AN APPROACH TO REALIZE HIGHER POWER PWM AC CONTROLLER

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ABSTRACT

AC controllers are widely used in industry in many applications. Recent research has shown that PWM operation of ac controllers offers high performance characteristics. However, 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 an ac controller. The proposed approach permits 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 also discussed.

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 control 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 gate turn-off switches with pulse width modulation (PWM) schemes were proposed [2,3,4]. 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 switches 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 time between switching (i.e. from S_1 off to S_2 on) is provided during PWM operation, the source side 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 inductance (stray) also contributes to over voltages.
3. The excessive over voltages in a practical PWM controlled ac controller therefore warrants lossy snubber circuits both at the input and output terminals [5].

Hence, PWM operation of a higher power ac controller with bi-directional switches seems not 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 is an improvement over the strategies reported in [6,7]. The proposed approach independently controls each uni-directional switch within a bi-directional switch element depending on the input voltage polarity. This approach offers 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. Results from an experimental proto-type ac controller coupled to an inductive load are discussed and compared with the conventional control employing snubbers. Details on the design and implementation of the four-step switching strategy are also discussed .

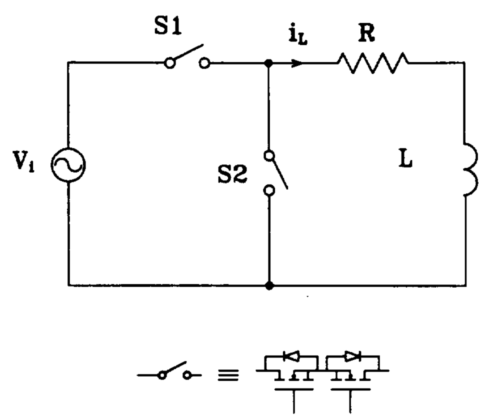

Fig. 1 A PWM controlled ac controller.

2. PROPOSED FOUR-STEP SWITCHING TECHNIQUE

The power circuit of a single phase ac controller is shown in Fig 1, where S1 and S2 are bidirectional switching elements. Each bidirectional 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, where the symbol for a switch is a power MOSFET. 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 gating signals for 50% duty cycle. Now if the 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 in this paper. With an inductive load, a cycle of input voltage which is sinusoidal is divided into four modes according to the direction of inductive load current i_L. These are,

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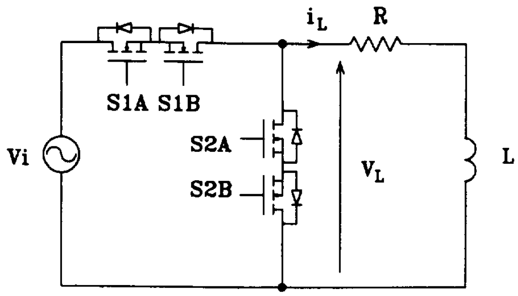

Fig. 2 A PWM controlled ac voltage controller denoting the internal conduction path.

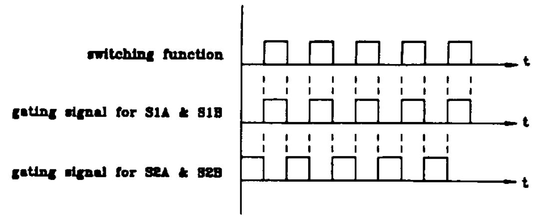

Fig. 3 Gating signals to perform a PWM 50% duty cycle.

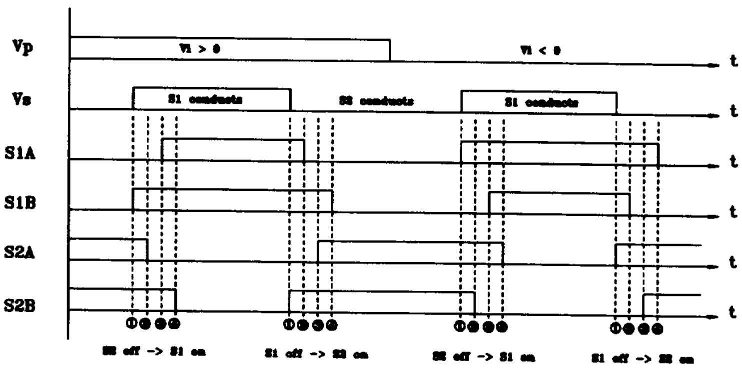

Fig. 4 Proposed four step switching sequences

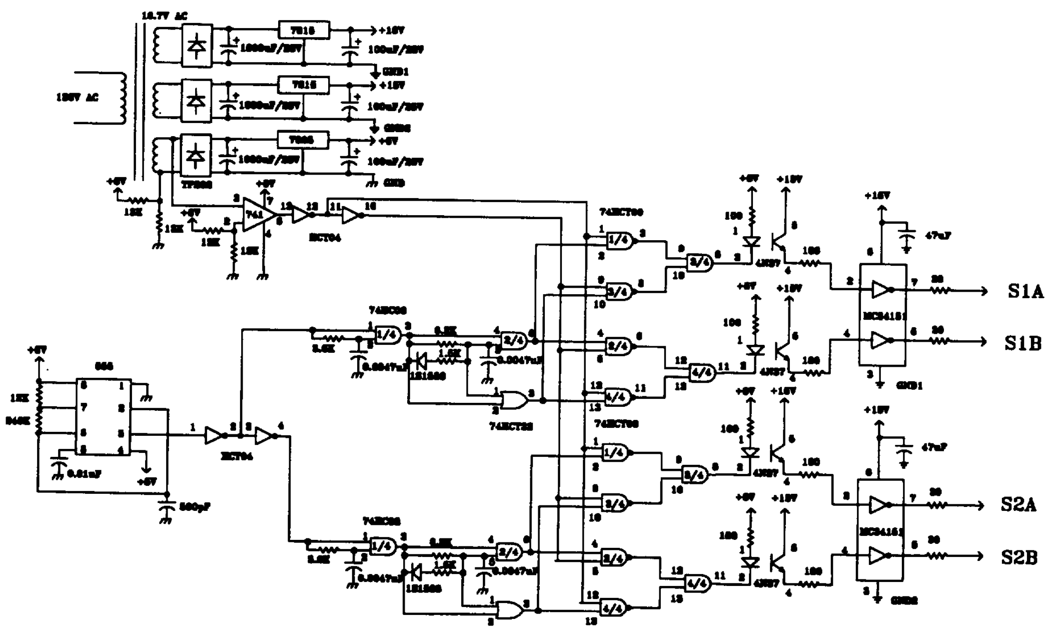

Fig. 5 Gate contol logic circuit

(a)

(b)

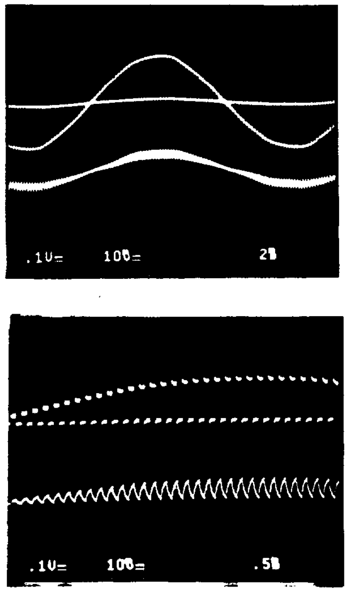

Fig. 6 Experimental waveforms for the ac controller(Fig.2) with the proposed four step switching technique

(a) Load voltage V_L/ current i_L

(b) V_L and i_L in extended time scale

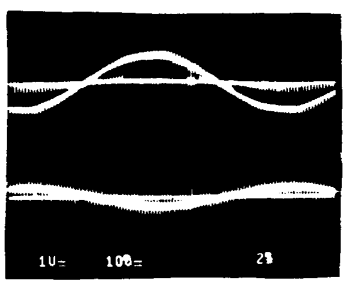

Fig. 7 Experimental waveforms for the ac controller(Fig.2) with a conventional switching method.

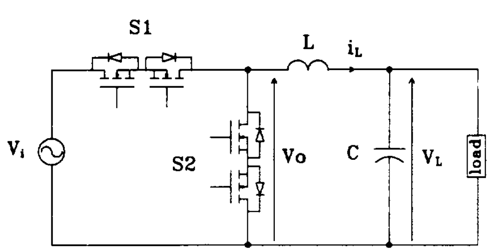

Fig. 8 AC buck converter

(a)

(b)

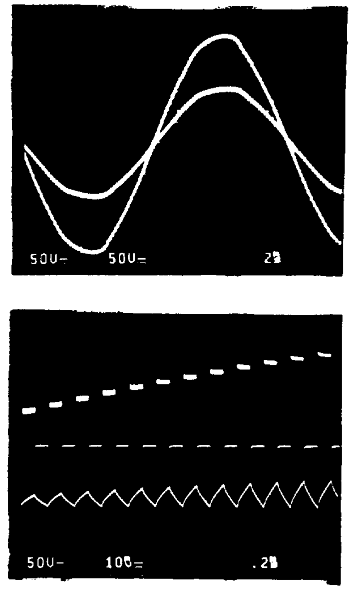

Fig. 9 Experimental waveforms for the AC buck converter(Fig.8)

(a) Input voltage V_i/ load voltage V_L for 50% duty cycle

(b) $V_{[illegible]}$ and i_L in extended time scale

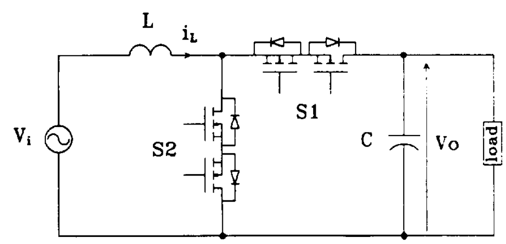

Fig. 10 AC boost converter

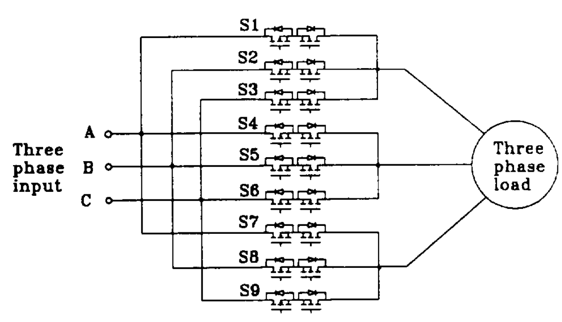

Fig. 11 Three phase to three phase matrix converter

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)

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

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.

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.
2. Turn off 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 Modes 1 to 4 it is clear that Mode 1 and Mode 2 consists of identical switching sequence for input voltage condition $V_i > 0$ and $0 < i_l < 0$. Similarly Mode 3 and Mode 4 have identical switching sequence for input voltage condition $V_i < 0$ and $0 < i_l < 0$. The firing sequences of the switches S1A, S1B, S2A and S2B for each mode of operation is shown in Fig 4. In Fig 4, V_p indicates the polarity of the input voltage : high for $V_i > 0$ and low for $V_i < 0$. Also, V_s is the PWM switching sequence for S1 and S2 switches. That is high for conducting S1 (S1A or S1B) and low for S2 conduction (S2A or S2B). Further, a small delay (1 or 2 micro seconds) is introduced between each of the four switching steps in each Mode (see Fig. 4)

3. HARDWARE IMPLEMENTATION

A prototype single phase ac controller employing power MOSFETs (Motorolla MTW16N40E) powering an inductive load current has been built and implemented. The gate control logic generating the required switching sequences is as shown in Fig. 5. The circuit employs a simple PWM which has 50% duty cycle and 6KHz frequency. The circuit is designed to have a delay of 2 μ sec for each switching step. The polarity of the input voltage is detected by a zero-crossing detector (LM741). Also, S1A and S2B are directly connected to the power MOSFETS. Isolation between delay logic (+5V) and gate drive (+15V) is achieved by opto-isolator. Furthermore, two grounds for +15V (GND1 and GND2) are isolated from each other to prevent shorted circuit while the MOSFET's are operating.

4. EXPERIMENTAL RESULTS

The experimental results were obtained at 6KHz switching frequency and 50% duty cycle for switching function of the PWM. Fig. 6(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. 6(b). No snubber circuits to limit the voltage/current spikes were employed in this implementation. It is clear from Fig. 6 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 4 μ sec for each commutation without employing the proposed strategy. The load voltage/current waveforms and their extended waveforms for this implementation are shown in Fig. 7 which shows large voltage/current spikes. Furthermore, severe current spikes are generated within the switches.

6. OTHER APPLICATIONS

The proposed four-step switching strategy for PWM operation of a bidirectional switch can be applied to different circuit topologies employing bidirectional switches.

5.1 AC to AC Buck Converter

AC to AC buck converters produce a lower AC output voltage than the AC input voltage. A realization of the AC buck converter is shown in Fig. 8. Its main application is in regulated ac power supplies and ac motor speed control. Fig. 9(a) shows the experimental input voltage V_i and load voltage V_l of the AC buck converter employing the proposed four-step switching strategy. Further Fig. 9 (b) illustrates voltage V_0 and current i_l for the ac/ac buck converter in Fig. 8. It can be seen that the load voltage V_l is sinusoidal and is reduced to 50% of the input voltages due to PWM operation having 50% duty cycle.

5.2 AC to AC Boost Converter

AC boost converters produce a higher AC output voltage than the AC input voltage, and possible realization of the AC boost converter is shown in Fig. 10. In Fig. 10 each switch is a bidirectional switch. Switch SW1 allows the energy stored in the inductor L pass the output voltage and switch SW2 provides a freewheeling path for the inductive current. The proposed four step switching strategy will render the ac/ac boost converter practically realizable for inductive loads.

5.3 Three Phase Matrix Converter

The idea of four step switching strategy to safely commutate an inductive load current between the bidirectional switches in single phase AC controllers can be applied to three phase AC controller, that is, direct AC to AC matrix converters as shown in Fig. 11. The operation of the three phase to three phase matrix converter is as follows. Three phase inputs are connected to the three phase load through the appropriate 3 switches. For simplicity, we can think a three phase to three phase converter is 3 to single phase converters. Switch pairs within a three phase to single phase converter can not be turned on at the same time to prevent the shorted circuit between the input phases (for example, S1 and S2) and switching sequences vary with the applications. Now, we see a three phase to single phase converter in which three switch pairs (S1 to S2, S2 to S3 and S3 to S1) are considered to commutate an inductive load current. To commutate each switch pair according to the concept of four step switching, the voltage polarities of line to line three phase input (that is, V_{ab}, V_{bc} and V_{ca}) should be detected and fed to the gate control logic. Three switches (S4, S5 and S6) in another three phase to single phase converter can be explained in the same way.

6. CONCLUSION

In this paper, a four-step switching technique for PWM operation of bidirectional switches in an ac controller has been proposed. The proposed technique permits safe transition of inductive load current from one bidirectional switch to another. Experimental results on a proto-type ac controller demonstrate improved performance in the absence of snubber circuits.

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