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A New Ac-to-Dc Power Converter for a Load with Frequent Short Circuits

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Abstract - This paper describes a new ac-to-dc power converter using a multilevel converter. A conventional multilevel ac-to-dc converter has large output dc filter capacitors. When a short circuit happens in a load, the stored energy in the capacitors should be discharged through the load with a high short circuit current. The high current may cause considerable damage to the capacitors and the load. The output dc capacitors of the proposed converter do not discharge even under load short circuit condition. In the case of a load short circuit, the capacitors become a floating state immediately and remain in the state. Then the stored capacitor energy is supplied to the load again as soon as the short circuit has been cleared. Therefore, the rising time of the load voltage can be significantly reduced. This feature satisfies the requirement of a power supply for a load with frequent 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.

Key Words : Frequent output short circuits, Floating state capacitor, Rapid connection and disconnection of a power to a load

1. Introduction

Most of dc power supplies provide a protection function against over current or short circuit current at the output side. Usually, a short circuit results in the shut down of the power supply, which happens rarely. However, in a special power supply for a specific dc load such as an ion source, the short circuit occurs frequently due to the spark downs of the ion source. In order to protect the ion source and the power supply for the ion source against short circuit current, it is necessary to disconnect the ion source from the power supply as fast as possible. It is also desirable to turn on the power supply again as soon as the fault has been cleared to keep the total on-time as long as possible. Therefore, a power supply requires not only a voltage regulation function but also a high speed switching function, and a protective function at the instant of a load fault [1,2].

Many efforts have been made to satisfy the above requirements. Up to the middle of the 1980's, tetrodes had been used for the rapid switching of a dc power source. The tetrode has a good switching characteristic, but it has some problems such as a flashover in the tube, poor efficiency, X-ray radiation, short life time, high cost, and difficulty in maintenance. To overcome the problems, Yukio Watanabe [3] used GTO thyristors instead of the tetrode. A GTO thyristor has high speed turn on/off characteristic, and the device loss is considerably low compared with 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 need to be connected in series to match the required voltage rating of the switching element at the dc side. Since gate driver power of each GTO is supplied through an insulating transformer, the series-connected stack becomes bigger in size and weight. In addition, the entire GTO turn on/off synchronization is difficult. In [4], there is no switching device at the dc side. The switching operation 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, and the other is the reduction of the step-up transformer's volume and weight. A high frequency operation of the inverter reduces the

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transformer size.

It is well known that a multilevel converter has good characteristics in high voltage and high power applications [6]. The power supply can be considerably simplified by using a multilevel converter, because there is no need for GTO inverters, step-up transformers, and a diode rectifier. However, the conventional boost type multilevel rectifiers [7,8] can not be applied to the above mentioned purpose power supply. When a load short circuit occurs, the energy discharged from the rectifier output capacitors may damage the load and the capacitors severely. Furthermore, it is difficult to switch off the output dc power rapidly. This paper describes a new scheme for the power supply using a modified boost type multilevel rectifier. 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.

2. Proposed Circuit Diagram and Operating Principle

2.1 Proposed Circuit Diagram

Fig. 1 shows the generalized circuit diagram of the proposed scheme. The circuit diagram is basically similar to that of 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}~S_{on}) 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 changed off-state just at the instant of load short circuit. Therefore, the switching loss of the additional switches is extremely low compared to the main switches of S1~S(n-1). And the number of switching devices 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 simple switch but not as an ac thyristor controller. The switches S_{o1}~S_{on} prevent the output capacitors C1~Cn from being discharged during the load short circuiting intervals. When the load is connected to the output capacitors after the short circuit has been cleared, the load voltage should build up rapidly, and the build up time should be minimized. Therefore, it is important to keep the capacitors undischarged floating state.

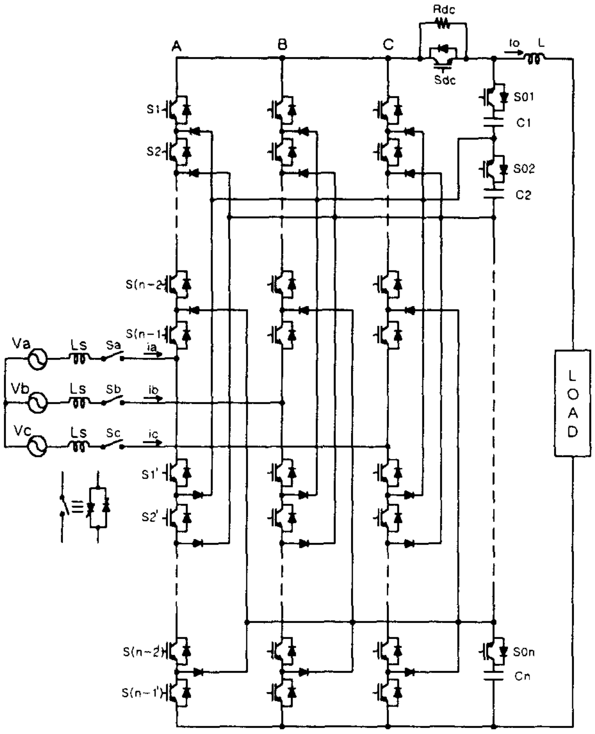


Fig. 1 Generalized circuit diagram of the proposed scheme

2.2 Operating Principle

The operating principle is described with a 3-level rectifier circuit shown 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 additional switches are turned off properly according to a pre-defined 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, the voltage of capacitors C1 and C2 is applied to the inductor L, and thus the load current I_O begins to increase linearly. When the short circuit current reaches the previously set up value I_{OS} at time t_2, both the switches S_{o1} and S_{o2} are turned off at the same time to prevent the capacitor from being discharged. Just after the switches are turned off, all the main switches S11-S34 are turned on to interrupt 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 turning off the switch Sdc at time t_3 , the stored energy in the inductor begins to discharge through a resistor R_{dc} which is connected parallel to the switch Sdc.

Fig. 4 shows the switching sequence of Sa, Sb, and Sc

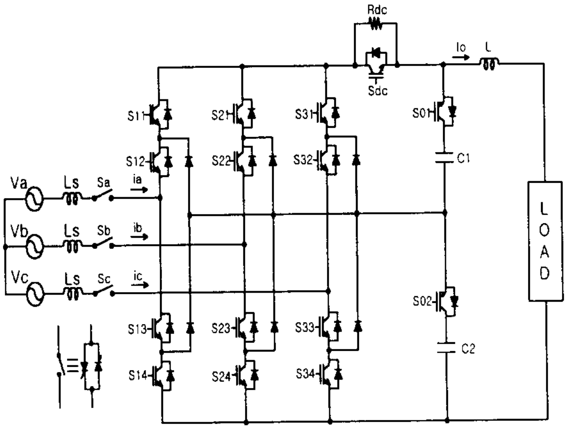


Fig. 2 Proposed 3-level rectifier circuit diagram

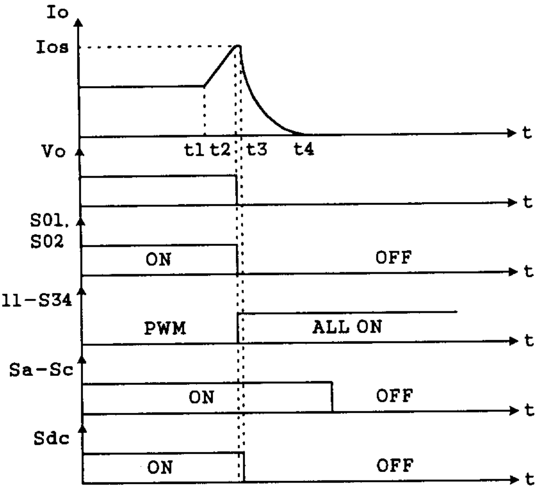


Fig. 3 Switching sequence of each switch in the case of a load short circuit

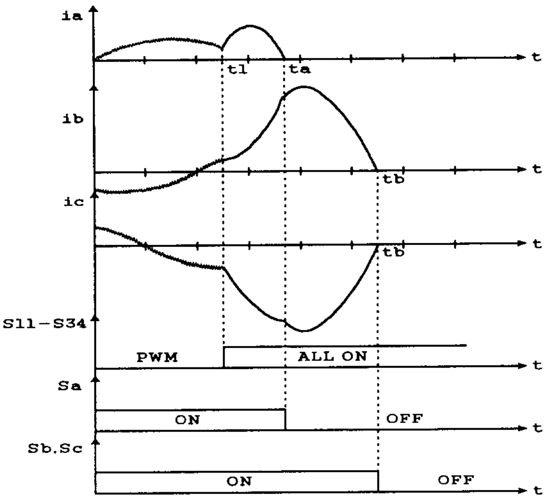


Fig. 4 DEtailed switching sequence of Sa-Sc after turning on of S11-S34

after the switches S11-S34 are turned on. When all the switches S11~S34 are turned on at time t_1, an equivalent load of 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 decreases to zero at time t_a and t_b, respectively by natural commutation of the SCR thyristor. After the switches S11-S34 are turned on at time t_1, each ac line current varies as follows.

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

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

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

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

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

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

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

3. Analysis of the Characteristics in the Case of a Load Short Circuit

3.1 Dc Output Voltage Connection and Disconnection to the Load

When a load short circuit occurs under a normal operating condition, 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

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

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 detection value of the short circuit current I_{OS}, all the main switches S11-S34 are turned on. Then the switch Sdc is turned off at t_3. By turning off Sdc, 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.

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

where, $\tau_1 = \frac{L}{R_{dc}}$ and the voltage drops of the main switch diodes are also neglected. After enough time passes to clear 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 is built up as

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

where, $\tau_2 = \frac{L}{R_L}$ and R_L is a 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 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 are the time interval $t_2 - t_1$ and $t_4 - t_3$ as shown 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 $P_{R_{dc}}$ is the average power dissipated in the resistor R_{dc} during the time t_f.

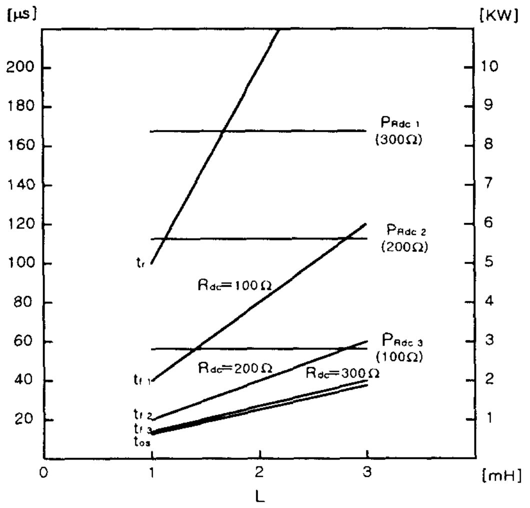


Fig. 5 Time of t_{os}, t_f, t_r, and P_{Rdc} with the variation of L and Rdc

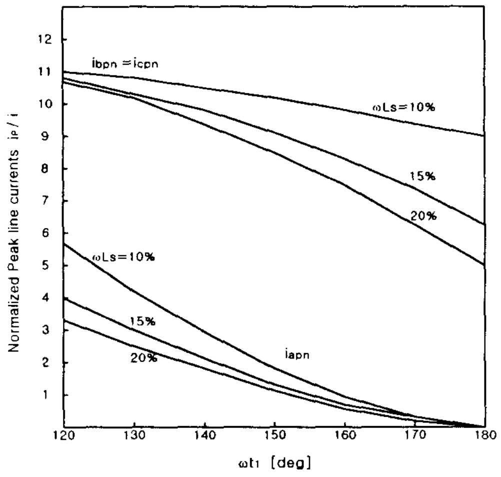


Fig. 6 Normalized peak line current versus the time instant of a load short

3.2 Ac Input Current Break

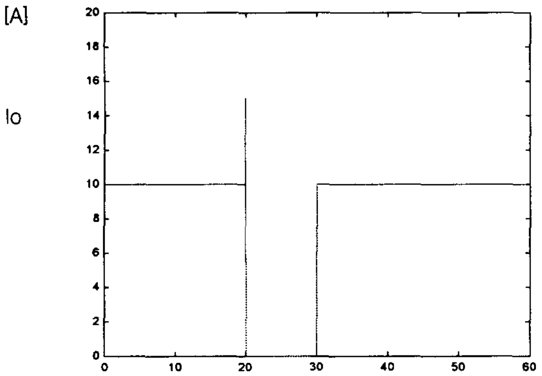
During a load short circuit state, a power transfer from the ac source to the dc output should be interrupted. For this purpose, all the main switches S11-S34 should be turned on first. Then, the power transfer is prevented, but the ac line currents still flow through Ls and IGBTs. The line currents 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 decrease to zero when the SCRs are turned off by a natural commutation. Since the 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 instant of a load short circuit under the condition of Vo=400V, Io=10A, 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 depending on time t_1 . The current variation pattern is the same every 60 degrees. Therefore, the variation range of the phase angle ωt_1 is $\frac{2\pi}{3} < \omega t_1 \le \pi$. If the interfacing reactor impedance is 10 % of the base impedance, the highest peak line current is 11 times of the normal full load peak current.

4. Simulation Result

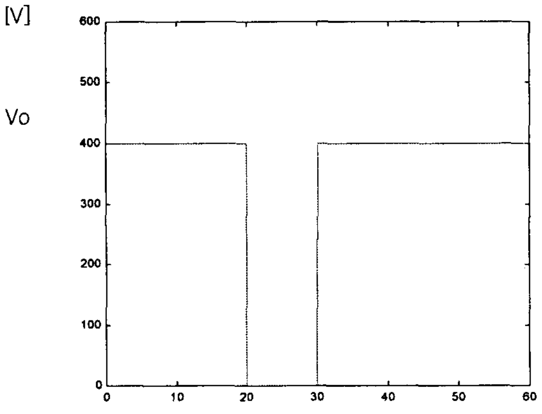
The output switching characteristic of the proposed power converter is simulated with the following parameters. The ac input line-to-line voltage = 220 V, Ls = 2 mH, Rdc = 300 Ω, C1, C2 = 2,200 μF, L = 2 mH, output dc voltage = 400 V, and load resistance = 40 Ω.

Fig. 7(a) and (b) show the load current Io and 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 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 setting value of short circuit current detection, the switches S_{O1} and S_{O2} are turned off simultaneously to disconnect the output capacitors from the load.

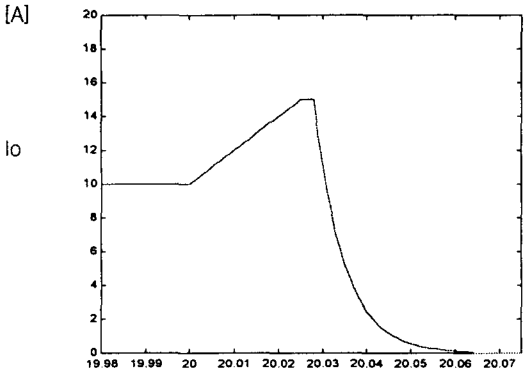
By turning off the switch Sdc, the output current decreases exponentially and the discharging time interval is almost 30 μs. When the output capacitors are connected to the load by turning on the switches S_{O1} and S_{O2}, the load current increases exponentially and the increasing time interval is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



(a) Time [ms]



(b) Time [ms]



(c) Time [ms]

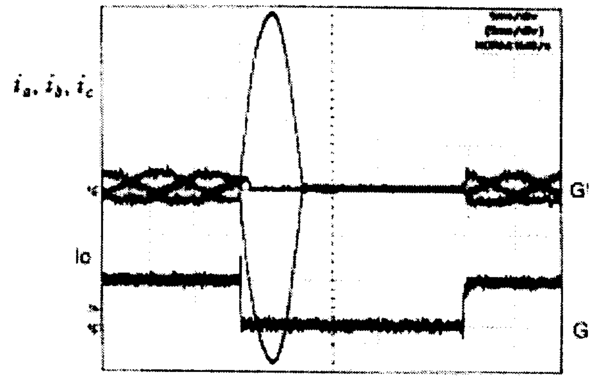
Fig. 7 Waveforms of Io and Vo in the case of a load short circuit
(a) Waveform of Io
(b) Waveform of Vo
(c) Detailed waveform of Io

5. Experimental Results

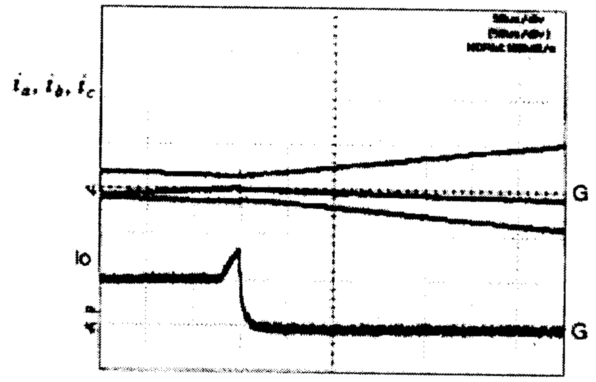
To prove the validity of the proposed topology, the proposed converter has been built and tested. The parameters used in the experiment are the same as those in the simulation.

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 15 ms. The waveforms become normal again after the output voltage reapplication at 39.5 ms. To make the load short circuit condition, an IGBT is connected parallel to the load. By turning 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 short circuit clearing operation. Then, an output current builds up within around 200 μs. Fig. 8(b) and (c) show the detailed waveforms during disconnection of the power from the load and connection of the power to the load, respectively.

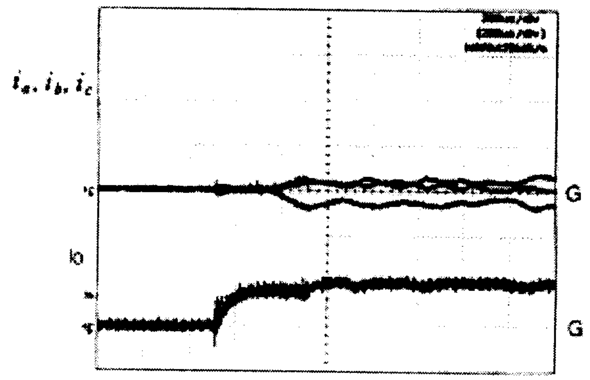
Fig. 8(d) shows the output capacitor voltage Vc, the load voltage Vo, and the output current Io. When a load short circuit occurs, the load voltage becomes almost zero. The load current also becomes zero according to the sequence in Fig. 3. However, there is no capacitor discharge because the output switches S_{O1} and S_{O2} are turned off.



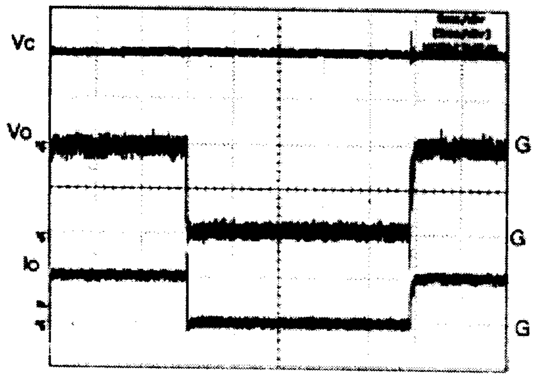
(a) Time scale : 5 ms/div.



(b) Time scale : 50 μs/div.



(c) Time scale : 200 μs/div.



(d) 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
(a) Waveforms of i_a, i_b, i_c (50A/div.) and Io (10 A/div.)
(b) Detailed current waveforms during disconnection of the power from the load
(c) Detailed current waveforms during connection of the power to the load
(d) Waveforms of Vc, Vo (200 V/div.) and Io (10 A/div.)

6. Conclusion

A new boost type ac-to-dc power converter is described. The proposed converter provides sufficiently fast disconnection time of output power from a short circuit load in order to protect both the converter and the load. The output filter capacitors of the converter do not discharge even in a load short circuit condition. These undischarged capacitors are connected to the load again after the short circuit has been cleared. Therefore, the build up time of the load voltage is short. Experimental results show that the falling and rising times of the load voltage during a disconnection and a reapplication are around 30μs and 200μs, respectively. The proposed converter provides a high speed output switching function. Since spark down happens frequently on an ion source, a power supply for an ion source requires fast output power disconnection at a spark down, and recovery within several tens ms. Also, the output power should be reapplied to the load as soon as the short circuit load has been 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) High disconnecting speed of the dc output power from a short circuit load.

2) No discharge of the output capacitor even at a load short circuit.
3) Rapid reapplication of the output power to the load after the short circuit has been cleared.
4) Negligible switching loss of the auxiliary switches.
5) Low device voltage and current stresses of the dc side auxiliary awitches.
6) 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. The proposed converter could be applied in the field of a dc power supply with frequent load short circuits, and a pulsed dc power supply.

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