Minimization of Rising and Falling Times of A Boost Type Converter Output Voltage in Pulsed Mode Operation

Eui-Cheol Nho*, In-Dong Kim*, Cheol-Je Joe*, Tae-Won Chun**, and Heung-Geun Kim***

*: Dept. of Electrical Eng. Pukyong National Univ. Busan, 608-739, Korea
**: School of Electrical Eng. & Auto. Univ. of Ulsan, Ulsan, 689-749, Korea
***: Dept. of Electrical Eng. Kyungpook National Univ. Taegu, 702-701, Korea

Abstract - This paper describes an improved short-circuit protection method with a boost type rectifier using a multilevel ac/dc power converter. The output dc power of the proposed converter can be disconnected from the load within several hundred microseconds at the instant of short-circuit fault. Once the fault has been cleared the dc power is reapplied to the load. The rising time of the dc load voltage is as small as several hundred microseconds, and there is no overshoot of the dc voltage because the dc output capacitors hold undischarged state. The converter, which employs the proposed method, has the characteristics of a simplified structure, reduced cost, weight, and volume compared with a conventional power supply, which has frequent output short-circuits. Experimental results are presented to verify the usefulness of the proposed converter.

1. Introduction

An ac/dc power converter with special load such as an ion source requires excellent protective function at the time of load fault besides a precise regulation performance. The converter is different from the conventional power supply, its load - ion source will experience frequent spark downs. To protect both the ion source and the converter from the source short-circuit current, some methods of diverting current from the source and disconnecting the source from the accel power supply are necessary. It is also desirable to turn the converter on again as soon as the fault has been cleared to keep the total on-time as long as possible.

Many efforts have been made to satisfy the above requirements. At first, to obtain a high speed switching function and protective function at the time of load fault, a tetrode was used as a switching element. The tetrode is connected in series to the positive output of a three-phase full-wave bridge rectifier. Since 1980's, GTO thyristors have been adopted as excellent switching devices in high power applications with the remarkable advance in semiconductor power switching device technology. The GTO thyristor has high speed turn on/off characteristic, and the device's losses are considerably low compared with those of the tetrode. Therefore, GTO thyristors were used as a dc side switching element to overcome some problems of a tetrode such as short life time, poor efficiency, maintenance difficulty, etc.,[1]. However, for a high voltage application above several tens of kV, a large number of GTO thyristors need to be connected in series to match the required voltage rating of the switching element at the dc side. Accordingly, the switching element using GTO thyristors is bulky, and it is difficult to guarantee the turn on/off synchronization of each GTO thyristor. High voltage power supplies without dc switch were proposed to improve the performance[2,3]. This system consists of a rectifier, inverters, step-up transformers, and a 3-phase diode full bridge rectifiers. This inverter type dc power supply satisfies the required output switching performance by run/stop of the inverter operation. The inverter also enables the step-up transformer to be reduced in size and weight by increasing the inverter output frequency.

Recently, multilevel PWM converters have been proposed as one of the practical solutions in high voltage and high power applications[4,5]. Multilevel rectifier has good features such as high power factor and sinusoidal input line current. Furthermore, the converter provides the possibility of simplified structure and high performance without step-up transformer. To obtain a high speed switching performance at the time of load fault with a conventional multilevel PWM rectifier, modified boost type multilevel converter was proposed[6]. In [6], however, there is a large ac line current approximately for half cycle after the instant of a load short-circuit.

This paper describes a new PWM rectifier suitable for a load with frequent short-circuit to improve the performance of the output short-circuit protection. The proposed circuit operation and characteristics are described and analysed, respectively. Experimental results with reduced prototype verify the usefulness of the proposed scheme.

2. Proposed Circuit Diagram and Operating Principle

2.1 Proposed circuit diagram

Fig. 1 shows the generalized multilevel ac/dc converter 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 (So1 ~ 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 the states are changed to off-state just at the instant of load short-circuit. Therefore, the switching loss of the additional switches is extremely low compared to that of 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 of the converter. Each switch of Sa ~ Sc consists of antiparallel connection of two SCR thyristors and operates not as an ac thyristor controller but as a simple switch. The switches of So1 ~ Son prevent the output capacitors of C1 ~ Cn from being discharged during the load short-circuit intervals.

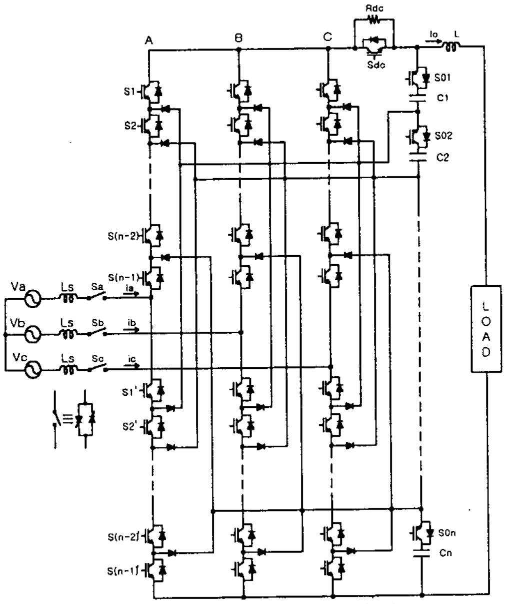


Fig. 1 Multilevel ac/dc converter of the proposed scheme

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.

2.2 Operating principle

In normal operating mode, all the auxiliary switches of Sa, Sb, Sc, Sdc, and So keep on state while the main switches are turned on/off according to the generated PWM signals from a controller. In this mode, each operating state of the proposed converter and a conventional PWM rectifier is the same. The switching state of the switching devices following a sudden dc output short-circuit changes as shown in Fig. 2. The switching state of each device, load voltage, and output dc current waveform in each time interval are described as follows.

1) to≤t<t1

During this mode, the output capacitor voltage of V_c is applied to the inductor L, and hence the output dc current i_o increases linearly as follows.

$$i_0(t) = i_0(t_0) + \frac{V_c}{L}(t - t_0), \quad t_0 \le t \le t_1 \tag{1}$$

Each switching device keeps a normal operation.

2) t1≤t<t2

At time t1, the dc current i_o reaches a previously set up output short-circuit current level of I_{os}. Then an output short-circuit signal of OS becomes Low.

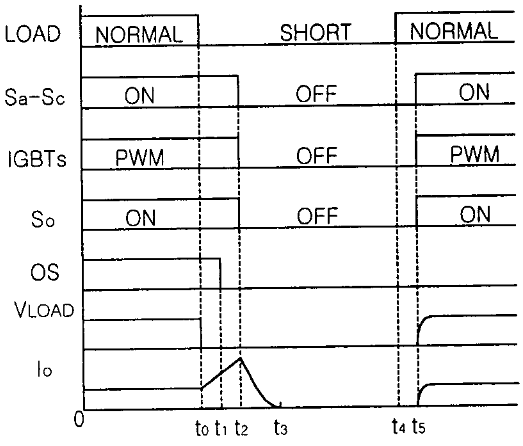


Fig. 2 Switching state, output voltage and current waveform

As soon as the OS signal becomes low gating signals for thyristors Sa, Sb, and Sc are turned off and the power flow direction of the PWM converter is reversed. In other words, the converter operating mode becomes regeneration. As a result, it is possible to cause ac line currents to vanish as fast as possible. The magnitudes of ac line currents of i_a, i_b, and i_c, under regeneration mode, decrease as follows.

$$i_a(t) = -(i_b(t) + i_c(t)) \tag{2}$$

$$i_b(t) = i_b(t_1) - \frac{1}{2Ls}\int_{t_1}^{t}(V_c - v_{ab})dt \tag{3}$$

$$i_c(t) = i_c(t_1) - \frac{1}{2Ls}\int_{t_1}^{t}(V_c - v_{ac})dt \tag{4}$$

This mode ends when all the line currents cease to flow.

3) t2≤t<t3

Once the line currents become zero, there is no more current flow through switches Sa, Sb, and Sc because the gate signals for the switches are turned off already. Then, there is no need of PWM switching in the main switches S1~S6. By turning off both Sdc and So at time t_2, the stored energy in the inductor begins to discharge through a resistor Rdc which is parallel connected to the switch Sdc. The output current through inductor L decreases as follows.

$$i_o(t) = i_o(t_2)e^{-\frac{t-t_2}{\tau 1}}, \qquad t_2 \le t \le t_3 \tag{5}$$

where $\tau_1 = \frac{L}{R_{dc}}$ and the diode voltage drops of the main switches are neglected.

4) t3≤t<t4

There is no current flow from ac or dc source to the load under the condition where the load keeps short-circuit. Each output dc capacitor maintains floating state without discharging.

5) t4≤t<t5

The short-circuit condition is cleared at time t_4, and thus, the load becomes normal state. It is necessary to connect the dc source to the load again. The output dc current increases as follows after the dc source is applied to the load.

$$i_o(t) = \frac{Vc}{R_L}(1 - e^{-\frac{t}{\tau 2}}) \tag{6}$$

where $\tau_2 = \frac{L}{R_L}$ and R_L is a load resistance.

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

3.1 AC input line current

The fundamental component of input current i_a is

$$i_a(t) = \sqrt{2}I_a \sin(\omega t) \tag{7}$$

where I_a is a rms value of i_a.

The line current vanishing mechanism following an output short-circuit repeats with the same pattern every 60 degrees in one cycle of $i_a(t)$. The specific values of i_a, i_b, and i_c are now introduced for 60 degrees.

1) 60°≤wt<90°

In (3) and (4), let

$$V_1 = V_c - v_{ab} \tag{8}$$

$$V_2 = V_c - v_{ac} \tag{9}$$

In this phase angle interval, V_1 and i_c are smaller than V_2 and i_b, respectively. As a result, the first line current to be vanished among three phase currents is the phase c current i_c. A required time for the current i_c to be zero can be calculated from (4). In (4),

$$v_{ac}(t) = \sqrt{2}V \sin(\omega t - \frac{\pi}{6}) \tag{10}$$

Fig. 3 shows the required time t_{co} with the variation of Ls under full load condition. AC input line voltage, line current, and output dc voltage are 220V, 10.5A, and 400V, respectively. As soon as the line current i_c reduces to zero, the magnitude of the other two line currents i_a and i_b become equal as follows.

$$\begin{aligned} i_a(t) &= -i_b(t) \\ &= -i_b(t'_{co}) + \frac{1}{2L_s}\int_{t'_{co}}^{t}(V_c - v_{ab})dt \end{aligned} \tag{11}$$

where a time instant of t'_{co} corresponds to a time t_{co}. From (11) a time duration for the currents i_a and i_b to be zero can be calculated. Fig. 4 shows the time duration under the same condition as is used in Fig. 3.

2) 90°≤wt<120°

In this interval, the magnitude of V_2 and i_b is smaller than that of V_1 and i_c, respectively. Accordingly, the phase b current i_b becomes zero first. Through a similar calculating procedure that used in the interval of $60° \leq wt < 90°$ t_{co} and t_{bo} are calculated. Fig. 5 and 6 show the resulting values.

3.2 DC output current

The dc output current begins to increase after the instant of a short-circuit as in (1). As soon as the input currents i_a, i_b, and i_c become zero, the dc side switches of So and Sdc should be turned off to prevent the capacitor from being discharged and provide an output current discharging path comprising L, diodes, and Rdc. Fig. 7 and 8 show the normalized peak output current magnitude at the instant of turn off of So and Sdc and the current falling time after turn off, respectively, with the variation of L and Rdc.

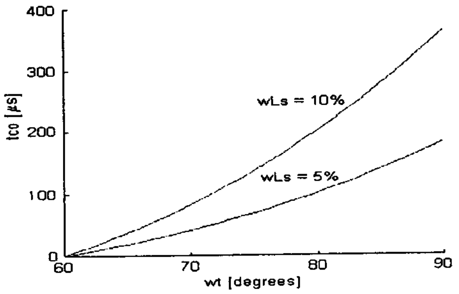


Fig. 3 Required time for ic to be vanished ($60° \leq wt < 90°$)

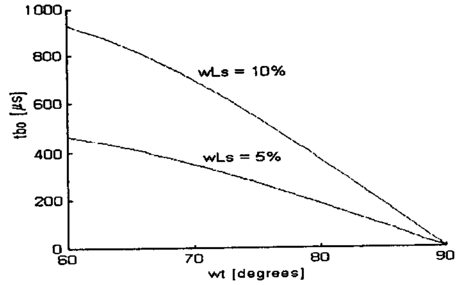


Fig. 4 Required time for i_a and i_b to be vanished after i_c becomes zero ($60° \leq wt < 90°$)

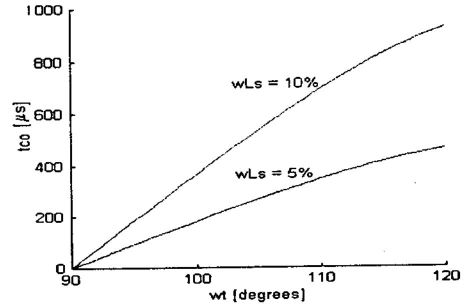


Fig. 5 Required vanishing time of i_b ($90° \leq wt < 120°$)

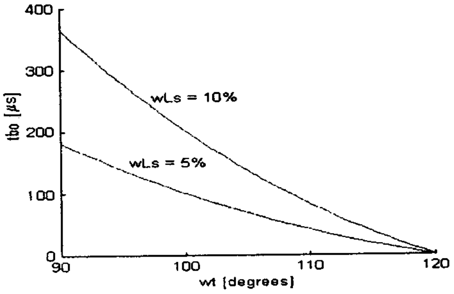


Fig. 6 Required time for i_a and i_c to be vanished after i_b becomes zero ($90° \leq wt < 120°$)

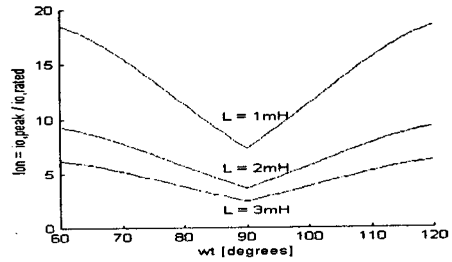


Fig. 7 Normalized peak output dc current during short-circuit period.

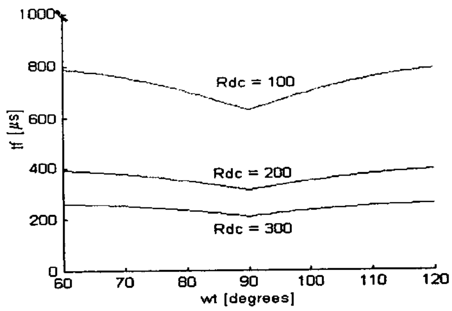
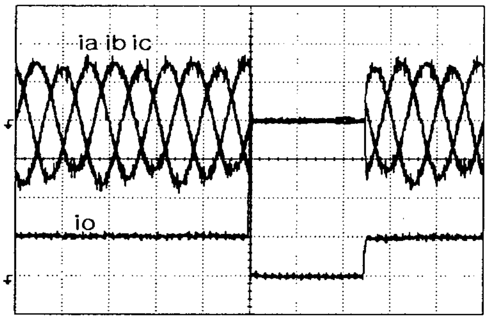


Fig. 8 Output current falling time with L=2mH.

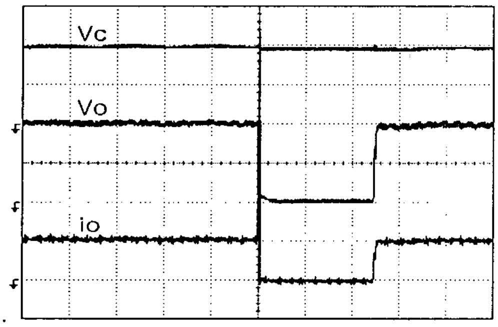
4. Experimental Results

To verify the validity of the proposed scheme, the proposed converter has been built and tested for a 2-level converter. The parameters used in the experiment are as follows. The ac input line-to-line voltage is 220V. Ls=1.6mH, Rdc=300Ω, C=2200µF, L=2mH, Vo=400V, and load resistance=40Ω.

Fig. 9(a) shows the waveforms of the ac line currents i_a, i_b, and i_c and the output dc current i_o. After the instant of load short each line current begins to change its polarity since the converter operating mode reversed from powering to regeneration one. As soon as the currents reduce to zero, ac side auxiliary switches Sa, Sb, and Sc are turned off. To make the load short-circuit state, an IGBT is connected parallel to the load. By turn on and off the IGBT, the load condition can be short-circuit and short-circuit cleared, respectively. After the instant of short-circuit the load current i_o begins to increase until the dc side auxiliary switches Sdc and So are turned off. Once Sdc and So are turned off, the load current decreases to zero, and the falling time depends on a time constant $\tau_1 = \frac{L}{R_{dc}}$. Fig. 9(c) shows the output capacitor voltage V_c, the load voltage V_o, and the output current i_o. When a load short-circuit occurs, the load voltage becomes almost zero. The load current also becomes zero according to the sequence shown in Fig. 2. It is obvious that there is no capacitor discharging.



(a) time scale : 10 ms/div.



(b) time scale : 10 ms/div.

Fig. 9 Waveforms of i_a, i_b, i_c, V_o, and i_o
(a) i_a, i_b, i_c (50A/div.) and i_o (10A/div.)
(b) V_c, V_o (200V/div.) and i_o (10A/div.)

5. Conclusions

A new PWM rectifier suitable for a short-circuit protection is described. The structure of the proposed converter scheme is simpler than that of the conventional inverter type power supply. The disconnection speed of dc output source from a short-circuit load is sufficiently fast to protect both the power converter and the load. The dc power source keeps a normal rated voltage value even under a short-circuit condition. An auxiliary switch connected in series to an output filter capacitor provides a floating state of the capacitor in the case of a short-circuit by turn off the switch. Accordingly, a fast build up of the load voltage can be achieved. The major features of the proposed scheme are summarized as follows:

1) Simplified structure compared with the conventional inverter type power supply.
2) High speed disconnection a dc source from a short-circuit load without damage.
3) Rapid connection of a dc source to a normal load with reduced load voltage build up time.
4) Low device voltage and current stress of all the auxiliary switches.
5) Natural commutation of the ac side auxiliary switches.
6) Negligible switching losses of the auxiliary switches.

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6. References

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