A Switching Technique for Common Mode Voltage Reduction of 2-Level Inverter

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Abstract--Much attention has given to EMI effects created by variable speed ac drive system. This paper focuses on the switching technique to mitigate common mode voltage.

Zero switching states of inverter control invoke large common mode voltage. Using inversed carrier wave, zero switching states are removed. In addition, proposed technique is easy to apply to existing 2-level inverter design. And common mode mitigation technique for sinusoidal PWM is also presented.

Proposed switching technique is implemented with a 2.2kw 1735rpm induction motor.

Index Terms—Conducted emissions, drives, electromagnetic compatibility.

I. INTRODUCTION

Advanced power electronic switching devices has enabled high frequency switching operation and has improved the performance of PWM inverters for induction motor. And now, industrial ac drives has achieved dominance in adjustable speed applications. However, the advent of fast power devices has generated several unexpected problems.

High-frequency leakage current flows through stray capacitors between stator windings and a motor frame due to a large step change of the common-mode voltage produced by a PWM inverter. It may cause EMI to electronic equipment or results incorrect operation of current-operated circuit breakers.[1]

To minimize the common-mode voltage, several techniques have been presented. Among these techniques, improvement of switching patterns takes advantage of economy.

A switching technique for common-mode voltage reduction is proposed in this paper. It eliminates zero-vector without additional calculation and its application range reaches to sinusoidal PWM.

Basic theory for the development will be presented. And then, the novel switching technique will be proposed. Simulation and experimental results are also presented to confirm the theoretical analysis.

II. THEORY

The common mode voltage is voltage between the star center of electric machine and the ground. It is equal to average value of the three phase voltages[2].

In this paper, S_A represents switching state either (0 0 1), (0 1 0) and (0 0 1). And S_B represents switching state either (0 1 1), (1 0 1) and (1 1 0). Switching state configuration is summarized in Table 1.

Table 1. Common-mode voltage

State	v_U	v_V	v_W	Vector Class.	V_{CM}
V_0 (0 0 0)	$-1/2V_{dc}$	$-1/2V_{dc}$	$-1/2V_{dc}$	Null vector	$-1/2V_{dc}$
V_1 (1 0 0)	$1/2V_{dc}$	$-1/2V_{dc}$	$-1/2V_{dc}$	S_A	$-1/6V_{dc}$
V_2 (1 1 0)	$1/2V_{dc}$	$1/2V_{dc}$	$-1/2V_{dc}$	S_B	$1/6V_{dc}$
V_3 (0 1 0)	$-1/2V_{dc}$	$1/2V_{dc}$	$-1/2V_{dc}$	S_A	$-1/6V_{dc}$
V_4 (0 1 1)	$-1/2V_{dc}$	$1/2V_{dc}$	$1/2V_{dc}$	S_B	$1/6V_{dc}$
V_5 (0 0 1)	$-1/2V_{dc}$	$-1/2V_{dc}$	$1/2V_{dc}$	S_A	$-1/6V_{dc}$
V_6 (1 0 1)	$1/2V_{dc}$	$-1/2V_{dc}$	$1/2V_{dc}$	S_B	$1/6V_{dc}$
V_7 (1 1 1)	$1/2V_{dc}$	$1/2V_{dc}$	$1/2V_{dc}$	Null vector	$1/2V_{dc}$

Fig. 1 shows circuit of voltage source inverters. In case of all the switching state of 3 phases are equal, i.e. switching state is (0 0 0) or (1 1 1), magnitude of voltage difference between stator and ground will reach $1/2V_{dc}$. It is 3 times higher than S_A state and S_B state.

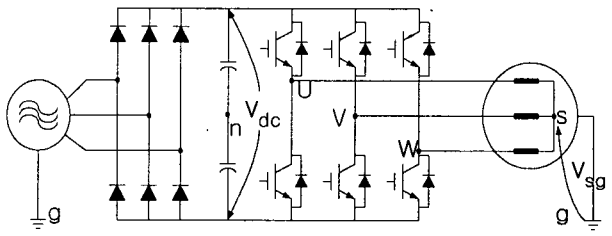


Fig. 1 Inverter-induction motor drive system

If inverter control doesn't allow null vector as (0 0 0) or (1 1 1), the magnitude of common-mode voltage will be reduced significantly.

III. COMMON MODE VOLTAGE REDUCTION

A. Sinusoidal PWM

Switching function is defined as comparing sinusoidal reference wave and triangular carrier wave in sinusoidal PWM. In Fig. 2, switching state will be (0 0 0) or (1 1 1) if all the voltage references are lower or higher than carrier wave.[2]

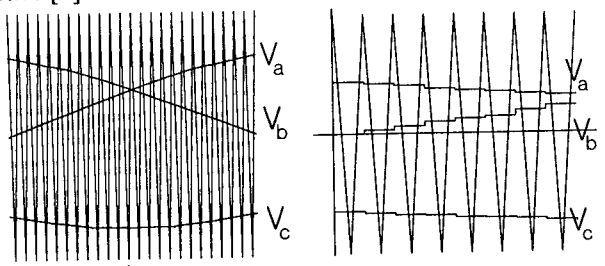


Fig.2 Reference and carrier wave of sinusoidal PWM

(a) 0° - 60° area (b) 0° - 30° area

In a period of carrier wave, average voltage output of both former and later part is voltage reference. So using inverted carrier as a carrier will not change average voltage.

In Fig. 3, inverted carrier wave is adapted to a phase with intermediate voltage reference. Adapting inverted carrier wave to the phase, state-changing point 1 to 0 is located at other changing point. Thus switching state of (0 0 0) and (1 1 1) are eliminated.

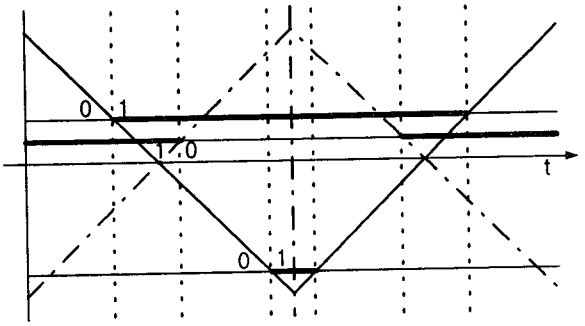


Fig.3 proposed switching technique for sinusoidal PWM

B. Space Vector Modulation

In SVM, two adjacent vector to reference voltage vector and null vector are combined to the reference vector.[4] Corresponding vector times are calculated by (1).

$$T_A = T_S \frac{V^*}{2V_{dc}/3} \cdot \frac{\sin(\pi/3-\alpha)}{\sin(\pi/3)}$$

$$T_B = T_S \frac{V^*}{2V_{dc}/3} \cdot \frac{\sin(\alpha)}{\sin(\pi/3)} \qquad (1)$$

$$T_0 = T_7 = 0.5(T_Z - T_A - T_B)$$

Triangular carrier wave and T_0, T_0+T_A, $T_0+T_A+T_B$ are inputted to comparator and PWM pulse is generated. As a result, switching sequence is $S_0 \rightarrow S_A \rightarrow S_B \rightarrow S_7$ in leading sequence and $S_7 \rightarrow S_B \rightarrow S_A \rightarrow S_0$ in trailing sequence as shown in Fig.4. Note that S_0 and S_7 have the same duration time by (1).

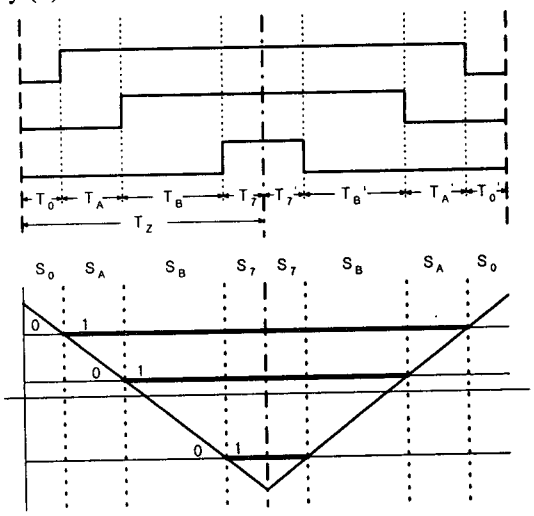


Fig. 4. PWM waveform and carrier wave of conventional SVM

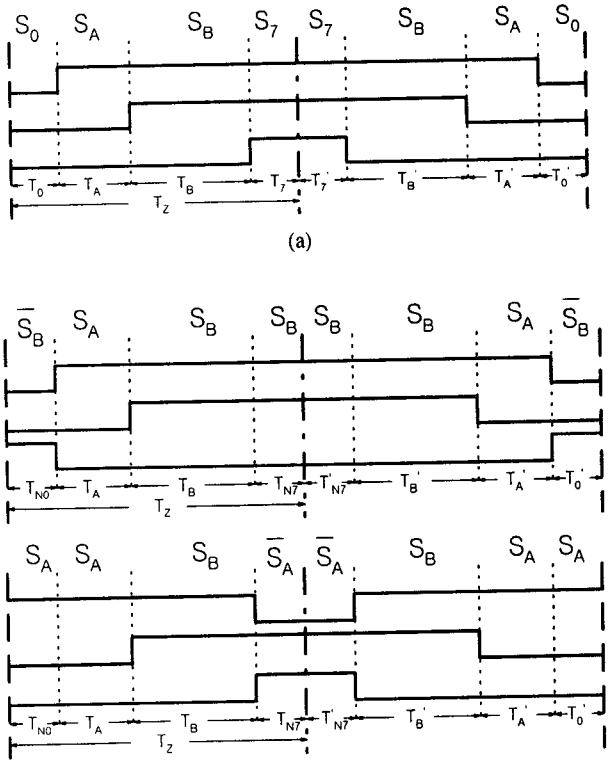


Fig 5. PWM waveform and switching pattern

(a) conventional SVM

(b) null vector replaced SVM

(c) null vector and active vector replaced SVM

A technique for common mode voltage reduction by replacing null vector with two reciprocal vectors was introduced.[5-6] In addition, we can replace the sequence of S_A and S_B as Fig. 6(c).

However, in Fig 5(b) and Fig 5(c), leading and trailing sequence of a phase's switching state is replaced each other. In Fig 5(b), phase with highest or lowest reference voltage has replaced sequence, while phase with intermediate voltage has replaced in Fig 5(c).

Table 2. highest/lowest reference voltage on sector

	Phase with highest reference	Phase with middle reference	Phase with lowest reference
Sector 1	A	B	C
Sector 2	B	A	C
Sector 3	B	C	A
Sector 4	C	B	A
Sector 5	C	A	B
Sector 6	A	C	B

Noting that all the patterns in Fig. 6 are feasible, novel algorithm for null vector state elimination is established. That is, we don't need to get the information about which sector the reference vector locates. As shown in Table 2, highest and lowest reference voltage varies by the sector. Voltage reference of phase A is highest or lowest in sector 1, 3, 4, 6 and intermediate in sector 2, 5.

If we adapt inversed carrier wave to phase A consistently, inverter control acts as null vector replaced technique in sector 1, 3, 4, 6 and as null vector and active vector replaced technique in sector 2, 5.

This technique eliminates all the null vector state adapting symmetrical SVM. When T_0 and T_7 are not equal, null vector may occur. In this case, like sinusoidal PWM, adapting inversed carrier to a phase with middle reference voltage can be a practical technique. In this selective phase carrier inverted technique, sector discrimination is needed.

C. Implementation of proposed technique

By adapting inverted carrier wave to a single phase consistently or selectively, null vector state can be eliminated. But in some case inversing carrier wave is impossible or troublesome. In Fig. 6, voltage reference is inversed instead of carrier wave. Changing active high/low will results the same effect as inverting carrier wave.

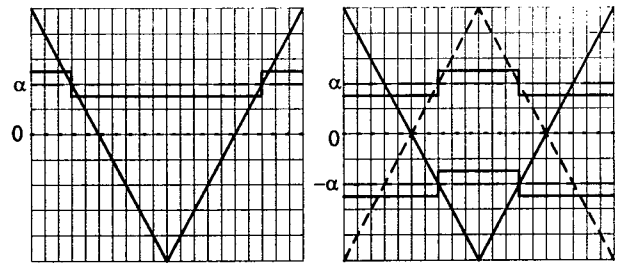


Fig. 6 inverting reference instead of carrier wave for proposed technique

Meanwhile, in down counter adapted inverter controller, adding a not gate to leading/trailing sequence input of a phase as shown in Fig. 7, proposed technique can be implemented.

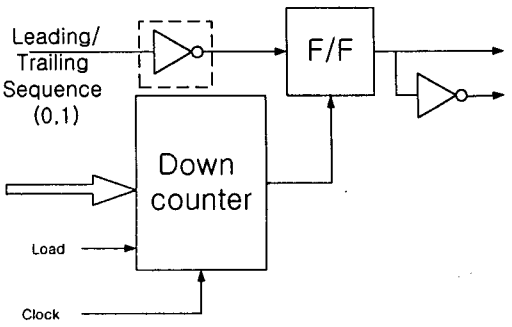


Fig. 7 down counter used gating for proposed technique

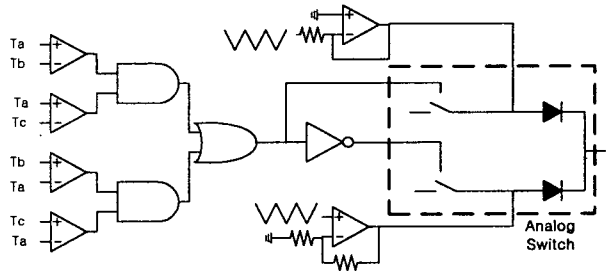
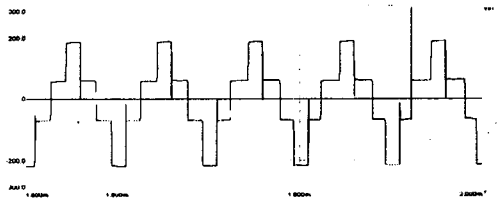


Fig 8. analog circuit for proposed selective phase inverted carrier technique

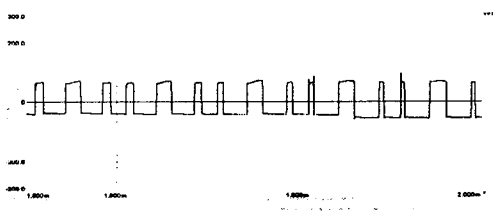
Fig. 8 shows analog circuit for proposed selective phase inverted carrier technique. When voltage reference of phase A is highest or lowest, output of OR gate is high. Then the output of analog switch such as AH5010 will be inverted carrier wave.

IV. SIMULATION

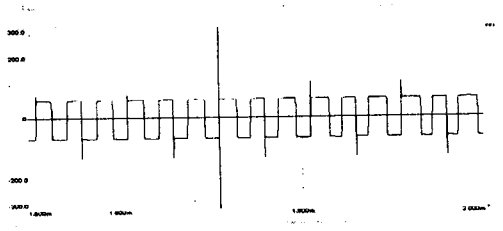
Fig 9 illustrates simulation results of voltage differential between stator and ground. Common mode voltage is reduced in proposed technique while conventional SVM results common mode voltage reaching to $1/2V_{dc}$.



(a)



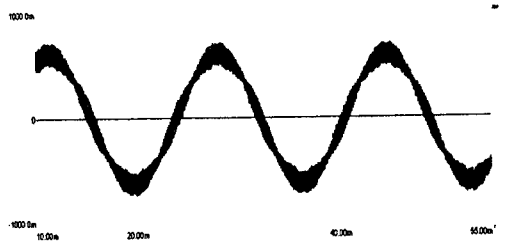
(b)



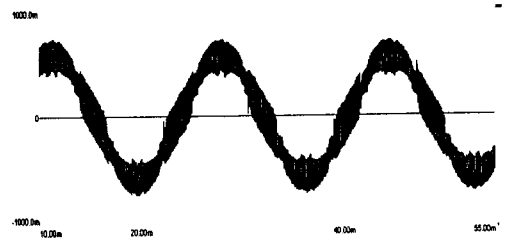
(c)

Fig. 9 simulation results: common mode voltage
(a) conventional SVM
(b) proposed consistent phase inverted carrier technique
(c) proposed selective phase inverted carrier technique

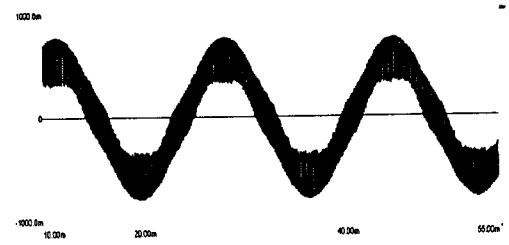
Fig. 10 illustrates q-axis currents of inverter output. Eliminating null vector, current ripple is somewhat increased.



(a)



(b)



(c)

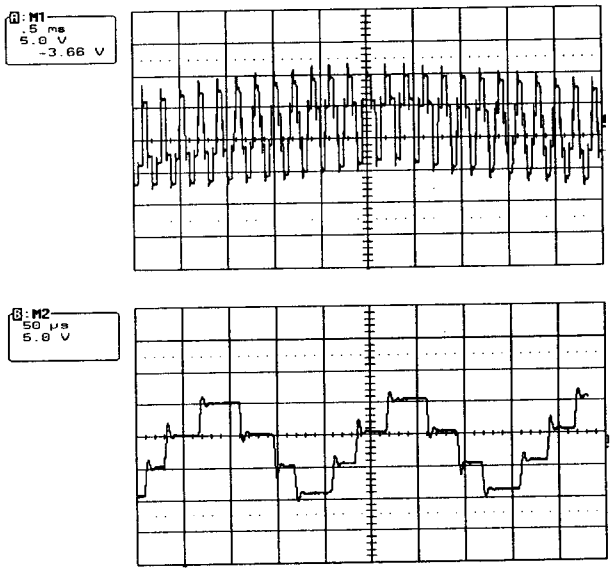
Fig. 10 simulation results: q-axis current of inverter output
(a) conventional SVM
(b) proposed consistent phase inverted carrier technique
(c) proposed selective phase inverted carrier technique

V. EXPERIMENT

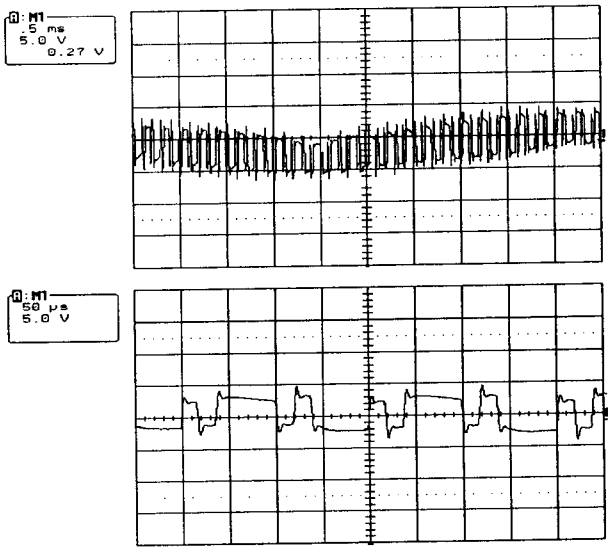
Proposed switching technique was implemented with TMS320C240 based inverter and 2.2kW rating induction motor. Noise spectrum ware analyzed by Advantest R3132 spectrum analyzer. Conventional SVM and proposed consistent phase inverted carrier technique are tested.

Common mode voltages are illustrated in Fig. 11. Under the influence of bridge rectifier, common mode voltage vibrates a little. And additional current ripple is appeared in Fig. 12.

In Fig. 13, spectra of conducted noise that covers the range of 150kHz-30MHz are shown. As magnitude of common-mode voltage decreases, conducted noise is reduced.

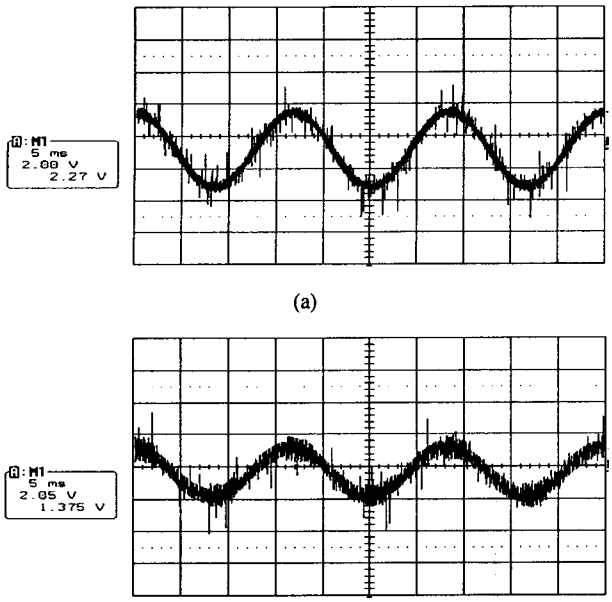


(a)



(b)

Fig. 11 experimental results: common mode voltage
(a) conventional SVM
(b) proposed consistent phase inverted carrier technique



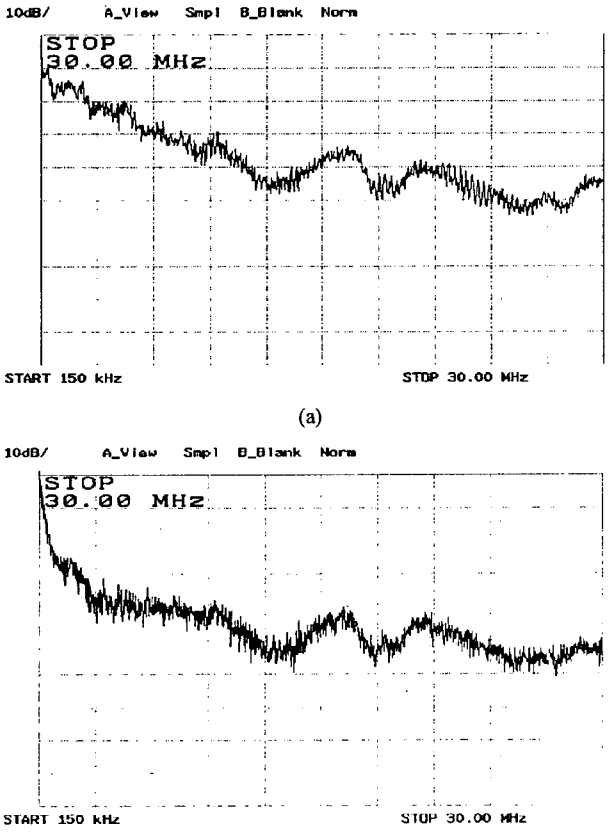
(a)

(b)

Fig. 12 experimental results: current of a phase

(a) conventional SVM

(b) proposed consistent phase inverted carrier technique



(a)

(b)

Fig. 13 spectrum of conducted noise

(a) conventional SVM

(b) proposed consistent phase inverted carrier technique

VI. CONCLUSION

Inverter switching techniques for reduction of common mode voltage is proposed. Adapting inverted carrier wave to a phase consistently or selectively, null vector is eliminated. Selective phase inverted carrier technique can be applied to sinusoidal PWM and SVM, while consistent phase inverted carrier technique can be applied to symmetric SVM.

Simulation and experiment were performed and following results are acquired.

1) Proposed techniques eliminates null vector. As a result, conducted noise is decreased.

2) In proposed technique, additional current ripple arises at inverter output.

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