An Approach to Realize Higher Power PWM AC Controller

Sewan Choi*

Abstract – High Power AC controllers are widely used in many industry applications. Recent research has shown that PWM operation of ac controllers offers high performance characteristics. However, high power PWM-controlled ac controllers are plagued with difficulties to commutate inductive load current from one bi-directional switch to another due to finite switch on/off times. This paper proposes a four step switching strategy for repeated on/off operation of bi-directional switches in some high power ac controllers. The proposed approach provides safe transition of inductive load current at all power factors from one bi-directional switch to another even in the presence of source side stray inductance. Results from an experimental proto-type ac controller coupled to an inductive load are presented.

1. Introduction

AC controllers are widely used in many applications such as industrial heating, lighting controls, speed control of induction motor drives for fan and pump loads etc. [1]. The conventional ac controllers are phase-controlled type employing thyristors as switching devices. This approach has several disadvantages which include : increased harmonics at the input and output terminals ; poor input power factor even if load power factor is unity. To overcome these problems, ac controllers designed with self-turned off devices with pulse width modulation (PWM) schemes were proposed[2-4]. This approach has several advantages including high quality input and output waveforms, unity input power factor over a wide range of output voltage variation.

However, despite the availability of higher power gate turn-off devices such as MOSFET's and IGBT's, the advancements in realizing a higher power PWM-operated ac controller seem to be plagued with difficulties. The factors contributing to this can be listed as follows,

1. The on/off operation of a semiconductor switch requires a finite delay time associated with the storage charge. If an overlap between switching (i.e. from S_1 off to S_2 on) occurs during PWM operation, the source voltage is essentially short circuited (see Fig. 1).

2. A finite amount of switching delay (from S_1 off to S_2 on) is therefore mandatory. This, however, results in the interruption of inductive load current causing damaging over voltages. In the same manner, the presence of any source side (stray) inductance also contributes to over voltages.

3. Due to the over voltages, lossy snubber circuits are required both at the input and output terminals of practical PWM-controlled ac controllers[5].

Hence, PWM operation of a higher power ac controller with bi-directional switches seems not to be practical.

The objective of this paper is to propose a four step switching strategy suitable for PWM operation of the bi-directional switches in ac controller for commutating inductive load current. The proposed approach independently controls each uni-directional switch in a bi-directional switch element according to the input voltage polarity. This approach provides safe transition of inductive load current from one bi-directional switch to another and ensures safe PWM operation even in the presence of source side stray inductance. Several ac to ac converter topologies to which

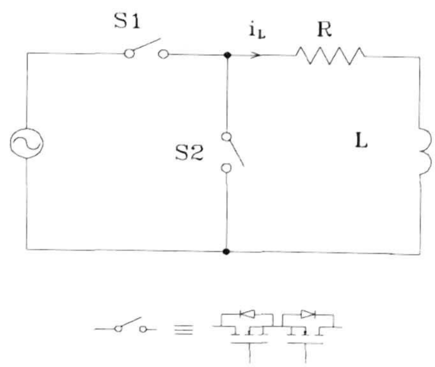

Fig. 1 A PWM operated ac controller

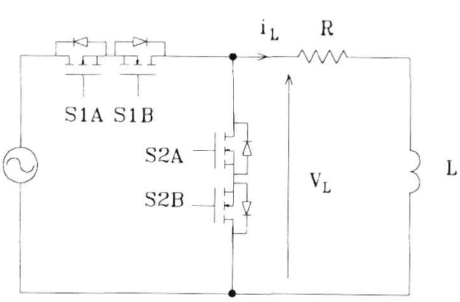

Fig. 2 A PWM operated ac controller denoting the internal conduction path

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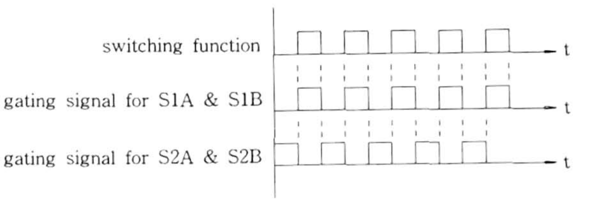


Fig. 3 Gating signals to perform a PWM (50%) duty cycle

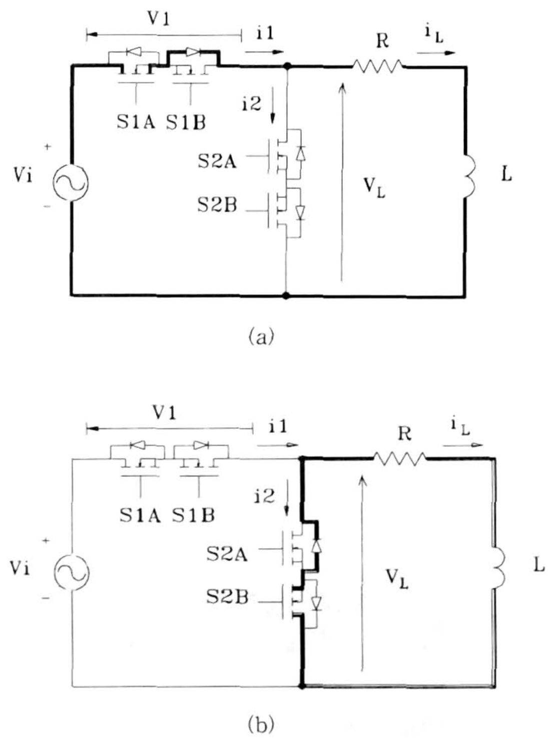


Fig. 4 (a) Ac controller shows a conduction path (dark trace) via S1A for $i_L > 0$
(b) Ac controller shows a conduction path (dark trace) via S2B for $i_L > 0$

the proposed four step switching strategy can be applied is examined with selective simulation and experimental results.

2. Proposed Four-Step Switching Technique

The power circuit of a single-phase ac controller is shown in Fig 1, where S_1 and S_2 are bi-directional switching elements. Each bi-directional switch is composed of two unidirectional switches such as MOSFET's connected in anti-series. The internal conduction path is separately denoted as shown in Fig 2. The series switches, S1A and S1B, regulate the power delivered to the load, and the shunt switches, S2A and S2B provide the freewheeling path for the inductive load current. The switches S1 and S2 are operated in a PWM fashion and Fig. 3 illustrates relative gating signals with 50% duty cycle. Now, suppose switches S1A and S1B are turned on, and one of the switches is conducting the inductive load current. If an attempt is made to turn off S1A and S1B and turn on S2A and S2B at the same time, the commutation problem discussed earlier will be encountered. To avoid this situation, a more sophisticated four-step switching strategy is proposed. With an inductive load, a period of sinusoidal input voltage is divided into four modes according to the direction of inductive load current i_L. These are,

- Mode 1 : $V_i > 0$ and $i_L > 0$
- Mode 2 : $V_i > 0$ and $i_L < 0$
- Mode 3 : $V_i < 0$ and $i_L > 0$
- Mode 4 : $V_i < 0$ and $i_L < 0$

The four-step switching method according to each mode is described as follows :

Mode 1 : $V_i > 0$ and $i_L > 0$ (S1A is conducting)

Consider a moment at which input voltage $V_i > 0$ and load current $i_L > 0$ and the gating signals for switches S1A and S1B are enabled. For this situation switch S1A is conducting load current i_L represented by a thick line as shown in Fig. 4(a).

At this time load voltage V_L is following the input voltage. The four step switching to commutate i_L from switch S1 to switch S2 is given in the below.

Step 1. Turn on S2B - Nothing happens since S2B is reverse biased.

Step 2. Turn off S1A - S1A is turned off and S2B being gated from step 1 is the only switch which can carry the load current. Thus, the load current is transferred from S1A to S2B as shown in Fig. 4(b).

Step 3. Turn on S2A - Nothing happens since S2B is already conducting load current i_L.

Step 4. Turn off S1B - Nothing happens since S1B is reverse biased.

Therefore, at the end of step 4 inductive load current i_L is safely transferred from switch S1 to S2. PSPICE simulation of this transition is shown in Fig. 5. The gating signals for the MOSFET's are shown in Fig. 5(a) to (d). Fig. 5(e) and (f) show the voltage and current transition in the switch pair S1 and S2. Fig. 5(g) and (h) is the expended version of (e) and (f).

The above described switching strategy is applied for Mode 2.

Mode 2 : $V_i > 0$ and $i_L < 0$ (S1B is conducting)

1. Turn on S2B - Nothing happens since S2B is reverse biased.
2. Turn off S1A - Nothing happens.
3. Turn on S2A - The load current is transferred from

S1B to S2A.

4. Turn off S1B - Nothing happens.

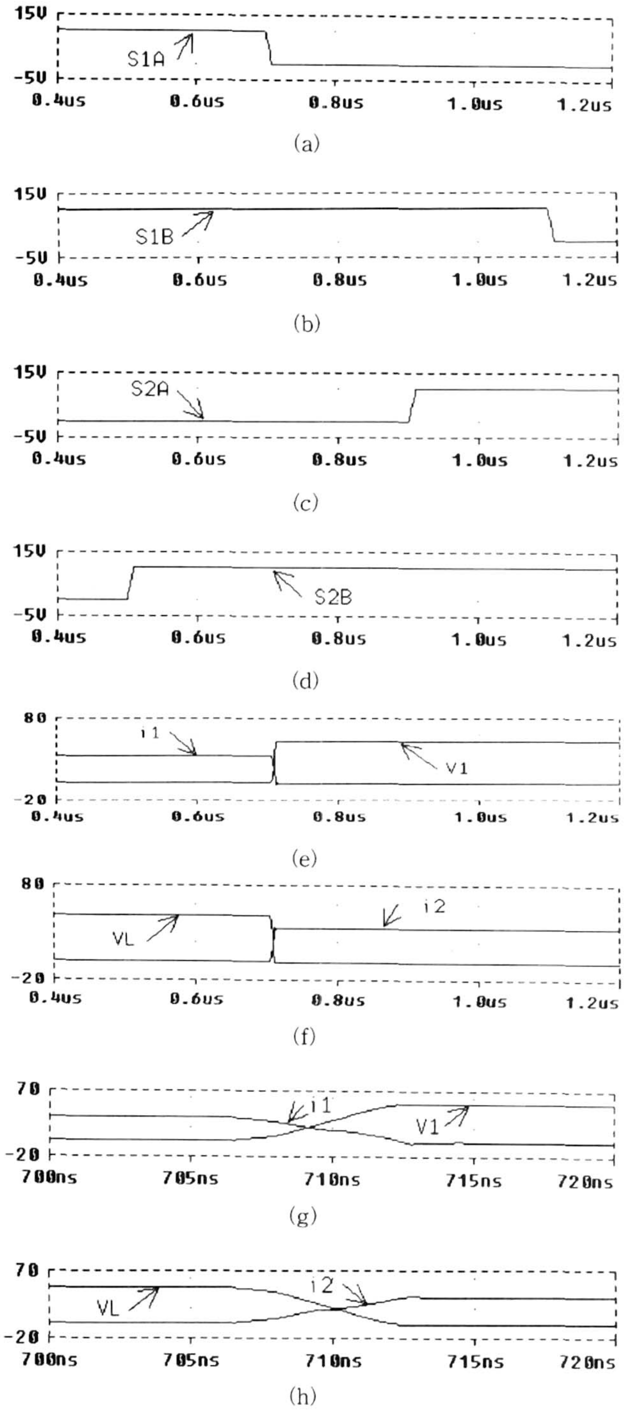


Fig. 5 Simulation of the four step switching strategy for Mode 1
(a) to (d) Gating signals for the switches. (e) and (f) Voltages and currents transition across the switch pair S1 and S2. (g) and (h) Extended version of (e) and (f).

Mode 3 : $V_i < 0$ and $i_L > 0$ (S1A is conducting)

1. Turn on S2A - Nothing happens since S2A is reverse biased.
2. Turn off S1B - Nothing happens.
3. Turn on S2B - The load current is transferred from S1A to S2B.
4. Turn off S1A - Nothing happens.

Mode 4 : $V_i < 0$ and $i_L < 0$ (S1B is conducting)

1. Turn on S2A - Nothing happens since S2A is reverse biased.

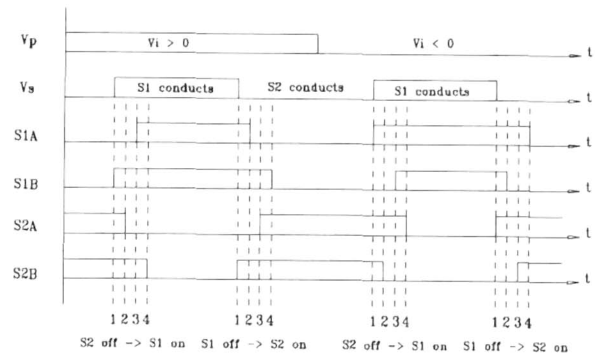


Fig. 6 A summary of the proposed four step switching sequences

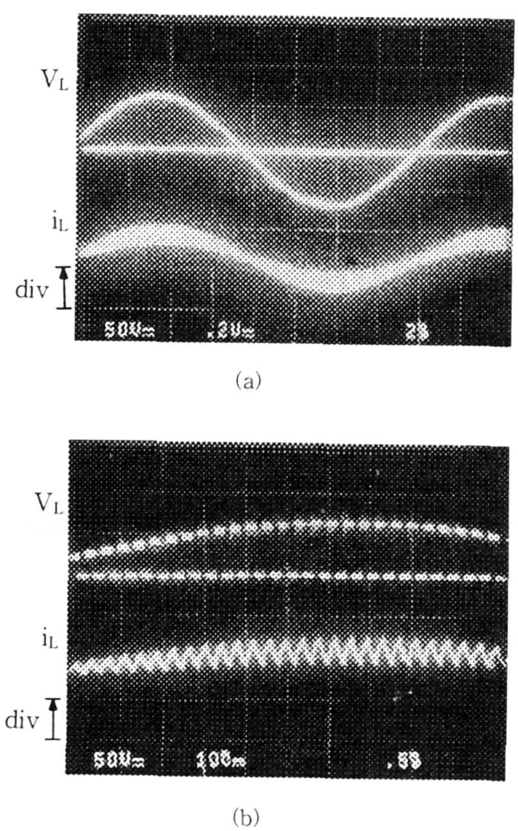
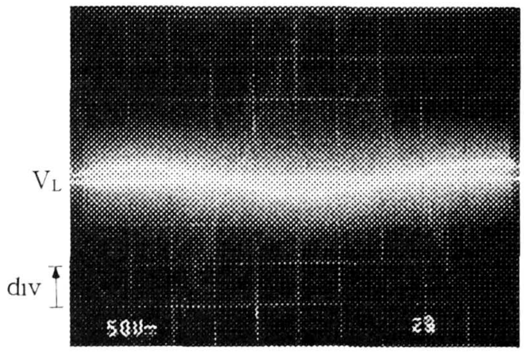
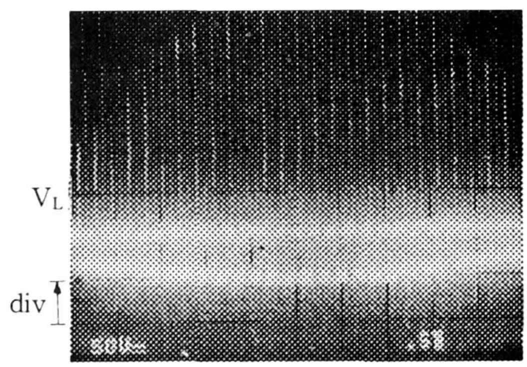


Fig. 7 Experimental waveforms for the ac controller with the proposed four step switching (a) Load voltage V_L and current i_L (b) V_L and i_L in extended time scale



(a)



(b)

Fig. 8 Experimental waveforms for the ac controller with a conventional switching(1 μdelay)
(a) Load voltage V_L (b) V_L in extended time scale

2. Turn on S1B - The load current is transferred from S1B to S2A.
3. Turn on S2B - Nothing happens.
4. Turn off S1A - Nothing happens.

From the above description of Mode 1 to Mode 4 it is clear that Mode 1 and 2 have identical switching sequence with input voltage condition $V_i > 0$. Similarly Mode 3 and 4 have identical switching sequence with input voltage condition $V_i < 0$. The firing sequence of the switches S1A, S1B, S2A and S2B for each mode of operation is shown in Fig 6. In Fig 6, V_p indicates the polarity of the input voltage : high for $V_i > 0$ and low for $V_i < 0$. Also, Vs is the PWM switching function for S1 and S2. That is high for conducting S1 (S1A or S1B) and low for S2 (S2A or S2B). Further, a small delay (1 or 2 μsec.) is introduced between each of the four switching steps in each Mode as shown in Fig. 6.

3. Experimental Results

A prototype single phase ac controller employing power MOSFETs and powering an inductive load has been

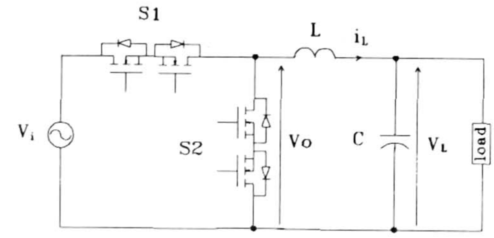
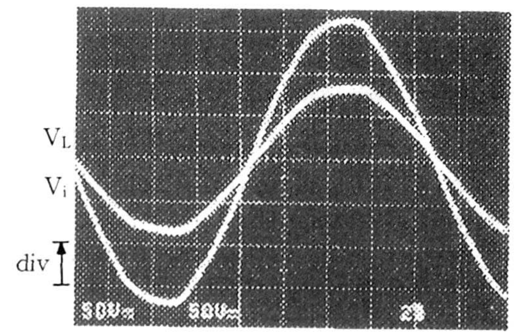
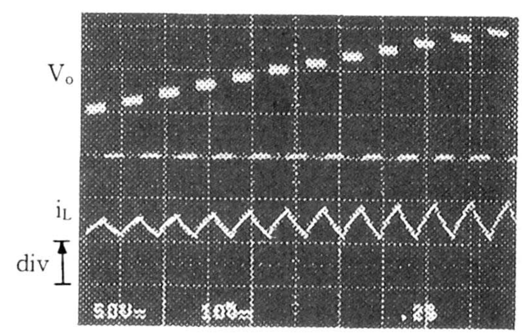


Fig. 9 Ac buck converter



(a)



(b)

Fig. 10 Experimental waveforms for the Ac buck converter
(a) Input voltage V_i and load voltage V_L
(b) V_o and i_L in extended time scale

implemented. The experimental results were obtained at switching frequency of 6KHz and duty cycle of 50% for switching function of the PWM. Fig. 7(a) shows the load voltage and current waveforms of the ac controller with R-L load employing the proposed four-step switching technique. Extended waveforms of the load voltage/current are shown in Fig. 7(b). No snubber circuits to limit the voltage/current spikes were employed in this implementation. It is clear from Fig. 7 that the voltage and current are devoid of excessive spikes. For the purpose of comparison, the gate logic circuit is modified to generate the gating signals with a delay of 1 μsec for each commutation without employing the proposed strategy. The load voltage waveforms for this implementation are shown in Fig. 8.

Notice the large voltage spikes due to the interruption of inductive load current. The conventional approach therefore necessitates the use of snubber circuits to limit over voltages.

4. Other Applications

The proposed four-step switching strategy for PWM operation of bi-directional switches can be applied to circuit ac to ac converter topologies employing bi-directional switches.

4.1 AC to AC Buck Converter

AC to AC buck converters provide a lower AC output voltage than the AC input voltage. A realization of the AC buck converter is shown in Fig. 9. Its main application is in regulated ac power supplies and ac motor speed control. Fig. 10(a) shows input voltage Vi and load voltage VL of the AC buck converter employing the proposed four-step switching strategy. We can see that load voltage VL is sinusoidal and is reduced to 50% of the input voltage due to PWM operation having 50% duty cycle. Extended output voltage/current waveforms are shown in Fig. 10(b).

5. Conclusion

In this paper, a four-step switching technique for high power PWM operation of bi-directional switches in ac controllers has been proposed. The proposed technique provides safe transition of inductive load current from one bi-directional switch to another. The proposed approach has been applied to several AC to AC converters employing bi-directional switches. Experimental results on a proto-type ac controller demonstrate improved performance in the absence of snubber circuits.

References

[1] T. A. Lipo, "The Analysis of Induction Motors With Voltage Control By Symmetrically Triggered Thyristors", *IEEE Trans. Power App. Syst.,* Vol. PAS-90, pp. 515~525, Mar./Apr. 1971

[2] A. Mozder,Jr and B. K. Bose, "Three-Phase AC Power Control Using Power Transistors", *IEEE Trans. Ind. Appl.*, Vol. IA-12, pp. 499~505, Sept./Oct., 1976.

[3] G. N. Revankar, et al., "Symmetrical Pulse Width Modulated AC Chopper, *IEEE Trans. Ind. Electron. Contr. Instrum.*, Vol. 24, No. 1, pp. 39~45, 1977.

[4] G. H. Choe, et al, "An Improved PWM Technique for AC Chooper", *IEEE Trans. Power Electron.*, Vol. 4, no. 4, pp. 496~505, Oct. 1989.

[5] W. McMurray, "Resonant Snubbers With Auxiliary Switches", *IEEE IAS Conf.*, pp. 829~834, 1988.

[6] J. Oyama, T. Higuchi, E. Yamada, T. Koga and T. Lipo, "New Control Strategy for Matrix Converter", *IEEE Power Electronics Specialists Conf. Rec.*, pp. 360~367, 1989.

[7] A. Alesina and M. Venturini, "Analysis and Design of Optimum-Amplitude Nine-Switch Direct AC-AC Converters", *IEEE Trans. Power Electron.*, Vol. 4, no. 1, pp. 101~112, Jan. 1989.

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