A HIGH VOLTAGE DC POWER SUPPLY SUITABLE FOR AN ION SOURCE

Eui-Cheol Nho
Dept. of Elec. Eng. Pukyong Nat'l Univ.
San 100, YongDang-Dong, Nam-Ku, Pusan,
608-739, Korea
Phone+82-51-620-1439
Fax+82-51-628-9510

In-Dong Kim
Dept. of Elec. Eng. Pukyong Nat'l Univ.
San 100, YongDang-Dong, Nam-Ku, Pusan,
608-739, Korea
Phone+82-51-620-1429
Fax+82-51-620-1420

ABSTRACT−This paper proposes a novel dc power supply using modified multilevel ac/dc converter. The output voltage of the power supply can be disconnected from and reapplied to the load rapidly. Therefore the power supply is suitable for a load having frequent short circuit such as ion source. The proposed scheme improves the performance, efficiency, and reliability and reduces the cost of the conventional power supply system for an ion beam acceleration.

1. INTRODUCTION

In this paper a new dc power supply using modified multilevel ac/dc converter is proposed. The output voltage of the proposed power supply can be disconnected from and reapplied to the load rapidly without severe electrical transient. This good characteristic can be effectively applied to the power supply system for an ion beam acceleration. A power supply for an ion beam acceleration will experience frequent spark downs in an ion source. Therefore the applied dc power should be disconnected from the ion beam acceleration grid rapidly after breakdown detection to protect both the power supply system and the ion source from short circuit current. It is also desirable to turn the supply on again as soon as the spark down cleared to keep the total on-time as long as possible.

A tetrode was used for the fast switching of the dc power source. However, the tetrode has some disadvantages as follows. 1) Sometimes a flashover may occur in the tetrode at the time of ion source spark. Thus a crowbar switch is necessary to protect the tetrode and ion source from excess energy dump. 2) A water cooling system is necessary to limit the tetrode temperature rise resulted from the high anode dissipation. 3) X-ray radiation requires a lead shielding. 4) The life time of a tetrode is short. 5) The maintenance of a tetrode is not easy.

To overcome the above mentioned problems the tetrodes have been replaced by GTO thyristor with the increased power capabilities [1,2]. However the dc switch using GTOs for high voltage application becomes huge and the reliable control is difficult because of a large number of the elements in series.

Some high voltage ac switching type power supplies without dc switch have been proposed [3,4]. Generally, the system of these power supplies consist of SCR rectifier, GTO inverter, step-up transformer, and 3 phase diode full bridge rectifier. The GTO inverter part provides the switching function of the dc output power. The term of ac switching stems from the fact that the switching occurs in GTO inverter not in dc part.

Multilevel converters have been proposed for high voltage and high power application. However multilevel rectifier itself does not provide the required rapid switching function of the dc power source. The proposed modified multilevel rectifier simplifies the power supply system for ion beam acceleration because there are no need of inverter, step-up transformer, and diode rectifier which are the components of the ac switching type high voltage power supply. Furthermore the PWM multilevel rectifier improves the power factor significantly compared to that of the SCR rectifier. Therefore the proposed scheme improves the efficiency and reliability and reduces the cost, size, and weight of the power supply system.

Analyses and simulations about the proposed converter operation and characteristics are carried out.

2. PROPOSED CIRCUIT DIAGRAM AND OPERATING PRINCIPLE

Proposed Circuit Diagram

Fig. 1 shows an example of the proposed scheme concept. In this case the proposed scheme is applied to a 3-level rectifier. The proposed scheme can be applied to higher level multilevel converter to obtain a high voltage dc output. The proposed circuit has additional switches (Sa-Sc, S_{01}, S_{02}, S_{dc}) compared with the conventional 3-level rectifier. However the switching loss and device stress of these switches are negligible because the turn off of the switches occurs just at the instant of the power supply dc output fault of short circuit. In other words, the switching frequency of the additional switches is extremly low compared to the main switches of S11-S34. Furthermore the number of switching elcments of Sa-Sc and S_{dc} is constant regardless of the level number of the multilevel rectifier. Switches Sa-Sc consist of anti parallel connection of SCR thyristors and operate just as switch not ac thyristor controller. These switches can be constructed with another kind of power devices such as IGBT or GRO. However SCR thyristor is the most effective choice because of low on state loss. S_{01} and S_{02} are normally on state and become off state when load short circuit occurs to prevent the discharge of the output filter capacitors C1 and C2. The undischarged state is important to minimize the output voltage build up time and the electric transient when the load is connected to the output filter capacitor again after the short circuit cleared. Switches S_{dc} also maintains on state normally. In case of load short the switch become off state to make a path of the discharging of the stored energy in inductor(L) through resistor R_{dc}.

Operating Principle

In normal condition, all the additional switches maintain on state. Therefore the proposed converter operates as the conventional 3-level PWM rectifier does. When the load short circuit occurs, the switches should be turned off properly according to the sequence. Fig. 2 shows the switching sequence of each switch when load

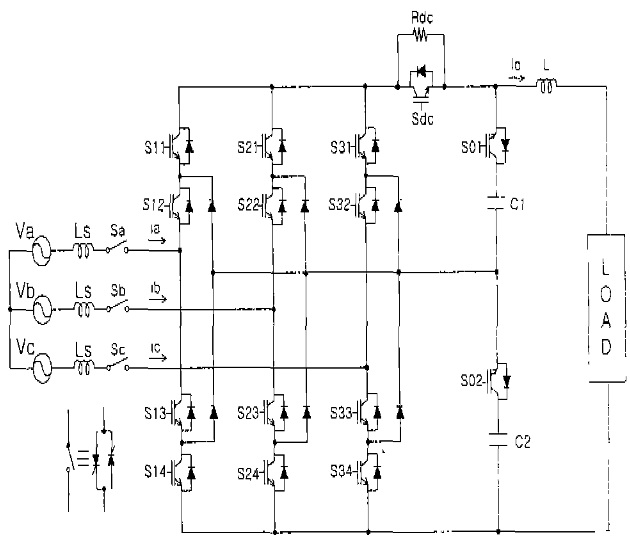


Fig. 1 Proposed circuit diagram applied to 3-level converter

short circuit occurs. Assume that the load is short circuited at time $t = t_1$. Then the load current I_O begins to increase and reaches the short circuit detection current setting value I_{OS} at time t_2. At that time both S_{01} and S_{02} are turned off at the same time and all the main switches of S11-S34 are turned on to disconnect the energy flow from the source to the load. Then the inductor current I_O begins to flow through the path comprising L-load-diodes-S_{dc} By turn off the switch Sdc the stored inductor energy can be discharged through resistor R_{dc} which is parallel connected to the switch Sdc.

On the other hand, the input line currents $i_a - i_c$ begin to increase because all the main switches are turned on. Which results in the short circuit at the input of the rectifier. Fig. 3 shows the switching sequence of Sa, Sb, and Sc after turn on of the switches S11-S34. If all of the switches S11-S34 are turned on the ac interfacing reactor Ls output becomes short circuited. Therefore the ac source voltages $v_a - v_c$ are applied only to the reactor Ls. The magnitude of the current flowing through Ls is determined by the magnitude of source voltages and inductance of Ls. To make the 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, t_b and t_c, respectively, by the nature of SCR thyristor. Therefore the SCR thyristors are turned off under natural soft switching condition. If S11-S34 are turned on at time t_1 the ac line currents vary as follows.

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

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

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

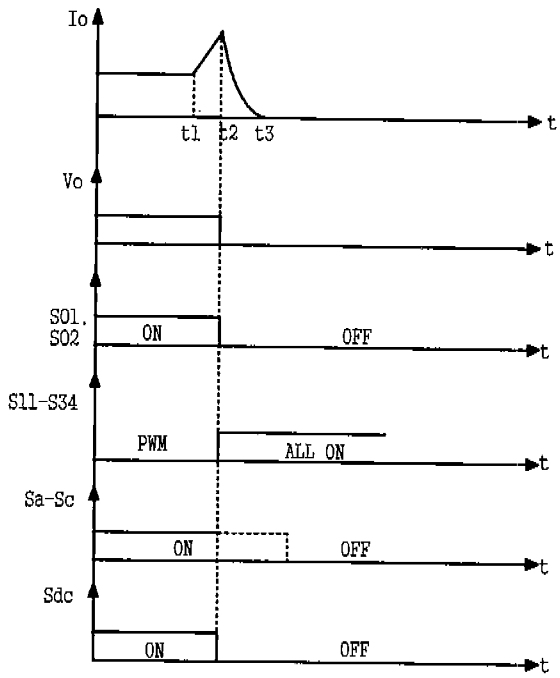


Fig. 2 Switching sequence in case of load short

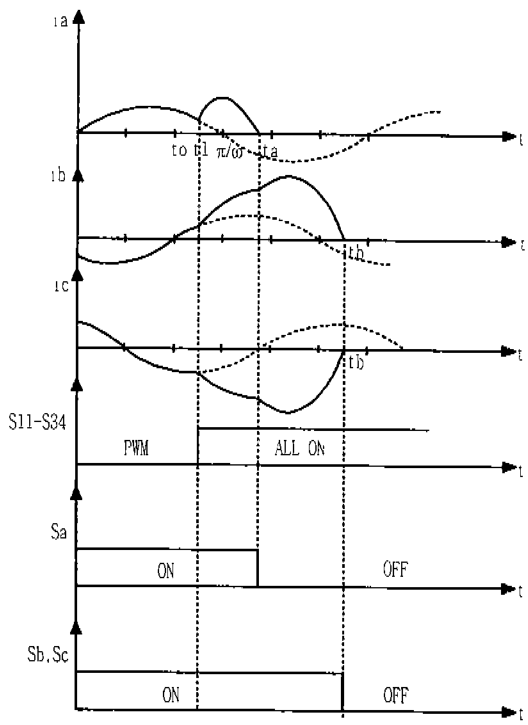


Fig. 3 Switching sequence of Sa, Sb, and Sc in case of load short

After i_a becomes zero at $t = t_a$ 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 SWITCHING FUNCTION

The more detailed input and output voltages and currents at the instant of load short circuit are analyzed.

Dc Output Voltage Connection And Disconnection To The Load

Under the normal operation when load short circuit occurs the output current I_O through inductor L begins to increase as shown in Fig. 2. 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 IGBT 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 are turned on. The following sequence is turn off of the switch Sdc. Therefore the output current alters the flowing path from Sdc to Rdc. During the changed mode the current I_O varies as follows.

$$I_O(t) = I_O(t_2)e^{-\frac{t-t_2}{\tau_1}},\qquad t_2 \le t \tag{8}$$

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

The voltage drop of the diode of main switches 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. The build up current of I_O is

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

where, $\tau_2 = \dfrac{L}{R_L}$,

R_L : load resistance.

Fig. 4 shows t_{os}, t_f, t_r, and $P_{R_{dc}}$ with the variations of the inductor L and resistor Rdc under the condition of full load and 1 kV output voltage. The short circuit detection current setting value of I_{os} is 150 % of the full load current. The times t_{os} and t_f means the interval $t_2 - t_1$ and $t_3 - t_2$, respectively in Fig. 2. The time t_r is the rising time (from 0 % to 90 %) of I_O when the capacitor voltage ($V_{C1} + V_{C2}$) is reapplied to the load. The power $P_{R_{dc}}$ means the average dissipated power in resistor R_{dc} during the time t_f.

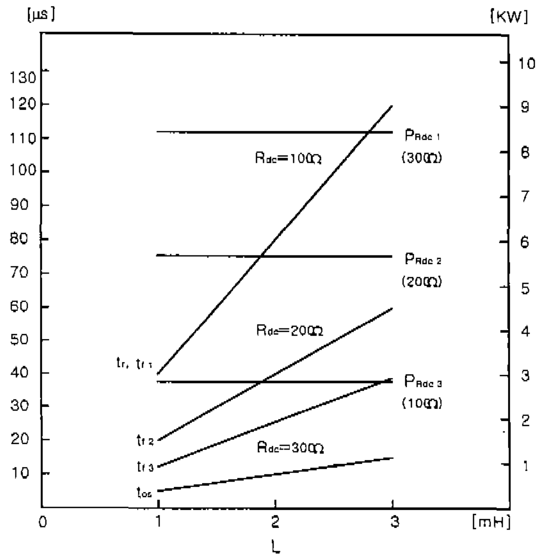


Fig. 4 Time of t_{os}, t_f, t_r, and $P_{R_{dc}}$ versus L and Rdc

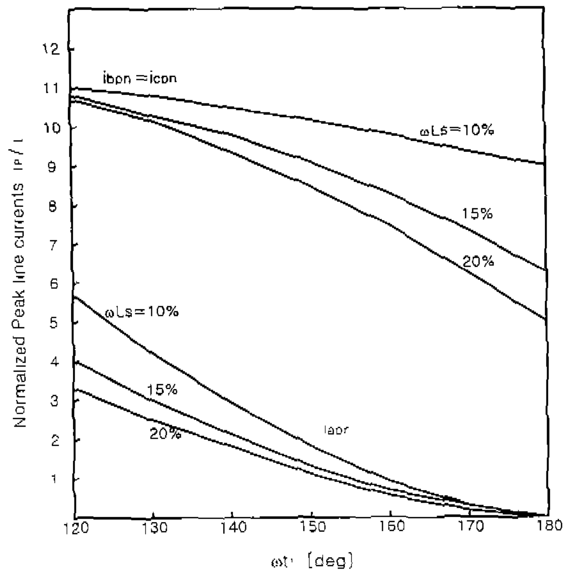


Fig. 5 Normalized peak line current versus the time instant of load short.

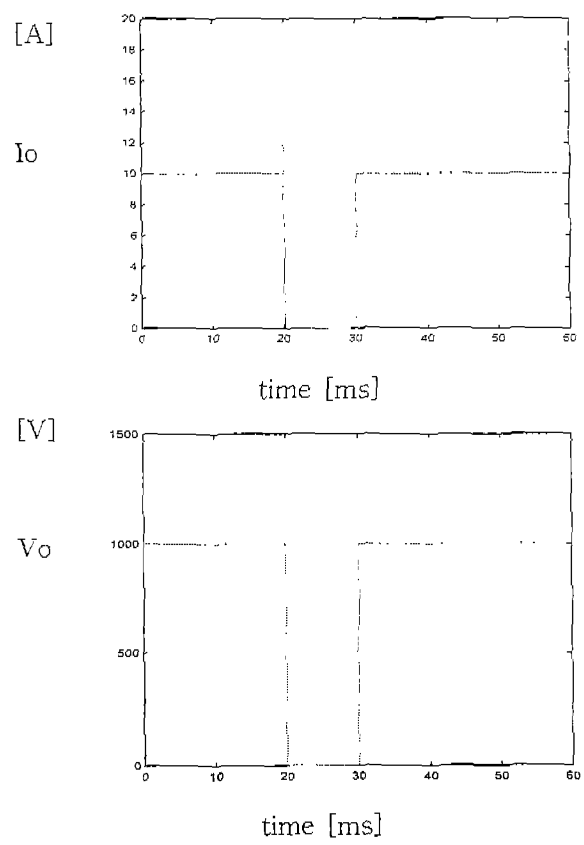
Ac Input Current Break

In order to prevent the power flow from ac power source to dc output in case of load short circuit all of the main switches are turned on simultaneously. In this case it is necessary to break the ac line current. However the line currents can not be broken at the same time because of the stored energy in interfacing reactor Ls. Therefore it is inevitable to allow the large ac current flow as shown in Fig. 3. Fig. 5 shows the each normalized peak line current versus the time instant of load short. The phase angle ωt_1 corresponds to the time t_1 in Fig. 3. 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 ωt_1 is $\frac{2\pi}{3} < \omega t_1 \leq \pi$. Generally, the SCR thyristor surge current rating is high enough to allow the current in Fig. 5 flow through SCR thyristor. If the impedance of the interfacing reactor is 10 % of the base impedance, the most peak line current is 11 times the normal full load peak current.

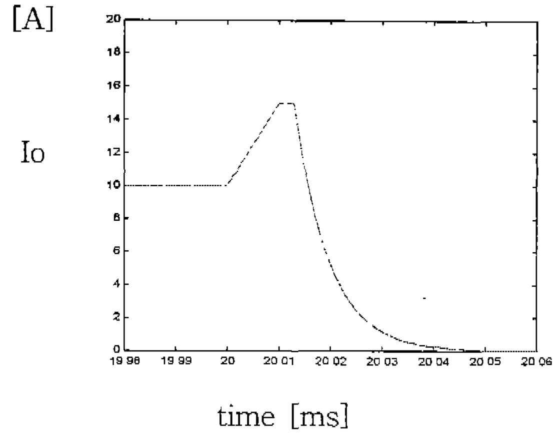
4. SIMULATION RESULT

The output switching performance of the proposed power supply is simulated with the following parameters. Ac input line-to-line voltage = 220 V, Ls = 2 mH, R_{dc} = 300 Ω, C1, C2 = 2,200 μF, L = 2 mH.

Fig. 6(a) shows load current Io and load voltage Vo in case of load short circuit. Fig. 6(b) shows the detailed output current waveform for the load short circuit. If the load is short circuited 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. 6(b), and the increasing time is 10 μs. When the current reaches the short circuit detection current setting value the switches S_{O1} and S_{O2} are turned off simultaneously to disconnect the output capacitor from the load.



(a) Load current and output voltage



(b) Detailed load current

Fig. 6 Output voltage and load current switching characteristic in case of load short

By turn off the switch Sdc the output current begins to decrease exponentially and the discharging time is almost 30 μs. When the output capacitor is connected to the load by turn on the switches S_{O1} and S_{O2}, the load current increases exponentially and the increasing time is around 80 μs. There is no severe electriacl transient such as overshoot or slow response time.

5. CONCLUSION

A new dc power supply having high speed switching function of output voltage is proposed. The high speed switching is especially important when the electrical breakdown occurs in ion source for ion beam acceleration. The proposed power scheme is modified multilevel rectifier. Because multilevel converter is suitable for high voltage and high power applications, the proposed scheme can be satisfied to the demand of high voltage power supply such as ion beam acceleration with the rapid switching performance.

The features of the proposed power supply scheme are summarized as follows:

1) High disconnecting speed of dc output from the load.
2) High reapplication speed of dc output to the load with the hold-on function of output capacitor voltage.
3) Negligible switching loss and device stress of the auxiliary switches.
4) Simplified structure without inverter, step-up transformer, and diode rectifier.
5) Improved efficiency and reliability.
6) Reduced cost, weight, and volume.

6. REFERENCES

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