New Topologies of Multi-Level Power Converters for Use of Next-Generation Ultra High-Speed Switching Devices

Toshihiko Noguchi
Senior Member, IEEE
Shizuoka University
3-5-1 Johoku, Naka-Ku,
Hamamatsu, Shizuoka 432-8561, Japan
ttnogut@ipc.shizuoka.ac.jp

Suroso
Student Member, IEEE
Nagaoka University of Technology
1603-1 Kamitomioka
Nagaoka, Niigata 940-2188, Japan
suroso@stn.nagaokaut.ac.jp

Abstract -- **Next–generation power switching devices such as SiC-MOSFETs are very promising as future power converter components because their voltage rating and switching speed can dramatically be improved by approximately ten times of those of currently available Si devices without sacrificing ON-state resistance. However, they are likely to cause serious EMI noise problems due to their 10^4-V/μs order switching speed. It is rather difficult to drive such devices by using conventional isolated gate-drive power supplies and optocouplers because noise currents generated by extremely high dV/dt can easily penetrate parasitic capacitance between their primary and the secondary circuits. This paper proposes novel multi-level power converters through investigation of unique different circuit topologies than conventional converters, which can substantially solve the problems mentioned above. The key feature of the proposed topologies is that all switching devices used in the converters are connected on an exactly identical potential level without isolation; hence the proposed converters require only a single gate-drive power supply to drive all the devices and are inherently free from the violent potential variation. Several experimental test results are presented in the paper, which demonstrates proper operations of the new topology based multi-level power converters.**

Index Terms—**inverters, multilevel, topology, switching circuits, switching transients, electromagnetic interference, silicon carbide, MOSFET switches, JFET switches, isolation technology.**

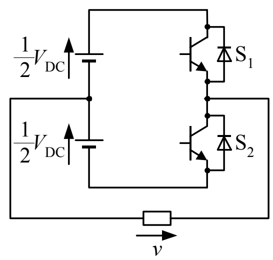
I. Introduction

Silicon Carbide (SiC) based MOSFETs and JFETs are very promising as next-generation power switching devices because their maximum voltage rating and switching speed can be approximately ten times of the conventional Si based devices. In addition, it is said that the ON-state resistance of SiC-MOSFETs will be reduced down to 1/500 of the currently available devices and that their operating temperature can be over 300 °C, which is considerably effective to improve efficiency and power density of the power converters. Focusing on significant enhancement of the switching speed of such SiC devices; serious EMI problems cannot be ignored, especially high-frequency conductive noise currents. The noise currents caused by extremely high dV/dt easily penetrate many electrically isolated parts needed for driving the power switching devices, e.g., gate-drive power supply transformers and optocouplers of switching signals, because there are parasitic capacitors between their primary and the secondary ports. Although the parasitic capacitance ranges from a few to several hundreds pF, the noise current level can be considerably high due to the 10^4-V/μs order dV/dt, which might result in severe malfunction of the gate drive. There must be two solutions to overcome the problems mentioned above. One is to reduce the overall parasitic capacitance in the isolation parts by introducing special transformer structure for the gate-drive power supplies and using optical fibers for the gate signal transmission. The other is to change drastically the power circuit topologies so that isolation is no longer required to drive the entire switching devices, which is more essential and substantial to take effective countermeasures for solving the future concerns. In this paper, in order to overcome such dV/dt problems of the next-generation power switching devices, novel multi-level power converters are proposed by investigating unique different circuit topologies than conventional converters. The key feature of the proposed topologies is that all switching devices used in the converters are commonly connected on an exactly identical potential level without isolation; hence the proposed converters require only a single non-isolated gate-drive power supply to drive all devices and are inherently free from the dV/dt issues. Several experimental test results are presented in the paper, followed by investigation of the novel circuit topologies of the multi-level power converters.

This work has been supported by Grant-in-Aid for Scientific Research (C) 20560262 from Ministry of Education, Culture, Sports, Science and Technology, Japan since 2008.

II. Duality of Basic Two-Level Power Converters

Figure 1 shows the most basic well-known voltage-source two-level half-bridge power converter. In the following discussion, half-bridge circuits are exclusively investigated for fundamental and essential understanding of circuit configurations and operations. This power converter works as either an inverter or a rectifier, depending on its power flow direction. Since the power supply is a DC voltage-source with extremely low impedance, simultaneous turning on both switching devices S_1 and S_2 is strictly prohibited to prevent a short circuit across the DC bus. In addition, simultaneous turning off the two devices is prohibited as well because an inductive load (a series connected L-R) is

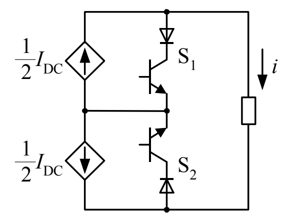


(a) Power circuit configuration

S_1	S_2	State
1	0	$v = +V_{DC} / 2$
0	1	$v = -V_{DC} / 2$
1	1	Prohibited
0	0	Prohibited (dead time)

(b) Operation modes

Fig. 1. Voltage-source 2-level power converter



(a) Power circuit configuration

S_1	S_2	State
0	1	$i = +I_{DC} / 2$
1	0	$i = -I_{DC} / 2$
0	0	Prohibited
1	1	Prohibited (overlap time)

(b) Operation modes

Fig. 2. Current-source 2-level power converter

connected to the power converter. Even if this switching state arises, the anti-parallel free-wheeling diodes automatically turn on depending on the load current flow direction and either a positive or a negative voltage is applied to the load. This power converter is able to output a 2-level voltage waveform, which consists of $+V_{DC}/2$ and $-V_{DC}/2$ levels. The output voltage levels correspond to 2 switching states of the power converter, i.e., an on-state: 1 and an off-state: 0, respectively, so there is no redundancy in relationship between the output voltage levels and the switching states.

Applying a theory of circuit duality to this basic power converter, a current-source 2-level power converter can be derived as shown in Fig. 2. The DC voltage-sources, the anti-parallel diodes and transistors, and the inductive load in Fig. 1 are replaced with DC current-sources, series-connected diodes and transistors, and a capacitive load (a parallel connected C-R), respectively. In addition, operation modes of this current-source 2-level power converter can easily be obtained by replacing 1, 0, v and V_{DC} in Fig. 1 with 0, 1, i and I_{DC} as indicated in Fig. 2, respectively. It is strictly prohibited to turn off the both switching devices S_1 and S_2 to maintain continuity of the current, and turning on both devices at the same time is not allowed because it makes the filter capacitance of the load shorted. However, there is an exceptional timing in which the both devices are simultaneously turned on, which is known as an overlap time never to discontinue the current. The most significant feature of this current-source 2-level power converter is that both of the switching devices never require electrically isolated gate-drive power supplies because their emitters or sources are commonly connected on an exactly identical potential level all together with the DC current sources. In other words, this power converter is inherently and completely free from a violent potential change caused by the high-speed switching actions. These features necessarily come up when the dual circuit of Fig. 1 is derived.

III. Voltage-Source Multi-Level Power Converters

A. *Neutral-Point-Clamped Power Converter*

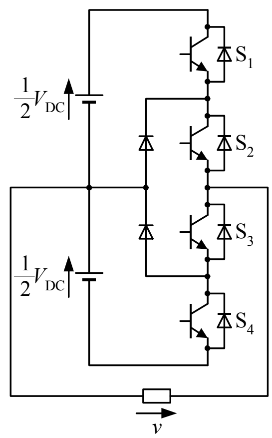
Figure 3 illustrates a typical voltage-source multi-level power converter, which is widely known as a neutral-point clamped (NPC) power converter. The NPC power converter can generate a 3-level voltage waveform, and its output levels are $+V_{DC}/2$, 0 and $-V_{DC}/2$, according to the switching states of the power converter, as shown in Fig. 3. This NPC circuit topology requires simultaneous turning on specific two switching devices for each output voltage level, which makes it rather difficult to improve efficiency of the power converter. However, since the voltage rating required for a off-state switching device is merely $V_{DC}/2$, it is possible to construct a high-capacity power converter by using low-voltage rating devices.

B. *Neutral-Point-Shorted Power Converter*

The power converter shown in Fig. 4 is not used very often, compared with the NPC power converter, but can similarly generate a 3-level voltage waveform, in which the zero-voltage level is generated by turning on S_2 and S_3 at the same time. This switching state allows S_2 and S_3 to act as a bi-directional switch and makes the load terminals shorted at the neutral point of the DC bus. This topology has an advantage over the NPC power converter in terms of the efficiency because it can reduce the number of switching devices in conduction states although each device requires a relatively high voltage rating of V_{DC}.

C. *Cascade-Capacitor Cell Power Converter*

This topology consists of a main power converter and an auxiliary power converter, where the latter is connected in series with the main power converter and the load to generate a multilevel voltage waveform. Figure 5 is an example of a combination of a 3-level NPC power converter and a full-bridge power converter, which is capable to deliver a 5-level voltage waveform to the load. The auxiliary power

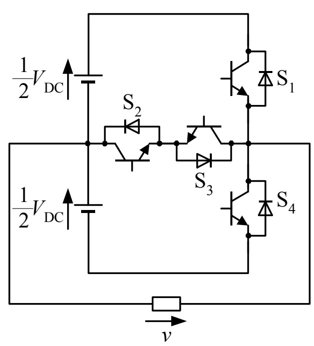


(a) Power circuit configuration

S_1	S_2	S_3	S_4	State
1	1	0	0	$v = +V_{DC}/2$
0	1	1	0	$v = 0$
0	0	1	1	$v = -V_{DC}/2$
Other Combinations				Invalid

(b) Operation modes

Fig. 3. Voltage-source 3-level neutral-point clamped power converter

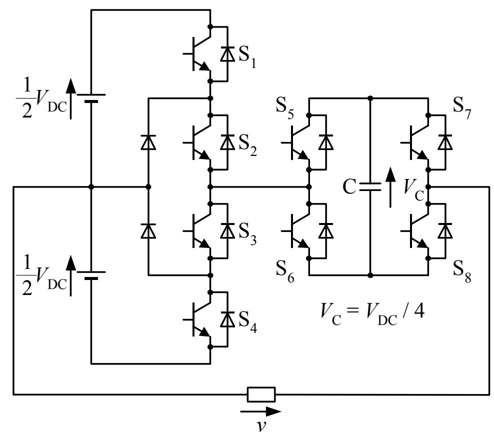


(a) Power circuit configuration

S_1	S_2	S_3	S_4	State
1	0	0	0	$v = +V_{DC}/2$
0	1	1	0	$v = 0$
0	0	0	1	$v = -V_{DC}/2$
Other Combinations				Invalid

(b) Operation modes

Fig. 4. Voltage-source 3-level neutral-point shorted power converter



(a) Power circuit configuration

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	State
1	1	0	0	0	1	0	1	$v = +V_{DC}/2$
1	1	0	0	1	0	1	0	$v = +V_{DC}/2$
1	1	0	0	1	0	0	1	$v = +V_{DC}/4$
0	1	1	0	0	1	1	0	$v = +V_{DC}/4$
0	1	1	0	0	1	0	1	$v = 0$
0	1	1	0	1	0	1	0	$v = 0$
0	1	1	0	1	0	0	1	$v = -V_{DC}/4$
0	0	1	1	0	1	1	0	$v = -V_{DC}/4$
0	0	1	1	0	1	0	1	$v = -V_{DC}/2$
0	0	1	1	1	0	1	0	$v = -V_{DC}/2$
Other Combinations								Invalid

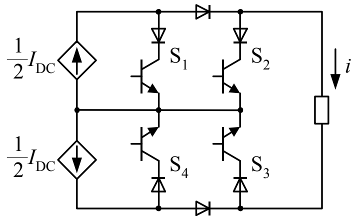
(b) Operation modes

Fig. 5. Voltage-source 5-level cascade-capacitor-cell power converter

converter, which is called a capacitor cell, has only a capacitor across its DC bus with no power supply, and the capacitor voltage is maintained at $V_{DC}/4$ by controlling charge and discharge of the capacitor with appropriate switching states. In order to maintain the capacitor voltage at a constant value, redundancy of the switching states is indispensable. For example, the power converter shown in Fig. 5 has two switching states to generate a $+V_{DC}/4$ level. Charging the capacitor is achieved by $+V_{DC}/2$ output from the NPC power converter and $-V_{DC}/4$ output from the capacitor cell, which results in the $+V_{DC}/4$ level output, while zero-voltage output from the NPC power converter and $+V_{DC}/4$ output from the capacitor cell makes discharge of the capacitor possible. By adding more capacitor cells of which capacitor voltages are $V_{DC}/8$, $V_{DC}/16$, ···, it is possible to increase the number of the voltage levels to 9, 17, ···.

D. Flying Capacitor Power Converter

A flying capacitor power converter is also employed very often to provide a multilevel voltage waveform. This topology has a configuration similar to the NPC power converter by replacing the neutral point clamping diodes with a flying capacitor. In the case of a half-bridge 3-level power converter configuration, however, it is impossible to generate a desired multilevel voltage waveform because there are no switching states that discharge the flying capacitor properly. A full-bridge configuration of the flying capacitor power converter is capable to generate multilevel waveforms owing to their redundancy of the switching states. However, this discussion is beyond the scope of this paper.

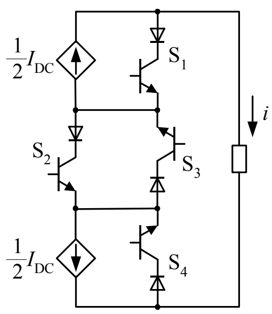


(a) Power circuit configuration

S_1	S_2	S_3	S_4	State
0	0	1	1	$i = +I_{DC}/2$
1	0	0	1	$i = 0$
1	1	0	0	$i = -I_{DC}/2$
Other Combinations				Invalid

(b) Operation modes

Fig. 6. Current-source 3-level power converter (dual circuit of voltage-source 3-level NPC power converter)



(a) Power circuit configuration

S_1	S_2	S_3	S_4	State
0	1	1	1	$i = +I_{DC}/2$
1	0	0	1	$i = 0$
1	1	1	0	$i = -I_{DC}/2$
Other Combinations				Invalid

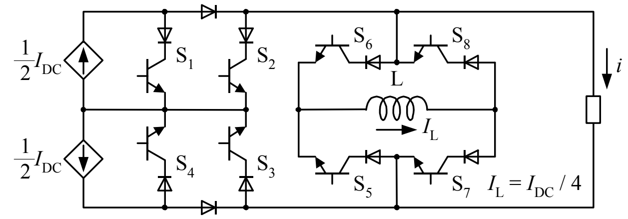
(b) Operation modes

Fig. 7. Current-source 3-level power converter (dual circuit of voltage-source 3-level neutral-point shorted power converter)

IV. New Topologies of Multi-Level Power Converters

A. Dual Circuit of NPC Power Converter

Figures 6 shows a current-source 3-level power converter, which can be derived from the voltage-source 3-level NPC power converter on the basis of a theory of circuit duality. In this case, operation modes of this power converter are easily obtained by replacing 1, 0, v and V_{DC} in Fig. 3 with 0, 1, i and I_{DC}, respectively. As can be seen in Fig. 6, this power converter delivers a 3-level current waveform to the load without sacrificing the merits of the basic current-source 2-level topology described in Fig. 2. All of the power switching devices can be driven on an identical potential level with no isolated gate-drive power supply. Therefore, it



(a) Power circuit configuration

S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	State
0	0	1	1	1	0	1	0	$i = +I_{DC}/2$
0	0	1	1	0	1	0	1	$i = +I_{DC}/2$
0	0	1	1	0	1	1	0	$i = +I_{DC}/4$
1	0	0	1	1	0	0	1	$i = +I_{DC}/4$
1	0	0	1	1	0	1	0	$i = 0$
1	0	0	1	0	1	0	1	$i = 0$
1	0	0	1	0	1	1	0	$i = -I_{DC}/4$
1	1	0	0	1	0	0	1	$i = -I_{DC}/4$
1	1	0	0	1	0	1	0	$i = -I_{DC}/2$
1	1	0	0	0	1	0	1	$i = -I_{DC}/2$
Other Combinations								Invalid

(b) Operation modes

Fig. 8. Current-source 5-level power converter using inductor cell (dual circuit of cascade-capacitor-cell power converter)

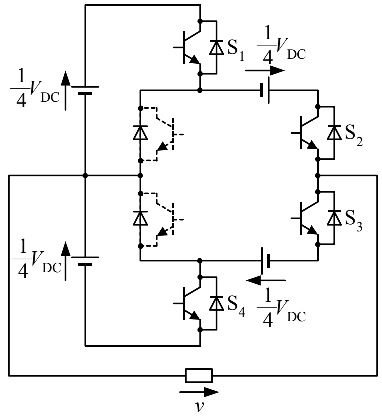
is remarkably easy to operate this power converter at several hundred kHz to several MHz, which implies that a large filter capacitor is no longer needed to reject harmonics in the load current. In addition, it is possible to reduce the current rating of each switching device to $I_{DC}/2$, which is another merit of this topology. This circuit topology is a basic configuration of a "fish-bone structure" as described later on.

B. Dual Circuit of Neutral-Point-Shorted Power Converter

Figure 7 shows a dual circuit of the voltage-source 3-level neutral-point shorted power converter. This topology generates zero-current level by not only opening a bi-directional switch (S_2 and S_3) between the two DC current sources, but also making both of the DC current sources shorted. All of the switching devices can be driven by only two isolated gate-drive circuits because a pair of S_1 and S_3 as well as the other pair of S2 and S4 are connected on common potential levels, respectively, which may be less advantageous than a dual circuit of the NPC power converter.

C. Dual Circuit of Capacitor Cell Power Converter

A dual circuit derived from the cascade capacitor cell power converter is presented in Fig. 8. As shown in this figure, the main circuit is a current-source 3-level power converter as described in Fig. 6, and an auxiliary full-bridge power converter with an inductor across the bridge is connected in parallel with the main power converter. This auxiliary power circuit is called an inductor cell, which is a dual circuit of the capacitor cell. The current flowing through the inductor cell is maintained at a constant value of $I_{DC}/4$ to generate intermediate current levels of $\pm I_{DC}/4$.

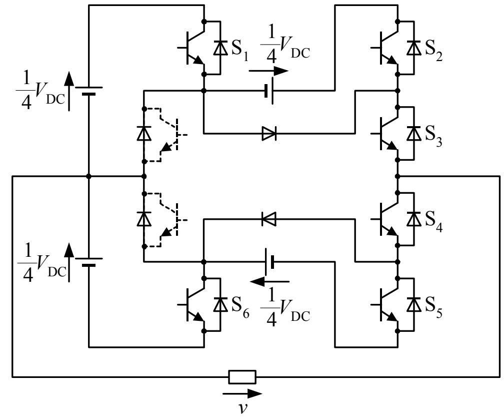


(a) Power circuit configuration

S_1	S_2	S_3	S_4	State
1	1	0	0	$v = +V_{DC}/2$
0	1	0	0	$v = +V_{DC}/4$
0	0	1	0	$v = -V_{DC}/4$
0	0	1	1	$v = -V_{DC}/2$
Other Combinations				Invalid

(b) Operation modes

Fig. 9. “Nest structure” based voltage-source 4-level power converter



(a) Power circuit configuration

S_1	S_2	S_3	S_4	S_5	S_6	State
1	1	1	0	0	0	$v = +V_{DC}/2$
0	1	1	0	0	0	$v = +V_{DC}/4$
0	0	1	1	0	0	$v = 0$
0	0	0	1	1	0	$v = -V_{DC}/4$
0	0	0	1	1	1	$v = -V_{DC}/2$
Other Combinations						Invalid

(b) Operation modes

Fig. 10. “Nest structure” based voltage-source 5-level power converter

When the highest current level, i.e., $+I_{DC}/2$, is delivered to the load, S_1 and S_2 are turned off and the inductor current circulates in the inductor cell by turning on S_5 and S_7 (or a pair of S_6 and S_8). The intermediate current level of $+I_{DC}/4$ is delivered to the load in the following two operation modes. One mode is achieved by providing $+I_{DC}/2$ from the main power circuit and shunting $I_{DC}/4$ with the inductor cell by turning on S_6 and S_7. This operation mode charges energy into the inductor. The other mode can be performed by providing zero current from the main power converter and delivering $I_{DC}/4$ from the inductor cell by turning on S_5 and S_8, which corresponds to a discharge operation of the inductor. The inductor current can be controlled at the constant value of $I_{DC}/4$ with these two operation modes that output the intermediate current levels. The number of the output current levels can be increased by inserting more than one inductor cell of which inductor currents are $I_{DC}/4$, $I_{DC}/8$, $I_{DC}/16$, ⋯.

V. NEST STRUCTURE AND FISH-BONE STRUCTURE BASED NEW TOPOLOGIES

A. “Nest Structure” Based Voltage-Source Multilevel Power Converters

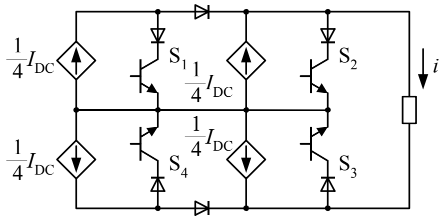
It is well known that the voltage-source multilevel power converter can be achieved by the following typical schemes:

a) Full-bridge configuration,
b) NPC or flying capacitor configuration,
c) Cascade power converter or cascade capacitor cell configuration, and
d) Synthetic operation of phase-shifted power converter outputs by transformers.

In the following discussion, voltage-source multilevel power converters with a “nest structure” are investigated as novel topologies. Figures 9 and 10 show voltage-source multi-level power converters with a “nest structure”. The former is created from a combination of two sets of voltage-source two-level power converters, which can generate a 4-level voltage waveform. The authors call this kind of topology a “nest structure” because one power converter involves the other power converter like a load. Therefore, this configuration can be regarded as a nest. The latter circuit shown in Fig. 10 is also a “nest structure” based voltage-source 5-level power converter, which is a combination of a 3-level and a 2-level power converters. These topologies have substantial drawbacks because they require floating DC power supplies.

B. “Fish-Bone Structure” Based Current-Source Multilevel Power Converters

As shown in Figs. 11 and 12, however, the current-source 4-level and 5-level power converters, which have been derived from a “nest structure” based voltage-source 4-level and 5-level power converters, still have the same unique feature as described in the previous chapters. The most significant feature of these topologies is that all of the switching devices are connected an exactly identical potential line as well as all of the DC current power sources without exception. The authors call these topologies a “fish-bone structure” because the shape of the circuit diagram looks like a fish bone. The current-source 4-level power converter



(a) Power circuit configuration

S_1	S_2	S_3	S_4	State
0	0	1	1	$i = +I_{DC}/2$
1	0	1	1	$i = +I_{DC}/4$
1	1	0	1	$i = -I_{DC}/4$
1	1	0	0	$i = -I_{DC}/2$
Other Combinations				Invalid

(b) Operation modes

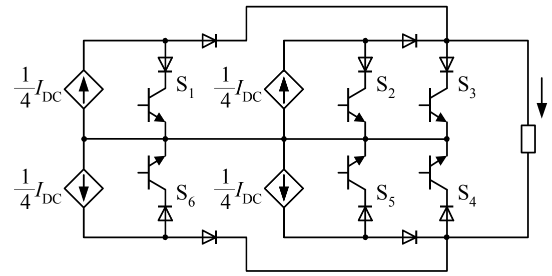
Fig. 11. Fish-bone structure based current-source 4-level power converter (Dual circuit of voltage-source 4-level power converter with nest structure)

shown in Fig. 11 has a multiple parallel configuration of 2 sets of the current-source 2-level power converter illustrated in Fig. 2. This converter is unable to output zero-current level, but can generate 4 current levels of $+I_{DC}/2$, $+I_{DC}/4$, $-I_{DC}/4$ and $-I_{DC}/2$. The topology shown in Fig. 12 corresponds to a combination of a current-source 2-level power converter and a current-source 3-level power converter, which can deliver a 5-level current waveform to the load. As can be seen in these figures, no isolated gate-drive power supplies are not required to drive the switching devices because their emitters or sources are connected on a single common potential line. In addition, the common line does not suffer from a violent potential change, which implies that the “fish-bone structure” based power converters can be operated at much higher switching frequency. Even if the number of the current levels are increased, this important feature never changes regardless of the nesting levels.

VI. Experimental Setup and Test Results

A. Operation of “Fish-Bone Structure” Based Current-Source 3-Level Power Converter

Figure 13 shows experimental waveforms of the current-source 3-level power converter indicated in Fig. 6. The two current power sources are composed with current controlled buck choppers of which current outputs are kept constant at 10 A. Since the switching frequency of the buck choppers is higher than 30 kHz, the smoothing inductors required in the buck choppers can be reduced down to 0.3 mH, which contributes compactness of the current power sources. On the other hand, the “fish-bone structure” based current-source 3-level power converter is controlled to deliver 100-Hz sinusoidal waveform, where a sub-harmonic pulse width modulation (PWM) technique is applied to generate the switching state signals with a 100-kHz triangular wave carrier. As shown in this figure, proper 3-level PWM waveform of



(a) Power circuit configuration

S_1	S_2	S_3	S_4	S_5	S_6	State
0	0	0	1	1	1	$i = +I_{DC}/2$
1	0	0	1	1	1	$i = +I_{DC}/4$
1	1	0	0	1	1	$i = 0$
1	1	1	0	0	1	$i = -I_{DC}/4$
1	1	1	0	0	0	$i = -I_{DC}/2$
Other Combinations						Invalid

(b) Operation modes

Fig. 12. Fish-bone structure based current-source 5-level power converter (Dual circuit of voltage-source 5-level power converter with nest structure)

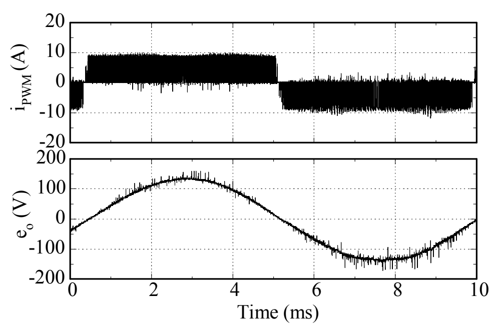


Fig. 13. Output waveforms of “fish-bone structure” based current-source 3-level power converter

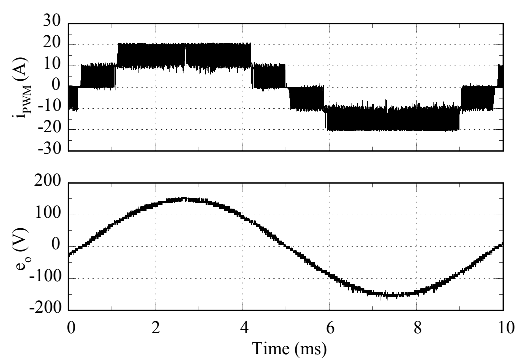
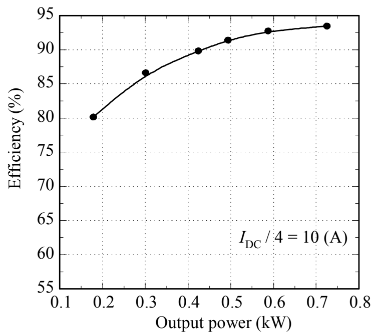
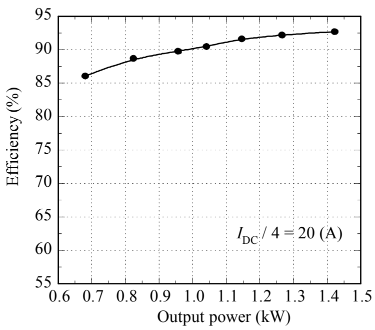


Fig. 14. Output waveforms of “fish-bone structure” based current-source 5-level power converter

the output current is obtained, of which amplitude exactly agrees with that of the 10-A current power sources. Although only a 5-μF small filter capacitor is added in parallel with the load, an excellent sinusoidal voltage waveform is obtained with low distortion across the load.



(a) Efficiency when low power source amplitude ($I_{DC}/4$ = 10 A)



(b) Efficiency when high power source amplitude ($I_{DC}/4$ = 20 A)

Fig. 15. Efficiency of current-source 5-level power converter

B. Operation of "Fish-Bone Structure" Based Current-Source 5-Level Power Converter

Figure 14 shows another experimental test result of a "fish-bone structure" based current-source multilevel power converter. An output current and a load voltage waveforms of the current-source 5-level power converter indicated in Fig. 12 are presented in the figure. The four current controlled buck choppers are employed as current power sources, in which each output current amplitude is controlled to be 10 A. A 100-Hz sinusoidal current command is given to the 5-level current-source power converter, and is modulated by a 100-kHz triangular wave carrier to generate switching state signals. As shown in Fig. 14, an excellent 5-level current waveform is confirmed, where zero current level as well as intermediate current levels of ±10 A is properly delivered to the load. Furthermore, an almost ideal sinusoidal voltage waveform is obtained across the load with only a 2-μF filter capacitor, which achieves as low THD as 1.52 %.

Figure 15 shows efficiency characteristics, where the current power source amplitude is set at 10 A or 20 A and efficiency is measured until the load voltage is 100 V. As can be seen, the efficiency becomes worse in light load conditions regardless of the current power source amplitude. This is because conduction losses of the switching devices becomes relatively dominant against the load power, which is a substantial drawback of current-source power converters. However, the efficiency is remarkably improved as the load

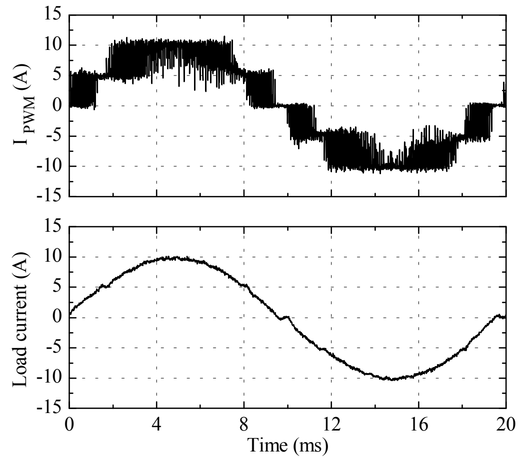


Fig. 16. Output waveforms of inductor cell based current-source 5-level power converter

is heavier, and the maximum efficiency can be confirmed to be 92.7 % at the load of 1.42 kW when the current power source amplitude is 20 A.

C. Operation of Inductor Cell Based 5-Level Current-Source Converter

Figure 16 shows operation waveforms of the inductor cell based current-source 5-level power converter, where the output current and the load current waveforms are presented. In this experiment, two current power sources of 10-A amplitude are constituted by current controlled buck choppers. On the other hand, the inductor cell employs 5-mH inductor, and the inductor current is regulated by a current control loop to be half of the current power source amplitude. A 10-A peak and 50-Hz sinusoidal current command is given to the controller, which is modulated by a sub-harmonic PWM technique at 22 kHz. The 5-level current waveform obtained through the experiment looks slightly noisy due to current ripples, but its THD is 3.3 % without a filter capacitor. It is inferred that the current ripples are caused by inductive elements included in the wires and the load. However, the load current can be regarded as almost sinusoidal because a 5-μF filter capacitor of the load effectively suppresses the current ripples.

VII. CONCLUSION

This paper reviewed an EMI noise current issue caused by an ultra high-speed switching operation, which is assumed when the next-generation SiC-MOSFETs and SiC-JFETs are employed as power switching devices in power converters. In order to solve this problem, several novel topologies of the "fish-bone structure" based multi-level power converters are proposed. The unique feature of the proposed topologies is that all power switching devices are connected on an identical potential line; therefore the power converters are substantially free from violent potential change. In addition, an inductor cell based multilevel current-source power converter is proposed, which is capable to increase the number of current levels by inserting multiple inductor cells in parallel with the load. Operation characteristics of these newly proposed power converters were experimentally examined, and proper waveforms and efficiency characteristics were confirmed.

REFERENCES

[1] J. Rodriguez, J. Lai, and F. Z. Peng, “Multilevel Inverters: A Survey of Topologies, Controls, and Applications,” *IEEE Trans. Ind. Elec.*, vol. 49, no. 4, Jul. 2002.

[2] A. Nabae, I. Takahashi, and H. Akagi, “A New Neutral-Point-Clamped PWM Inverter,” *IEEE Trans. Ind. Appl.*, vol. IA-17, no. 5, p.p. 518-523, Sep. 1981.

[3] T. Ohnishi, “Multiple Single Phase PWM Inverter by Means of Combination Control,” *IEE-Japan Trans. D*, vol. 115, no. 1, p.p. 63-69, 1995 (in Japanese).

[4] K. Crorzine, and Y. Familiant, “A New Cascaded Multilevel H-Bridge Drive,” *IEEE Trans. Power. Elec.*, vol. 17, no. 1, p.p. 125-131, Jan. 2002.

[5] C. K. Lee, S. Y. R. Hui, and H. S. H. Chung, “A 31-Level Cascade Inverter for Power Applications,” *IEEE Trans. Ind. Appl.*, vol. 49, no. 3, p.p. 613-617, May. 2002.

[6] K. Iwaya, and T. Noguchi, “High-Frequency Switched Mode Power Amplifier with Small Capacity Filter Inverters,” *IEEE IECON’04 Proc.*, CDROM WC2-1, Busan, Korea, 2004.

[7] K. Iwaya, and T. Noguchi, “Novel Current-Source Multi-Level Inverter Driven by Single Gate Drive Power Supply,” *IEE-Japan Trans D*, vol. 126, no. 1, p.p. 10-16, Jan. 2006 (in Japanese).

[8] J. L. Alqueres and J. C. Praca, “The Brazilian Power System and the Challenge of the Amazon Transmission,” *Proc. 1991 IEEE Power Eng. Soc. Transmission and Distribution Conf.*, p.p. 315-320, 1991.