A New Boost Type Rectifier for a DC Power Supply with Frequent Output Short Circuit

Eui-Cheol Nho*, In-Dong Kim*, and Thomas A. Lipo**

* Dept. of Electrical Engineering
Pukyong National University
San 100 Yongdang-Dong Nam-Gu
Pusan, 608-739 KOREA
E-mail : nhoec@dolphin.pknu.ac.kr

** Dept. of Electrical & Computer Eng.
University of Wisconsin-Madison
1415 Engineering Drive
Madison, WI 53706 USA
E-mail : lipo@engr.wisc.edu

Abstract-**This paper describes a new boost type rectifier. The proposed converter output dc capacitors do not discharge even in a load short circuit condition. When a load short circuit occurs, the capacitors become a floating state immediately. The stored capacitor energy is supplied to the load again as soon as the short circuit has been cleared. This feature satisfies the requirement of a dc power supply for a load with frequent output short circuits. The proposed converter has the characteristics of a simplified structure, a reduced cost, weight, and volume compared with conventional power supplies with frequent output short circuits. Experimental results are presented to verify the usefulness of the proposed converter.**

I. INTRODUCTION

Most dc power supplies have an output over current or short circuit current protection function. Usually, an output short circuit results in the shut down of the power supply, and this accident occurs at long intervals. However, in a special power supply for a specific dc load such as an ion source, the short circuit occurs frequently due to the ion source spark downs. To protect the ion source and the power supply from the ion source short circuit current, a fast disconnecting the ion source from the power supply is necessary. It is also desirable to turn the power supply on again as soon as the fault has been cleared, to keep the total on-time as long as possible. Therefore, the power supply is required to possess not only a voltage regulation function but also a high speed switching function, and a protective function at the time of a load fault [1,2].

Many efforts have been made to satisfy the above mentioned functions. Up to the middle of the 1980's, tetrodes had been used for the rapid switching of the dc power source. The tetrode has a good switching characteristic, but it has some problems such as a flashover in the tube, a poor efficiency, X-ray radiation, a short life time, high cost, and maintenance difficulty. To overcome the problems, Yukio Watanabe [3] used GTO thyristors instead of the tetrode. A GTO thyristor has a high speed turn on/off characteristic, and the device loss is considerably low compared to that of the tetrode. Therefore, the device can be suitably used as a dc switch. However, for a high voltage application above several tens kV, a large number of the GTO thyristors are connected in series to increase the voltage rating of the dc side switching element. Because each GTO gate driver power is supplied through an insulating transformer, the series connected stack becomes large in size and weight. And the entire GTO turn on/off synchronization is difficult. In [4], there is no dc side switching device. The switching function is provided by an inverter. The power supply using an inverter consists of a SCR rectifier, GTO inverters, step-up and summing transformers, and a 3-phase diode full bridge rectifier. The inverter has two important roles. One is a fast switching function at the load short circuit, the other is the reduction of the step-up transformer's volume and weight. An increased inverter output fundamental frequency reduces the transformer size.

This paper describes a new scheme for the power supply using a modified boost type multilevel rectifier. It is well known that a

0-7803-5589-X/99/$10.00 (c) 1999

multilevel converter has good characteristics in high voltage and high power applications [6]. By using a multilevel converter, the structure of the power supply becomes considerably simple compared with that of the conventional power supplies, because there is no need of GTO inverters, step-up transformers, and a diode rectifier. However, the conventional boost type multilevel rectifier [7] can not be applied to the above mentioned purpose power supply. The rectifier output capacitors discharging energy may damage the load and the capacitors severely at a load short circuit. Furthermore, the rapid output dc power switching is difficult. Therefore, a modified boost type rectifier is proposed to satisfy the required characteristics of the power supply for a load with frequent short circuit. The proposed converter circuit operation and characteristic analysis are described. Simulations and experiments are carried out with a 4 kW power supply to prove the fundamental operating principle. Experimental results show the validity of the proposed rectifier operation and characteristic.

II. Proposed Circuit Diagram And Operating Principle

A. Proposed Circuit Diagram

Fig. 1 shows the generalized circuit diagram of the proposed scheme. The circuit diagram is basically similar to the conventional multilevel converter. Switches Sa, Sb, and Sc are inserted in the ac input side. Each filter capacitor of the conventional multilevel converter is replaced with a series connected switch (S_{O1}~Son) and capacitor (C1~Cn), and one switch Sdc is inserted in the positive dc side. A resistor Rdc is parallel connected to the switch Sdc. However, these switches keep on state during normal operation and are become off state just at the instant of load short circuit. Therefore, the switching frequency and switching loss of the additional switches are extremely low compared to the main switches of S1~S(n-1). And the number of switching devices of Sa~Sc and Sdc is constant regardless of the level number. Each switch of Sa~Sc consists of antiparallel connection of two SCR thyristors and operates just as a switch not as an ac thyristor controller. The switches S_{O1}~Son prevent the

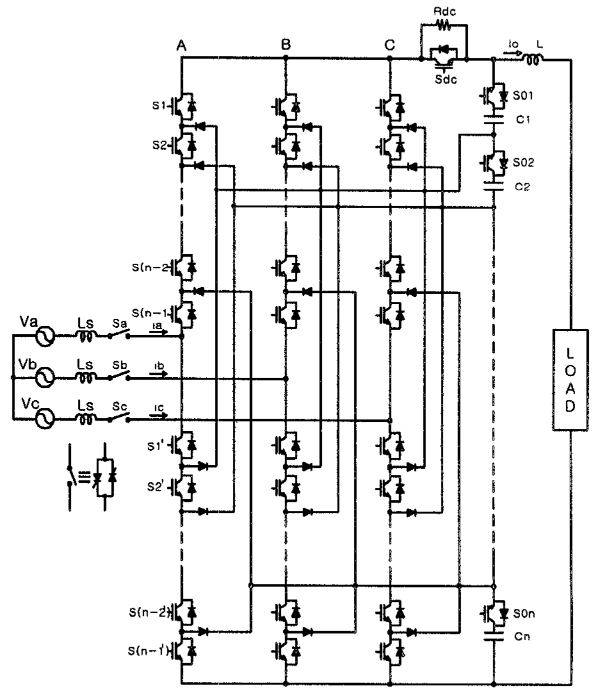


Fig. 1. Generalized circuit diagram of the proposed scheme.

output capacitors C1~Cn from discharging at the load short circuit. When the load is connected to the output capacitors again after the short circuit clear, the load voltage build up time should be minimized. Therefore, it is important to keep the capacitors undischarged floating state.

B. Operating Principle

The operating principle is described with a 3-level rectifier circuit in Fig. 2. In normal condition, all the additional switches maintain on state. Therefore, the proposed converter operates as a conventional 3-level PWM rectifier. When a load short circuit occurs, all the switches are turned off properly according to a sequence. Fig. 3 shows the switching sequence of each switch at the load short circuit. Assume that the load is short circuited at time t_1. Then, because the series connected capacitor voltage is applied to the inductor L, the load current I_O begins to increase linearly. The current reaches the short circuit current detection setting value I_{OS} at time t_2. At that time both the switches S_{O1} and S_{O2} are turned off at the same time to prevent the capacitor from discharging. As soon as the switches are turned off

0-7803-5589-X/99/$10.00 (c) 1999

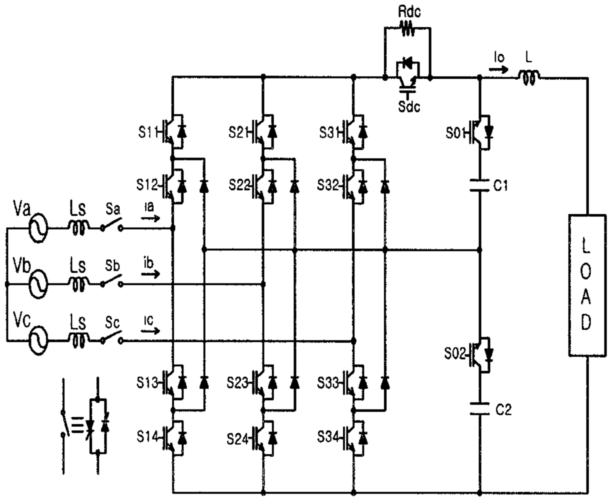


Fig. 2. Proposed 3-level rectifier circuit diagram.

all the main switches S11-S34 are turned on to disconnect the energy flow from the ac source to the load. Then the inductor current I_O begins to flow through the path comprising an inductor L, a load, the diodes of the main switches, and a switch Sdc. By turn off the switch Sdc at time t_3 , the stored inductor energy begins to discharge through a resistor R_{dc} which is parallel connected to the switch Sdc.

Fig. 4 shows the switching sequence of Sa, Sb, and Sc after the switches S11-S34 turn on. When all the switches S11~S34 are turned on at time t_1, an equivalent load seen from the ac source becomes the ac interfacing reactor Ls. To make the ac line currents zero within one cycle the SCR firing signals should be off as soon as all the main switches are turned on. Then each phase current ceases to flow when the current reduces to zero at time t_a and t_b, respectively by the SCR thyristor natural commutation. After the switches S11-S34 are turned on at time t_1, each ac line current varies as follows.

$$i_a = i_a(t_1) + \frac{1}{Ls}\int_{t_1}^{t} v_a \, dt \tag{1}$$

$$i_b = i_b(t_1) + \frac{1}{Ls}\int_{t_1}^{t} v_b \, dt \tag{2}$$

$$i_c = i_c(t_1) + \frac{1}{Ls}\int_{t_1}^{t} v_c \, dt \tag{3}$$

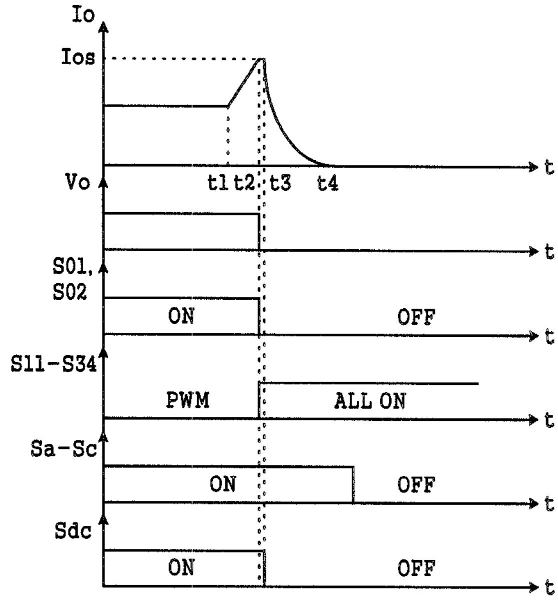


Fig. 3. Switching sequence of each switch in the case of a load short circuit.

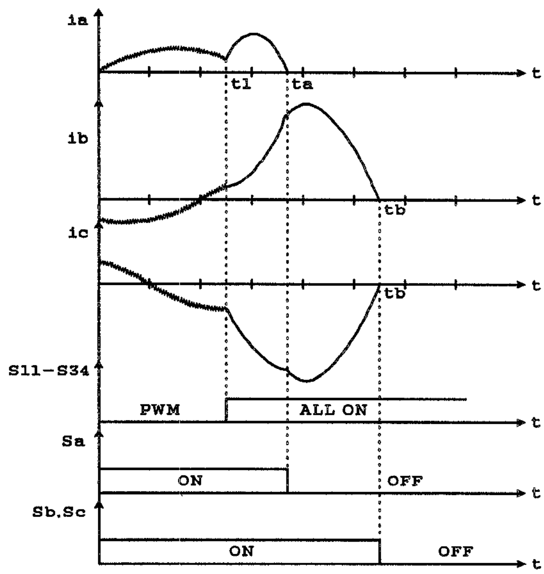


Fig. 4. Switching sequence of Sa-Sc after S11-S34 turn on.

After the phase a current of i_a becomes zero at t_a , the currents are

$$i_a = 0 \tag{4}$$

$$i_b = i_b(t_a) + \frac{1}{2Ls}\int_{t_a}^{t} (v_b - v_c) \, dt \tag{5}$$

$$i_c = -i_b. \tag{6}$$

0-7803-5589-X/99/$10.00 (c) 1999

III. Analysis Of The Characteristics In The Case Of A Load Short

A. Dc Output Voltage Connection and Disconnection to the Load

Under a normal operating condition, when a load short circuit occurs, the output current I_O through the inductor L begins to increase as shown in Fig. 3. During this mode the current I_O is

$$I_O(t)=I_O(t_1)+\frac{V_{C1}+V_{C2}}{L}(t-t_1),\ \ t_1\leq t. \quad (7)$$

In (7), the voltage drops of the IGBTs S_{O1} and S_{O2} are neglected.

As soon as the output current I_O exceeds the short circuit current detection setting value I_{OS}, all the main switches S11-S34 are turned on. The next sequence is the switch Sdc turn off at t_3. By the Sdc turn off, the output current path alters, and it begins to flow through the resistor Rdc. During the changed mode, the current I_O varies as follows.

$$I_O(t)=I_O(t_3)e^{-\frac{t-t_3}{\tau_1}},\quad t_3\leq t \quad (8)$$

where, $\tau_1=\frac{L}{R_{dc}}$.

In (8), the main switch diodes voltage drops are also neglected. After an enough time to be cleared the short circuit state in the load it is necessary to reapply the output dc voltage to the load to keep the total on-time as long as possible. The output current I_O build up is

$$I_O(t)=\frac{(V_{C1}+V_{C2})}{R_L}(1-e^{-\frac{t}{\tau_2}}), \quad (9)$$

where, $\tau_2=\frac{L}{R_L}$, R_L : load resistance.

Fig. 5 shows t_{os}, t_f, t_r, and $P_{R_{dc}}$ with the variations of the inductor L and the resistor Rdc under a 10 A and 400 V output power condition. The short circuit current detection setting value I_{os} is 150 % of the full load current. The times t_{os} and t_f mean the time interval t_2-t_1 and t_4-t_3 in Fig. 3, respectively. The time t_r is the Io rising time (from 0 % to 90 %) while the capacitor voltage ($V_{C1}+V_{C2}$) is reapplied to the load. The power $P_{R_{dc}}$ means the average dissipated power in the resistor R_{dc} during the time t_f.

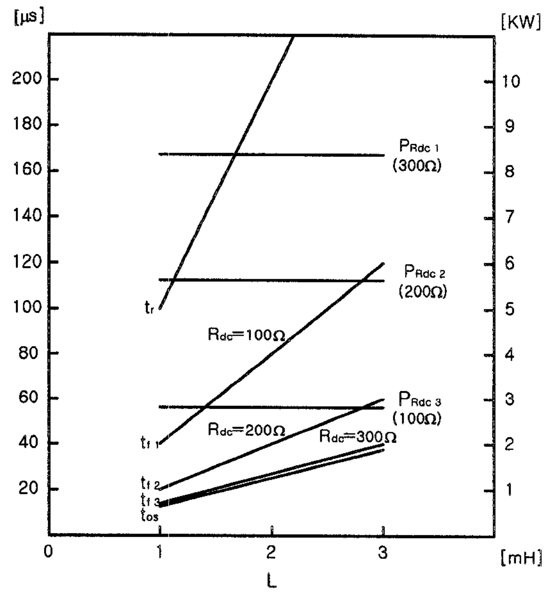


Fig. 5. Time of t_{os}, t_f, t_r, and P_{Rdc} with the variation of L and Rdc.

B. Ac Input Current Break

During a load short circuit state a power transfer from the ac source to the dc output should be prevented. For the purpose, all the main switches S11-S34 are turned on first. Then, the power transfer is prevented, but the ac line currents still flow through Ls and IGBTs. The line currents can not be broken at the instance of a load short because of the stored energy in the interfacing reactor Ls. To break the currents, each SCR gate signal of the switches Sa-Sc should be off. The currents become zero when the SCRs are turned off by a natural commutation. Because ac input voltage is applied to only the inductor Ls during this mode, the ac current magnitude is large as shown in Fig. 4. Fig. 6 shows each normalized peak line current versus the load short circuit instant under the condition of Vo=400V, Io=10A,

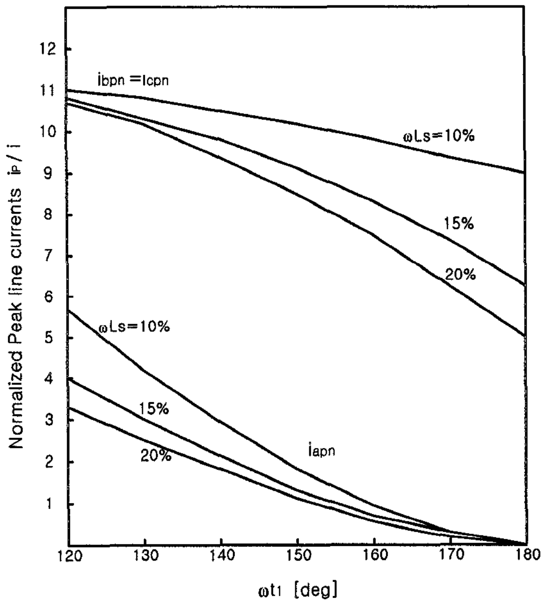


Fig. 6. Normalized peak line current versus the time instant of a load short.

and Vin=220V. The phase angle ωt_1 corresponds to the time t_1 in Fig. 4. The peak value of each phase current varies according to the time t_1. The current variation pattern is same every 60 degrees. Therefore, the variation range of the phase angle ωt_1 is $\frac{2\pi}{3} < \omega t_1 \leq \pi$. If the interfacing reactor impedance is 10 % of the base impedance, the most high peak line current is 11 times the normal full load peak current.

IV. SIMULATION RESULT

The output switching characteristic of the proposed power converter is simulated with the following parameters. The ac input line-to-line voltage = 220 V, Ls = 2 mH, R_{dc} = 300 Ω, C1, C2 = 2,200 μF, L = 2 mH, output dc voltage = 400 V, and load resistance = 40 Ω.

Fig. 7(a) and (b) show a load current Io and a load voltage Vo. Assume that the load becomes short circuit at time $t = 20\,\text{ms}$, and the output voltage is reapplied to the load at 30ms. The short circuit is cleared between 20ms and 30ms. The load voltage decreases to zero at 20ms and the zero voltage continues to 30ms. Fig. 7(c) shows the detailed output current waveform around 20ms. When the load becomes short circuit the output

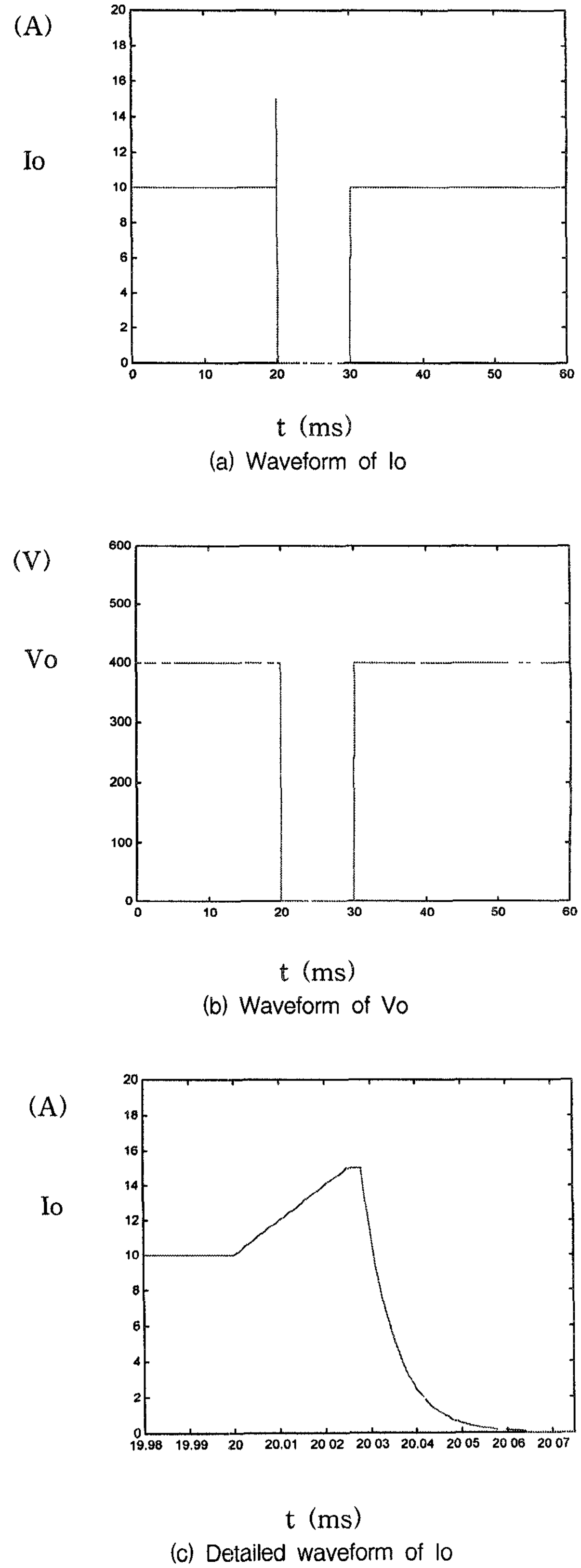


Fig. 7. Waveforms of Io and Vo in the case of a load short circuit.

0-7803-5589-X/99/$10.00 (c) 1999

voltage (V_{C1} + V_{C2}) is applied to the inductor L. Therefore, the load current begins to increase linearly up to 150 % of the rated output current as shown in Fig. 7(c), and the increasing time interval is 25 μs. When the current reaches the short circuit current detection setting value, the switches S_{O1} and S_{O2} are turned off simultaneously to disconnect the output capacitors from the load.

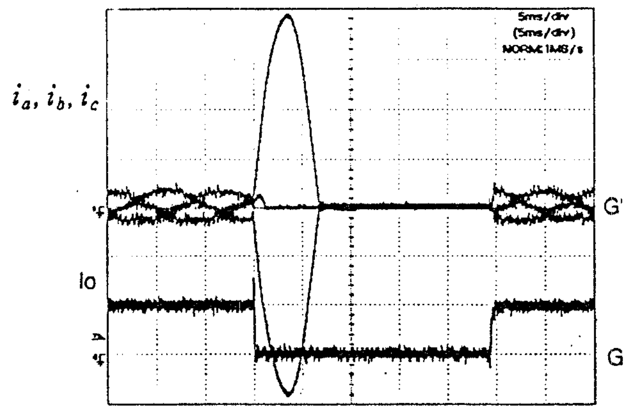
By turn off the switch Sdc, the output current decreases exponentially and the discharging time interval is almost 30 μs. When the output capacitors are connected to the load by turn on the switches S_{O1} and S_{O2}, the load current increases exponentially and the increasing time interval is around 200 μs.

V. Experimental Results

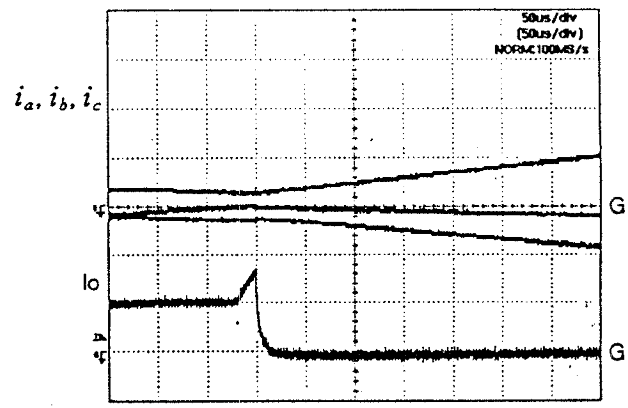
To prove the validity of the proposed topology, the proposed converter has been built and tested. The parameters used in the experiment are the same as those in the simulation.

Fig. 8(a) shows the ac line currents i_a, i_b, and i_c and the output dc current Io waveforms. The normal full load ac input and dc output current waveforms are changed when a load short circuit occurs at 15ms. The waveforms become normal again after the output voltage reapplication at 39.5ms. To make the load short circuit condition, an IGBT is parallel connected to the load. By turn on and off the IGBT, the load becomes short circuit and short circuit cleared, respectively. When a load becomes short circuit, the load current Io begins to increase up to the short circuit current detection level of 15 A. Then, the switches S_{O1} and S_{O2} are turned off, and all the main switches S11~S34 of the converter in Fig. 2 are turned on to interrupt a power transfer from the ac source to the load. Therefore, the dc output current decreases to zero and each ac line current ceases to conduct under the zero current switching condition. It is assumed that the short circuit condition is cleared after 20 ms. The output power is reapplied to the load 4.5 ms after the clear. Then, an output current builds up within around 200 μs. Fig. 8(b) and (c) show the detailed waveforms during the disconnection of the power from the load and connection of the power to the load, respectively.

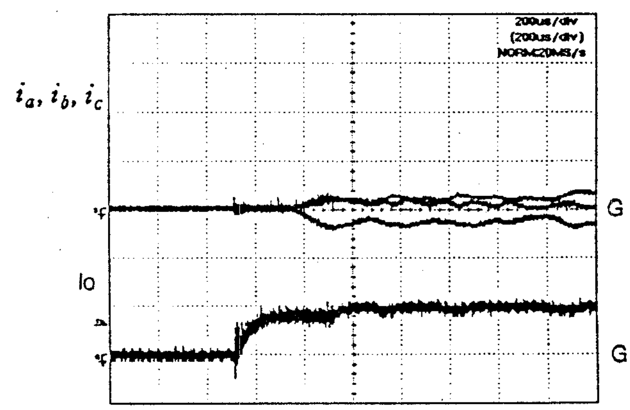
Fig. 8(d) shows the output capacitor voltage Vc, the load voltage Vo, and the output current Io.



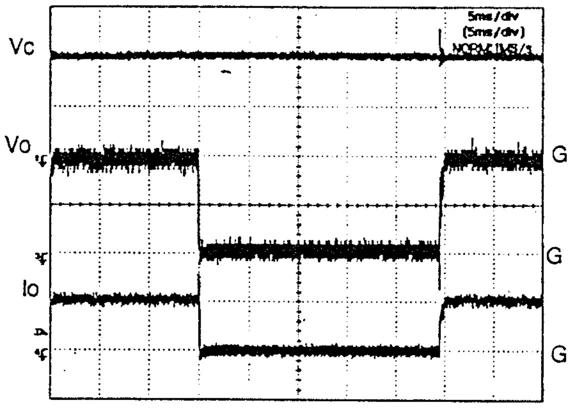
(a) Waveforms of i_a, i_b, i_c, (50 A/div.) and Io (10 A/div.). Time scale : 5 ms/div.



(b) Detailed waveforms during disconnection of the power from the load (50 μs/div.)



(c) Detailed waveforms during connection of the power to the load (200 μs/div.)



(d) Waveforms of Vc, Vo, (200 V/div.) and Io (10 A/div.) Time scale : 5 ms/div.

Fig. 8. Waveforms of i_a, i_b, i_c, Vc, Vo, and Io in the case of a load short under a full load condition.

When a load short circuit occurs, the load voltage becomes almost zero. The load current also becomes zero according to the sequence in Fig. 3. However, there is no capacitor discharge because the output switches S_{O1} and S_{O2} are turned off.

VI. Conclusion

A new boost type rectifier for a dc power supply with frequent output short circuit is described. The proposed converter output power disconnection time from a short circuit load is fast enough to protect both the converter and the load. The converter output filter capacitors do not discharge even in a load short circuit condition. The undischarged capacitors are connected to the load again after the short circuit clear. Therefore, the load voltage build up time is short. Experimental results show that the load voltage falling and rising times during a disconnection and a reapplication are around 30μs and 200μs, respectively. The proposed converter provides a high speed output switching function. An ion source experiences frequent spark downs. A power supply for an ion source demands a fast output power interrupt at a spark down. And the spark down is cleared within several tens ms. The output power should be reapplied to the load as soon as the short circuit load is cleared to keep the total operating time as long as possible. The proposed converter satisfies the requirement of the power supply for an ion source. The features of the proposed converter are summarized as follows:

1) A high disconnecting speed of the dc output power from a short circuit load.
2) No output capacitor discharging even at a load short circuit.
3) A rapid reapplication of the output power to the load after the short circuit cleared.
4) A negligible switching loss of the auxiliary switches.
5) Low device voltage and current stresses of the dc side auxiliary switches.
6) A simplified structure and reduced cost, weight, and volume of the power supply compared with the conventional power supplies for an ion source.

The experimental results show the usefulness of the proposed converter for a dc power supply with frequent output short circuit. It is expected that the proposed converter scheme can be applied in the field of a dc power supply with frequent load short circuits and a pulsed dc power supply.

VII. References

[1] Detai Wang, "The development of long pulse high voltage power supply for MNI-1U neutral beam injector", IEEE Proc. 13th Symp. on Fusion Eng. vol. 2, pp. 1210-1213, 1989.

[2] D. T. Wang, X. W. Xu, et al., "The power supply and control system for the MM-2U neutral beam injector", IEEE Proc. 15th Symp. on Fusion Eng. vol. 2, pp. 901-904, 1993.

[3] Yukio Watanabe, Nagataka Seki, et al., "Acceleration power supply system for neutral beam injector using GTO", IPEC, pp. 808-819. 1983.

[4] M. Mizuno, M. Dairaku, et al., "Inverter type high voltage dc power supply for negative-ion-based neutral beam injectors", IEEE Proc. 13th Symp. on Fusion Eng. pp. 575-577, 1989.

[5] R. Claesem and P. L. Mondino, "Neutral beam injection and radio-frequency power supplies", Fusion Tech. vol. 11 pp.141-162, 1987.

0-7803-5589-X/99/$10.00 (c) 1999

[6] A. Nabae, I. Takahashi, H. Akagi, "A new neutral point clamped PWM inverter", IEEE Trans. on Ind. Appl. vol. IA-17, no. 5, pp. 518-523, 1981.

[7] Y. Zhao, Y. Li, and T. A. Lipo, "Force commutated three level boost type rectifier", IEEE Trans. on Ind. Appl., vol. 31, no. 1, pp. 155-161, 1995.