requirements in medium- and high-power applications. The most significant feature of the current-source inverters is inherent simplicity of their configuration and control algorithm because they can directly inject the desired currents to the power grid without AC current feedback control, and can achieve a high power factor operation with ease. Therefore, the current-source inverters behave like buffers between the DC power sources and the AC power grid because of their robustness against the grid voltage fluctuation. In addition, the multilevel approach of the inverters is an indispensable key technology to reduce the output waveform distortion [2][3]. However, researchers and engineers have explored few topologies of the multilevel current-source inverters so far. One of the traditional methods to generate the multilevel current waveform is a parallel connection of H-bridge inverters, which is a dual circuit of a cascade multilevel voltage-source inverter [4]. This configuration requires, however, multiple isolated DC current sources, and a large number of isolated gate drive circuits as well as switching devices. Another approach is a multi-cell topology based multilevel current-source inverter, which is a dual circuit of a full-bridge voltage-source inverter with flying capacitors [5][6]. Complexity of the intermediate-current-level balancing control is a fatal drawback of this topology. Another different multilevel current-source inverter, which employs a single-rating inductor-cell topology, is also discussed in the past work, which is a dual circuit of the improved diode-clamped multilevel voltage-source converter. However, both of the multi-cell and the single-rating inductor-cell topologies require large inductors to obtain the stable intermediate level currents. These intermediate inductors cause extra losses in the multilevel current-source inverter, resulting in lower efficiency of power conversion.

This paper describes several approaches to create new configurations of the multilevel current-source inverters from two kinds of basic main circuits, i.e., an H-bridge-based and a common-emitter-based topologies. These configurations feature fewer switching devices, fewer isolated gate drive circuits and smaller inductors for generation of the intermediate current levels. The operation performances of the proposed strategies are examined through computer simulations and laboratory experimental tests in the paper.

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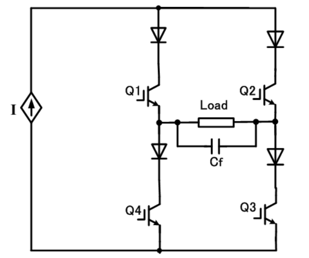
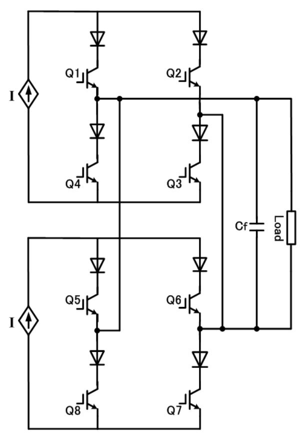


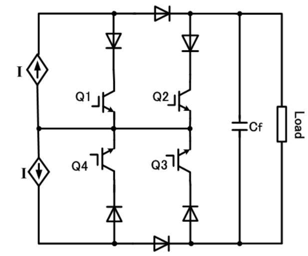
Q_1	Q_2	Q_3	Q_4	Output
1	0	1	0	+I
1	0	0	1	0
0	1	0	1	-I

Fig. 1. Conventional H-bridge current-source inverter



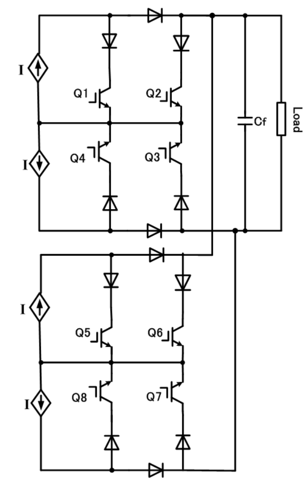
Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Output
1	0	1	0	1	0	1	0	+I
1	0	1/0	0/1	1	0	0/1	1/0	+I/2
1	0	0	1	1	0	0	1	0
0/1	1/0	0	1	1/0	0/1	0	1	-I/2
0	1	0	1	0	1	0	1	-I

Fig. 2. Conventional multilevel waveform generation with parallel-connected H-bridge current-source inverters



Q_1	Q_2	Q_3	Q_4	Output
0	0	1	1	+I
1	0	0	1	0
1	1	0	0	-I

Fig. 3. Three-level current-source inverter with common emitter topology (fish bone structure based topology)



Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Output
0	0	1	1	0	0	1	1	+I
0/1	0	1/0	1	1/0	0	0/1	1	+I/2
1	0	0	1	1	0	0	1	0
1	1/0	0	0/1	1	0/1	0	1/0	-I/2
1	1	0	0	1	1	0	0	-I

Fig. 4. Multilevel waveform generation with parallel-connected common-emitter current-source inverters

II. CONVENTIONAL APPROACH OF MULTILEVEL WAVEFORM GENERATION

A. Conventional H-Bridge Current-Source Inverter and Multilevel Waveform Generation Technique

Fig. 1 shows a traditional single-phase current-source inverter, which has an H-bridge (full-bridge) configuration and can generate a three-level (+I, 0 and -I) current waveform to the load. Each switching device requires a series diode to have a reverse-blocking capability against the lagging load voltage. It should be noted that the zero current output is achieved by a short circuit across the DC current source.

In order to achieve higher output power and lower waveform distortion simultaneously with lower-rated power devices, a multilevel approach is the most effective solution to address such problems. A conventional method to increase the number of the output waveform levels is a simple parallel connection of some three-level current-source inverters as shown in Fig. 2. A five-level output current waveform can be obtained with this configuration as indicated in the switching-state table. However, this conventional method has a drawback in the number of the switching devices and in requirement of the isolated DC current sources.

B. Common-Emitter-Topology (Fish Bone Structure) Based Current-Source Inverter and Conventional Approach of Multilevel Waveform Generation

Fig. 3 shows a new topology of a three-level current-source inverter, which is derived from the three-level half-bridge neutral-point-clamped (NPC) voltage-source inverter on the basis of the theory of circuit duality [7][8]. It is found from the switching-state table that the inverter is also capable to generate a three-level current waveform. The

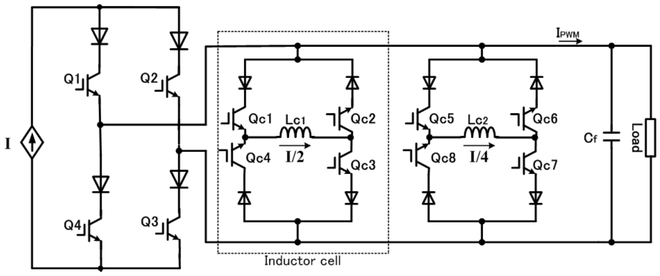


Fig. 5. Inductor cell based multilevel waveform generation applied to H-bridge current-source inverter

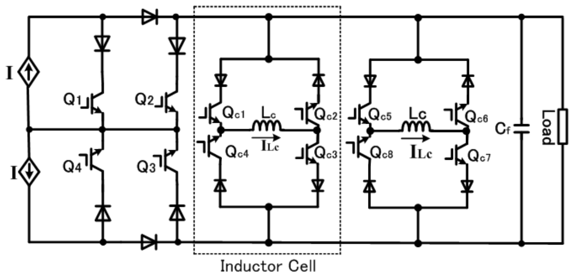


Fig. 6. Inductor cell based multilevel waveform generation applied to current-source inverter with common-emitter topology

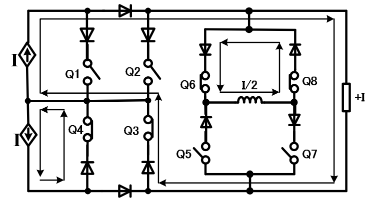
most significant feature of this topology is that all of the switching devices can be driven on an identical potential level with no isolated gate-drive power supplies. Therefore, it is remarkably easy to operate the inverter at a considerably high frequency of MHz order, which implies that a bulky filter capacitor is no longer needed to reject undesirable harmonic components in the load current. However, there is a drawback in this topology from the viewpoint of utility of the DC current sources because only one of the two DC current sources is alternately connected to the load at any time. This topology is named “fish bone structure” by the authors, associated with its circuit shape.

Fig. 4 shows parallel-connected configuration of the common-emitter current-source inverters that can deliver a five-level current waveform to the load. The conventional technique is applied to this configuration to increase the number of the output current levels; hence, similar problems pointed out in Fig. 2 still exist in this topology.

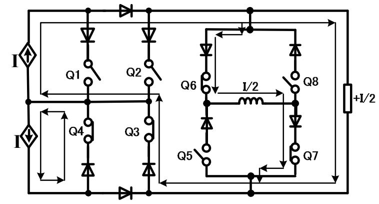
III. New Approach of Multilevel Waveform Generation with Inductor Cells

A. H-Bridge Current-Source Inverter with Inductor Cells

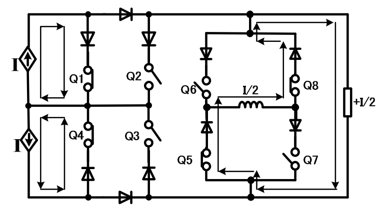
Fig. 5 shows an example of the proposed configuration of a multilevel current-source inverter. In this configuration, one or more inductor cells are connected in parallel with the main three-level H-bridge inverter to create more current waveform levels. Each inductor cell consists of four controlled switches with series diodes and an inductor Lc across the bridge. It should be noted that the inductor cell requires no external auxiliary power sources to keep the



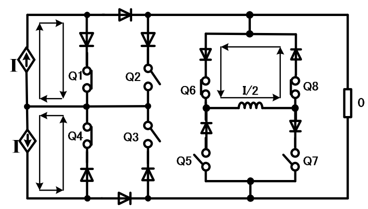
(a) Output current level +I



(b) Output current level +I/2 in energizing mode



(c) Output current level +I/2 in discharging mode



(e) Output current level 0

Fig. 7. Switching modes of inductor cell based five-level current-source inverter with common emitter topology

inductor current at a specified constant value. The relation between the level number of the output current waveform M and the number of the inductor cells N can be expressed as

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

For an M-level current-source inverter of which DC current source amplitude is I, the current flowing through the N-th inductor cell I_{LcN} must be regulated at the following value:

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

The combination of the three-level H-bridge inverter and the inductor cells has redundancy of the switching states to generate intermediate levels of the output current waveform. In order to regulate each inductor-cell current, two redundant switching states, i.e., charging and discharging modes of the specific inductor, are necessary. The operation principle of multilevel waveform generation using the switching-state redundancy is to be described in the next section.

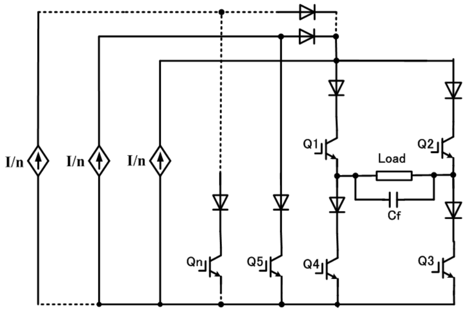
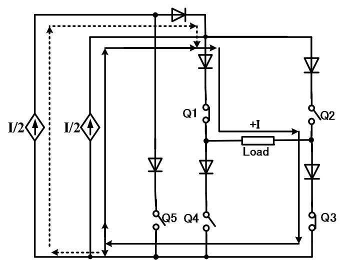
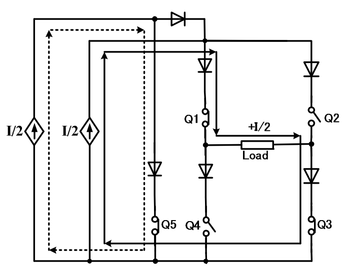


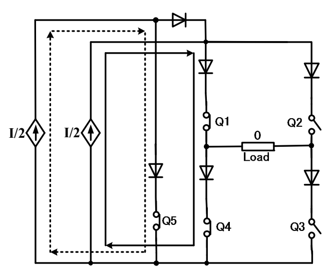
Fig. 8. Multilevel waveform generation with multiple DC current source modules superposed onto H-bridge inverter



(a) Output current level +I



(b) Output current level +I/2



(c) Output current level 0

Fig. 9. Switching modes of five-level current-source inverter with superposed DC current source modules onto H-bridge

B. Common Emitter (Fish Bone Structure) Current-Source Inverter with Inductor Cells

Fig. 6 shows another application of the inductor cells, i.e., a combination of the three-level current-source inverter with a common-emitter topology and the inductor cells [9]. This configuration can be obtained by connecting one or more inductor cells in a similar way as Fig. 5. The inductor cells are used to generate a multilevel output current by adding or subtracting their inductor currents to or from the basic three-level current waveform.

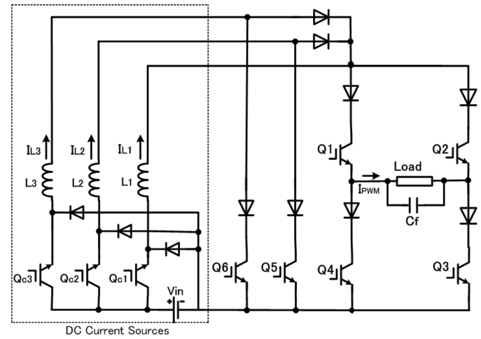


Fig. 10. Actual configuration of DC current-source modules

Fig. 7 shows an example of a five-level current-source inverter using a single inductor cell and its operation modes during a positive output current cycle. A charging mode of the inductor Lc is executed when the switches Q_6 and Q_7 are turned on, while the other switches Q_5 and Q_8 are turned off. A constant current $I_{lc} = +I/2$ keeps on flowing through the switches Q_6 and Q_7, which energizes the inductor Lc. A discharging mode is achieved vice versa, where the stored energy in the inductor is released to the load, keeping the current amplitude of $+I/2$. The inductance value of the inductor cell is designated as

$$L_c = \frac{I_{Lc} R}{f_s \Delta I_{Lc}}, \tag{3}$$

where R is a load resistance, f_s is a switching frequency of the inductor cell, and ΔI_{Lc} is an acceptable inductor current ripple. The inductor current I_{Lc} can be regulated at an almost constant value $I/2$ by switching over the charging and the discharging modes of the inductor, with delivering the identical output current level $+I/2$.

IV. Multilevel Waveform Generation with Multiple Superposed DC Current Source Modules

A. H-Bridge Current-Source Inverter with Multiple Superposed DC Current-Source Modules

Another different approach of the multilevel current-source inverter is shown in Fig. 8, which employs a multiple superposition technique of non-isolated DC current-source modules. Each module superposed onto the main H-bridge current-source inverter includes a single controlled switch with a series diode and an output diode. As illustrated in the figure, even though the DC current-source modules are extensively added, every auxiliary switching device Q_5, Q_6, and Q_n is connected at a common-emitter potential level with the switches Q_3 and Q_4 of the main inverter, which makes the gate drive design much simpler. No matter how many DC current-source modules are superposed onto the main inverter, only three isolated gate drive power supplies are needed to drive all the switching devices in this topology. The relation between the level number of the output current waveform M and the number of the superposed DC current-source modules N can be expressed as follows:

$$M = 2N + 3. \tag{4}$$

Fig. 9 illustrates operation modes of the five-level current-

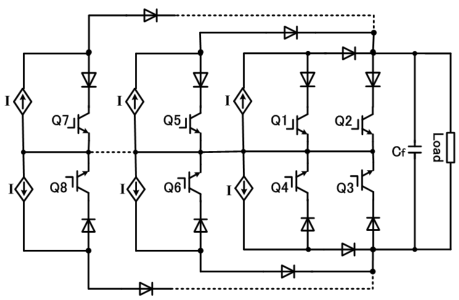


Fig. 11. Multilevel waveform generation with multiple symmetrical DC current source modules (extended fish bone structure based topology)

TABLE I
COMPARISON OF FIVE-LEVEL CURRENT-SOURCE INVERTERS

Device counts	Paralleled H-bridge (Fig. 2)	Multi-cell	Single-rating inductor cell	H-bridge with inductor cell (cf. Fig. 5)	Common-emitter with inductor cell (cf. Fig. 6)	H-bridge with DC module (cf. Fig. 8)	Common-emitter with DC module (cf. Fig. 11)
Controlled switches	8	8	8	8	8	5	6
Diodes	8	8	8	8	10	6	10
Inductors	0	2	4	1	1	0	0
Isolated gate drive circuits	4	4	4	4	4	1	1
DC current sources	2	1	1	1	2	2	4

source inverter incorporating the multiple superposed DC current-source modules. When the maximum current amplitude $+I$ is required, all of the outputs from the DC current sources are added and are delivered to the load. An intermediate level current $+I/2$ is generated by a short circuit of the superposed DC current source module. In general, each DC current-source module must have the following amplitude of the output current:

$$I_{DCN} = \frac{I}{N+1}. \quad (5)$$

Fig. 10 shows an actual configuration of the DC current-source modules, where independent current-controlled buck choppers are employed. It should be noted that only a single DC voltage source is used to create multiple DC current-source modules and that small inductance value is sufficient to regulate the DC currents owing to the high-switching-frequency operation of the choppers.

B. Multiple Superposed Common-Emitter Current-Source Inverters (Fish Bone Structure Based Topology)

Fig. 11 shows an extended configuration of the three-level current-source inverter with a common-emitter topology, which is an extended "fish bone structure." This multilevel current-source inverter can be obtained by connecting multiple symmetrical DC current-source modules to the main inverter. The relation between the level number of the output current waveform M and the number of the superposed symmetrical DC current-source modules N is identical to (4).

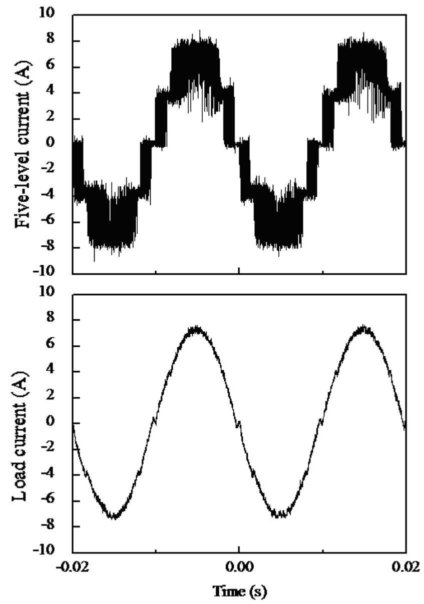


Fig. 12. Five-level PWM output and load current waveforms of common emitter current-source inverter with single inductor cell

The key feature of this topology is that all of the switching devices and the DC current sources are connected at an identical common potential level regardless of the circuit expansion scale. Therefore, the whole circuit requires neither isolated gate drive power supplies nor isolated DC current sources. In addition, no potential change occurs during the switching operations; hence, this configuration is suitable for high-switching-frequency applications, where a common mode noise is a delicate issue.

TABLE I represents a comparison summary of the device counts used in various five-level current-source inverters, for example. As can be seen here, the H-bridge inverter incorporating the superposed DC current-source module is the most effective to reduce the controlled switch counts.

V. EXPERIMENTAL SETUP AND TEST RESULTS

A. Inductor Cell Based Multilevel Current-Source Inverter

Some laboratory prototypes are set up and the performances are examined through experimental tests to verify feasibility of the proposed strategies. Fig. 12 is an experimental result of the common-emitter current-source inverter with a single inductor cell, which shows a proper five-level PWM output current and low distorted (THD = 3.3 %) load current waveforms. Amplitudes of the two DC current sources and the inductor cell are regulated at 8 A and 4 A, respectively. The switching frequency of the main inverter and the inductor cell is 22 kHz, which leads to great

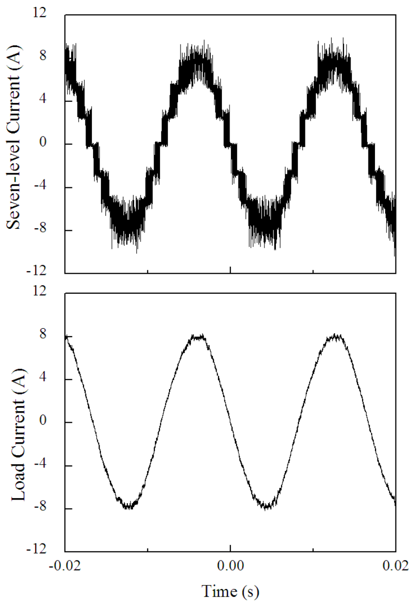


Fig. 13. Seven-level PWM output and load current waveforms of H-bridge inverter with doubly superposed DC current-source modules

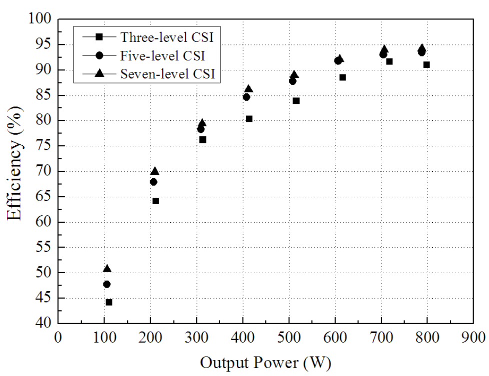


Fig. 14. Efficiency of H-bridge inverter with multiple superposed DC current-source modules

reduction of the load filter capacitance down to 5 μF.

B. Multilevel Current-Source Inverter with Multiple Superposed DC Current-Source Modules

Fig. 13 shows operation waveforms of a seven-level current-source inverter composed by an H-bridge inverter with doubly superposed DC current-source modules, where the switching frequency is 22 kHz and the amplitude of every DC current source is 2.7 A. A sinusoidal (THD = 1.98 %) load current is also obtained with as small filter capacitance as 5 μF. Fig. 14 shows experimentally measured efficiency of the power conversion, and it is found that the more intermediate current levels make it possible to improve the efficiency and that the highest efficiency reaches 94.2 %. Assuming that the peak value of the output multilevel current waveform is I, the total conduction loss P_{loss} in the DC current sources can be reduced as the number of the intermediate current levels M is increased as follows:

$$P_{loss} = \frac{R_c I^2}{N+1} = \frac{2R_c I^2}{M-1}. \tag{6}$$

In the above equation, N is the number of the superposed DC current-source modules, and R_c is an equivalent total conduction resistance of a smoothing inductor and a controlled switch in an individual DC current-source module. The equation obviously represents the total conduction loss is inversely proportional to the number of the output current levels or the number of the multiple superposed DC current-source modules, which is another fundamental property of the current-source inverters.

VI. Conclusion

This paper discussed new approaches of a multilevel current-source inverter, which applies inductor cells and multiple DC current-source modules to the H-bridge and the common-emitter (fish bone structure) circuits. The proper operations of generating five- or seven-level current waveforms are confirmed through the experimental tests. In addition, the H-bridge inverter incorporating the multiple superposed DC current-source modules achieved the highest efficiency of 94.2 %. The proposed configurations can generate a multilevel current waveform with fewer switching device counts, lower losses and better THD as the number of the intermediate current levels is increased.

References

[1] P. G. Barbosa, H. A. C. Braga, M. C. Barbosa, and E. C. Teixeria, "Boost Current Multilevel Inverter and Its Application on Single Phase Grid Connected Photovoltaic System," *IEEE Trans. on Power Electronics*, vol. 21, no. 4, pp. 1116-1124, Jul./Aug. 2006.

[2] K. Crorzine, and Y. Familiant, "A New Cascaded Multilevel H-Bridge Drive," *IEEE Trans. on Power Electronics*, vol. 17, no. 1, pp. 125-131, Jan./Feb. 2002.

[3] J. Rodiguez, J. S. Lai, and F. Z. Peng, "Multilevel Inverter: A Survey of Topologies, Controls, and Application," *IEEE Trans. on Industrial Electronics*," vol. 49, no. 4, pp. 724-738, Jul./Aug. 2002.

[4] S. Kwak, and H. A. Toliyat, "Multilevel Converter Topology Using Two Types of Current-Source Inverters," *IEEE Trans. on Industry Applications*, vol. 42, no. 6, pp. 1558-1564, Nov./Dec. 2006.

[5] B. P. McGrath, and D. G. Holmes, "Natural Current Balancing of Multicell Current Source Inverter," *IEEE Trans. on Power Electronics*, vol. 23, no. 3, pp. 1239-1246, May/Jun. 2008.

[6] F. L. M. Antunes, A. C. Braga, and I. Barbi, "Application of A Generalized Current Multilevel Cell to Current Source Inverters," *IEEE Trans. on Power Electronics*," vol. 46, no.1, pp. 31-38, Jan./Feb. 1999.

[7] T. Noguchi, and Suroso, "New Topologies of Multi-Level Power Converters for Use of Next-Generation Ultra High-Speed Switching Devices," *in Proc. 2009 the IEEE 1st Energy Conversion Congress and Expo*, San Jose, USA.

[8] T. Noguchi, Y. Nozuki, and Suroso, "Discussion on Novel Topologies of Multi-Level Power Converters Based on Duality," *in Proc. 2008 the IEE-Japan Static Power Conversion Technical Meeting*, SPC-08-89, Sapporo, Japan (in Japanese).

[9] T. Noguchi, and Suroso, "New Multilevel Current-Source PWM Inverter with Full-Bridge Inductor Cells," *IEE-Japan Trans. on Industry Applications*, vol. 130-D, no. 6, pp. 808-815, Jun. 2010.