A Modified Space-Vector PWM Inverter without Phase Current Sensors

Hyeong-Gil Joo, Hwi-Beom Shin, In-Hwan Oh, and Myung-Joong Youn

Abstract

A method of detecting the three phase currents for a voltage-fed pulse width modulated(PWM) inverter is proposed, where only one current sensor is utilized on the dc-link. The proposed method has the constant sampling time by employing the modified space-vector PWM technique which generates the rearranged switching pattern to detect a phase current from a dc-link current. Experimental results show that the proposed scheme provides a very good detection method of three phase currents without phase current sensors. This method is very simple and has small detection errors.

I. Introduction

The voltage-fed PWM inverters are widely used for the variable speed AC drives. They usually employ two or three current sensors at the three phase output and one current sensor at the dc-link. These sensors are used to implement the closed-loop current control and to limit the phase currents for the device protection[1]. The isolated current sensors like the Hall-effect sensors and current transducers are typically used so that the additional hardwares such as A / D converters are needed to implement a digital current control. However, these sensors may cause the additional problems such as complexity, cost, space, and reduction of system reliability.

Recently, a method obtaining the three phase currents from the dc-link current-steps has been studied[2]. This method requires two sampled values of the dc-link current for the detection of one phase current and has some difficulties for determining the sample points and sensing the dc-link current-steps with high frequency.

In this paper, a new method of detecting the three phase currents from the dc-link current is proposed and the modified space-vector PWM technique is employed. The proposed method has the constant sampling time by employing the space-vector PWM technique which generates the rearranged switching pattern. Thus, it is simple to implement using a microprocessor.

II. Detection Technique of Three Phase Currents

Fig. 1 shows a three phase voltage-fed PWM inverter. The inverter conduction state is represented by the switching function S_m ($m \in \{a, b, c\}$). One or zero of the switching function S_a corresponds to the on-state of T_a^+(or D_a^+) or T_a^-(or D_a^-), respectively. When S_a equals to one, either T_a^+ or D_a^+ conducts depending on the direction of the output current i_a. Similarly, when S_a is zero, either T_a^- or D_a^- conducts depending on the direction of i_a. Therefore, the switching devices and free-wheeling diodes in a leg can be replaced by a single-pole double-throw switch[3] and the equivalent PWM inverter shown in Fig. 2 can be used to analyze the waveform of the dc-link current regardless of the output current directions. It is assumed that a Y-connected AC motor with no neutral connection is employed in this analysis.

One of the three phase current waveforms appears in the dc-link current depending on the switching functions as shown in Table 1 When a switching function S_m equals to one, a corresponding motor phase is connected to the positive dc-link line so that its current waveform appears in the dc-link current, i.e., i_{dc} equals to i_m ($m \in \{a, b, c\}$). Similarly, when a switching function S_m equals to zero, a corresponding motor phase is connected to the negative dc-link line so that i_{dc} equals to $-i_m$. On the contrary, when all the switching functions equal to one or zero, i.e., during the free-wheeling mode, none of the three phases is connected to the dc-link line so that the phase currents are not involved in i_{dc}. In this case, no phase current can be detected

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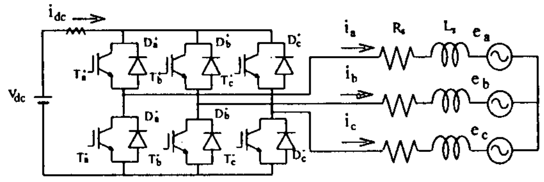


Fig. 1. Voltage-Fed PWM inverter.

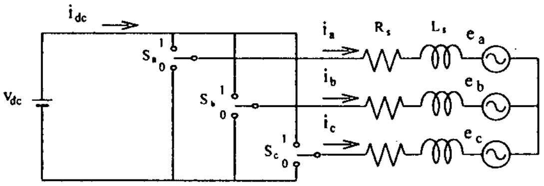
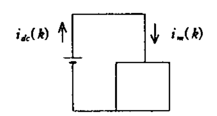
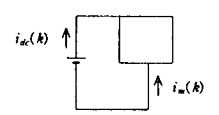
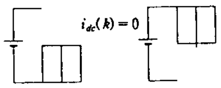


Fig. 2. Equivalent PWM inverter.

Table 1. $i_{dc}(k)$ corresponding to switching states.

(S_a, S_b, S_c)	$V_s(R)$	$i_{dc}(R)$	Operational Mode	Circuit Connection
(1, 0, 0)	V_a	$i_a(R)$	active	
(0, 1, 0)	V_b	$i_b(R)$	active	
(0, 0, 1)	V_c	$i_c(R)$	active	
(0, 1, 1)	$-V_a$	$-i_a(R)$	active	
(1, 0, 1)	$-V_b$	$-i_b(R)$	active	
(1, 1, 0)	$-V_c$	$-i_c(R)$	active	
(0, 0, 0)	V_0	0	free-wheeling	
(1, 1, 1)	V_0	0	free-wheeling	

from i_{dc}.

Table 1 summarizes the relationships between the dc-link current and the three phase currents according to the switching functions. It can be shown that the phase currents can be detected by sensing the dc-link current if the PWM inverter is operated in the active mode at the sampling instant of i_{dc}.

To derive the phase currents in terms of both the dc-link current and the inverter output voltage, the space-vector representation is useful. Therefore, the voltage space-vector v is defined as a combination of the phase voltages v_a, v_b, and v_c as follows[1]:

$$v = \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

where v_α and v_β denote the voltage components of the stationary $\alpha\beta$ frame. There are eight voltage space-vectors available in the PWM inverter depending on the switching functions as shown in Fig. 3 The six nonzero voltage vectors are expressed by using the voltage vectors V_a, V_b, V_c and the zero voltage vector is denoted by V_0.

Let $V_s(k)$ be defined as an inverter voltage vector at the sampling instant of i_{dc}. Then, one of three phase currents at the k-th sampling instant can be expressed from Table 1 as

$$i_m(k) = \mathrm{sign}(V_s(k)) \cdot i_{dc}(k) \tag{2}$$

where the subscript $m \in \{a, b, c\}$ denotes the subscript of the selected $V_s(k)$ and sign($\cdot$) is a sign function. When $V_s(k)$ is a zero voltage vector, the phase currents are not involved in the dc-link current. Otherwise, the dc-link current represents one of the three phase currents depending on $V_s(k)$.

Therefore, one of the three phase currents can be effectively detected from the sampled dc-link current $i_{dc}(k)$ if the PWM inverter generates a nonzero voltage vector at the sampling instant of i_{dc}. Also, it is noted that each of $i_{dc}(k-1)$ and $i_{dc}(k)$ should alternately indicate a different phase current depending on $V_s(k-1)$ and $V_s(k)$, respectively, in order to detect one of the remaining two phase currents with sufficient accuracy. Finally, the last remaining phase current can be obtained by using the equation such as $i_a + i_b + i_c = 0$.

To satisfy the above conditions, the switching sequence of the space-vector PWM method should be rearranged. It is noted that one phase current can be exactly detected from the dc-link current at each sampling instant. However, the remaining two phase currents may have the maximum errors with the current displacement during the sampling interval T_s because of using the previously sampled one phase current so called a Pre-data Hold Method.

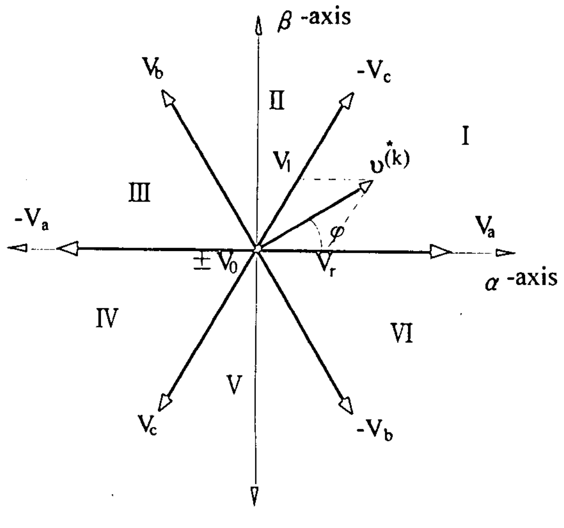


Fig. 3. Inverter output voltage space-vector.

III. Switching Patterns of Modified Space-Vector Modulation

In the space-vector PWM method, a desired inverter voltage vector υ^* is generated by using the two adjacent voltage vectors $\mathbf{V}_r$, $\mathbf{V}_l$, and a zero voltage vector $\mathbf{V}_0$ during a sampling interval, where $\mathbf{V}_r$ and $\mathbf{V}_l$ are determined according to a sector in which υ^* is located as shown in Fig. 3. The time durations T_r, T_l, and T_0 for $\mathbf{V}_r$, $\mathbf{V}_l$, and $\mathbf{V}_0$, respectively, are calculated by the time average of the participating voltage vectors within the sampling interval T_s[1] as follows:

$$\begin{aligned} &V_r=|\upsilon^*(k)|\cos\varphi-0.5V_l\ ,\ V_l=\frac{2}{\sqrt{3}}|\upsilon^*(k)|\sin\varphi \\ &T_r=\frac{2V_r}{3V_{dc}}T_s\ ,\ T_l=\frac{2V_l}{3V_{dc}}T_s\ ,\ T_0=T_s-T_l-T_r\ . \end{aligned} \tag{3}$$

The two phase modulation technique which has the small switching number and is simple[4] is employed as shown in Fig. 5. There are 7 switching patterns which are available for two phase modulation. But, all of the switching patterns are not available to apply for the proposed detection technique. The requirements for applying the proposed detection technique discussed previously are given as follows. It is assumed that the dc-link current is sampled at the beginning of a sampling interval. Firstly, the switching sequence should be rearranged to obtain a phase current from i_{dc} such a way that the PWM inverter generates a nonzero voltage vector at the sampling instant of i_{dc}. This is so called a detectable condition. Secondly, by placing the zero vector into the middle of the switching sequence, the switching number can be reduced. And, because the switching is not occurred at the sampling instant, the value of i_{dc} is not changed at this instant and the trend of i_{dc} is maintained. Then, the number of the available switching patterns becomes two. Lastly, successive voltage vectors should be different from each other at the sampling instant in order to detect a phase current with sufficient accuracy. To satisfy this requirement, two available switching patterns are alternatively used. These available switching patterns are as follows:

P1 : $\mathbf{V}_r \rightarrow \mathbf{V}_0 \rightarrow \mathbf{V}_l$

P2 : $\mathbf{V}_l \rightarrow \mathbf{V}_0 \rightarrow \mathbf{V}_r$.

Also, in a free-wheeling mode, only a zero voltage vector is generated. This pattern is P0. The pattern P0 may occur when the inverter operation is not needed. In this case, the desired voltage vector $\upsilon^*(k)$ has a magnitude of zero and the three phase currents are not involved in the dc-link current $i_{dc}(k)$. When the inverter is normally operated with a nonzero $\upsilon^*(k)$, the pattern P1 or P2 is generated. In this case, $i_{dc}(k)$ always indicates one phase current corresponding to $\mathbf{V}_s(k)$ which the PWM inverter generates at the k-th sampling instant. As shown in Table 2, $\mathbf{V}_s(k)$ depends on both the switching pattern and the sector in which $\upsilon^*(k)$ is located. Therefore, the patterns P1 and P2 are useful to detect a phase current from the dc-link current.

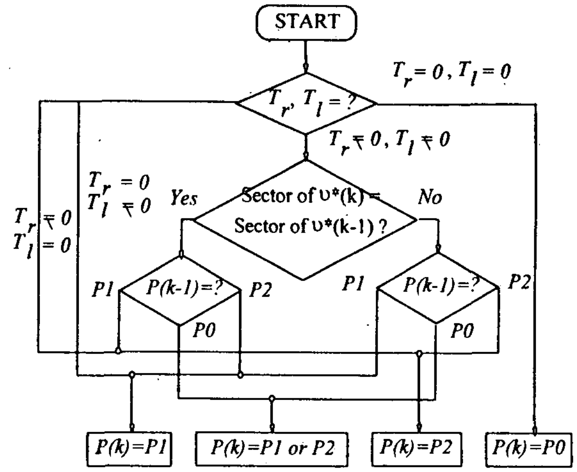


Fig. 4. Flow chart of switching pattern generation.

Next, in order that each of $i_{dc}(k-1)$ and $i_{dc}(k)$ may indicate a different phase current, $\mathbf{V}_s(k)$ should be different from $\mathbf{V}_s(k-1)$. If $\upsilon^*(k)$ is located in the same sector as $\upsilon^*(k-1)$, the k-th sequence pattern different from the (k-1)-th pattern should be generated. In this case, the sequence patterns are alternately generated such as P1→P2 or P2→P1. If the sector of $\upsilon^*(k)$ is different from that of $\upsilon^*(k-1)$, the same sequence pattern as the previous one should be generated, i.e., P1→P1 or P2→P2. It is noted that, with these sequences, $i_{dc}(k)$ always represents a different phase current at the successive sampling instants. Therefore, in the same sector, the number of phase currents obtained from i_{dc} is two. These phases are called a sensed phase when the phase current has been obtained from i_{dc} at previous sampling instant or a sensing phase when the phase current is obtained from i_{dc} at this sampling instant. The sensed phase current is held on the previously sampled value. In this sector, one remaining phase current which is not directly obtained from i_{dc} is called an insensible phase and this current is obtained by using the equation such as $i_a+i_b+i_c=0$. The flow chart of a switching pattern generation in a modified space-vector PWM technique is represented as shown in Fig. 4. Fig. 5 shows the space voltage vector patterns at the boundary between Sector I and Sector II. The phase A and the phase C are sensible phases and the phase B is an insensible phase in Sector I. In Sector II, the phase B and the phase C are sensible phases and the phase A is an insensible phase. The sensible phases which consist of the sensed phase and the sensing phase,

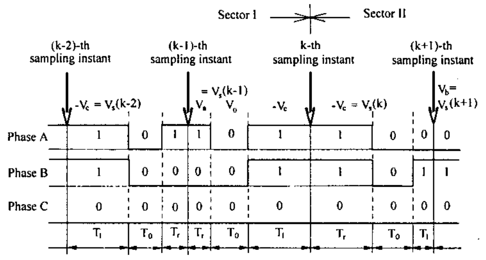


Fig. 5. Space voltage vector patterns.

Table 2. Mode of voltage vector generation.

k-th Pattern	$V_s(k)$ (sector of $v^*(k)$)	
P1	(V_r)	V_a(I), $-V_b$(II), V_c(III) $-V_a$(IV), V_b(V), $-V_c$(VI)
P2	(V_l)	$-V_c$(I), V_b(II), $-V_a$(III) V_c(IV), $-V_b$(V), V_a(VI)

and the insensible phase in each sector are shown in Table 3.

Ⅳ. Simulation and Experimental Results

Fig. 6 shows the configuration of the experimental system. A 4-pole, 3Hp, 220V induction motor is used in the experiment. The data used in the simulation are $R_s = 6.192[\Omega]$, L_s=46[mH], $f_s = 50[Hz]$, and V_{dc}=50[V]. The current is detected by a Hall-CT and is converted through a 12-bit A/D converter. The sampling time is 0.5[ms]. The inverter has a dead time of $5[\mu s]$ to protect the arm shortage of an inverter leg. The gate signals of switching devices are generated by the Programmable Array Logic(PAL) programming of 8253 counter signals.

Fig. 7 shows the experimental results of space voltage vector patterns and a detected phase A current corresponding to the case shown in Fig. 5. Since the switching functions (S_a, S_b, S_c) in Sector I equal to (1, 0, 0), (0, 0, 0), or (1, 1, 0), the phase A and the phase C are sensible phases. Because the phase A current is directly sampled from i_{dc} or is held on a previous value when the phase A is a sensing phase or a sensed phase, respectively, a detected phase A current has the form of one sampled and two steps hold. This is similar to a Sampled-and-Hold system with double the sampling time. When v^* is located closer to the boundary of Sector I and Sector II, the duration of V_a is shorter. The first magnitude change of this current is larger than the second magnitude change because the first duration of V_a is longer than the second duration. However, when the switching functions (S_a, S_b, S_c) in Sector II equal to (1, 1, 0), (0, 0, 0), or (0, 1, 0), the phase B and the phase C are sensible phases. Because the phase A is an insensible phase, its current is obtained from the other phase currents at each sampling instant. A detected phase A current is varied at each sampling instant and this current will have some detection error because of the error of a sensed phase current.

Table 3. Sensible phases and insensible phase in each sector

Sector	Sensible phases (a sensed or a sensing phase)	Insensible phase
I	a , c	b
II	b , c	a
III	a , b	c
IV	a , c	b
V	b , c	a
VI	a , b	c

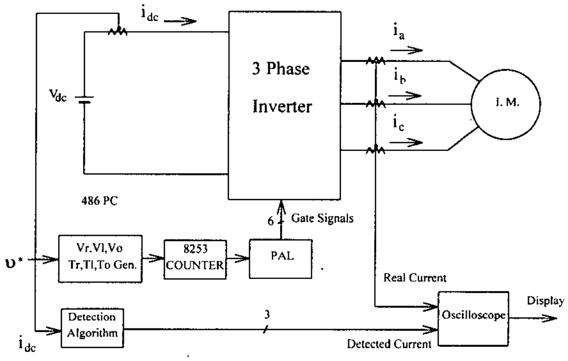


Fig. 6. Configuration of experimental system.

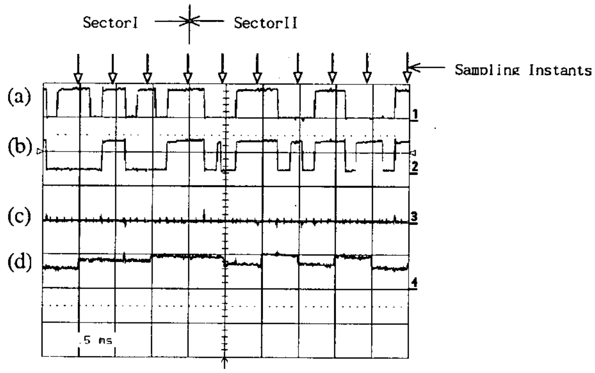


Fig. 7. Space voltage pattern and detected phase A current. (Experimental Results) ; (a) phase A switching sequence (b) phase B switching sequence (c) phase C switching sequence (d) detected phase A current

Fig. 8 shows the computer simulation for the transient responses of a real and a detected phase A currents from the pre-data hold method and Fig. 9 shows the experimental results. As discussed above, if the phase A is a sensible phase, a detected phase A current is corresponding to a real phase A current at any sampling instant and this current is held on for two sampling

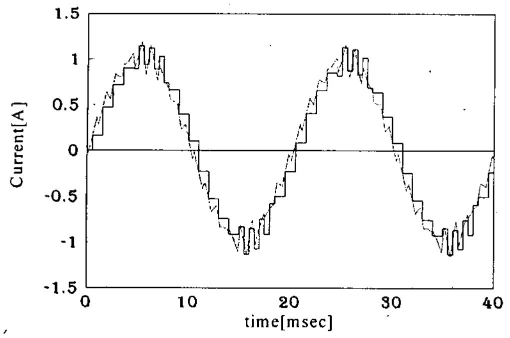


Fig. 8. Computer simulation results.
(··· : Real phase A current, - : Detected phase A current)

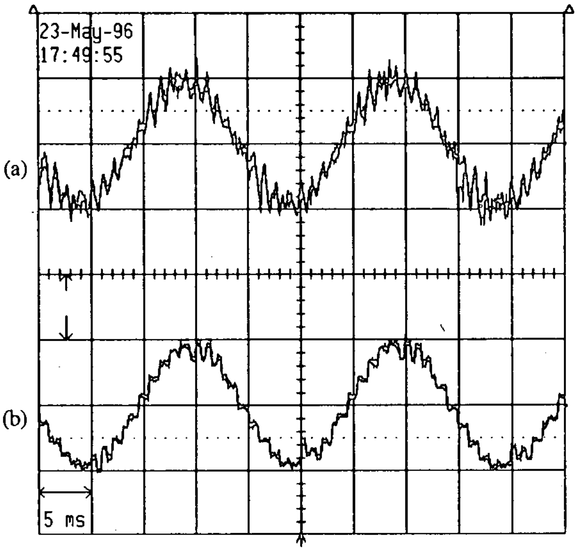


Fig. 9. Experimental results.
(a) Real phase A current (b) Detected phase A current

instants. When this current has the maximum value or the minimum value, the phase A becomes an insensible phase and v^* is located in Sector II and Sector V, respectively. Because $\mathbf{V}_a$ or $-\mathbf{V}_a$ is not generated in these sectors, the rate of change of i_a is small.

When the phase A is an insensible phase or a sensed phase, a detected phase A current has some detection error. But this error can be reduced by using a numerical technique or by shortening the sampling time. Also, this error has a sufficient bound and is not accumulated. It is shown in Figs. 8 and 9 that the proposed scheme is valid for detecting the three phase currents from the dc-link current without phase current sensors.

V. Conclusions

A method of detecting the three phase currents with one current sensor placed at the dc-link is proposed. In a three-phase PWM inverter fed AC drive system, one phase current appears in the dc-link current. The switching sequence of the space-vector PWM is modified in order that one phase current may alternatively appear in the dc-link current at each sampling instant. Then, with only one dc-link current sensor, three phase currents are obtained with sufficient accuracy. And, the proposed method has the constant sampling time by applying the modified space-vector PWM technique that generates the rearranged switching pattern. Therefore, the proposed detection method is simple to implement using a microprocessor and is able to cut down the cost.

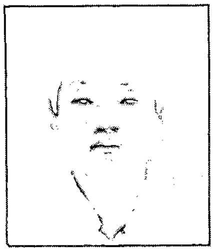
References

[1] D. M. Brod, and D. W. Novotny, "Current control of VSI-PWM inverters," *IEEE Trans., Industry Applications*, IA-21, pp. 562-570, 1985.

[2] Y. Murai, Y. Tanizawa, and M. Yoshida, "Three Phase Current Waveform Detection on PWM Inverters from DC Link Current-Steps," *IPEC-Yokohama 95*, pp. 271-275, 1995.

[3] H. L. HUY, and H. A. DESSAINT, "An adaptive current control scheme for PWM synchronous motor drives: analysis and simulation," *IEEE Trans., Power Electronics*, PE-4, pp. 486-495, 1989.

[4] D. C. Lee, S. K. Sul, and M. H. Park, "Comparison of AC current regulators for IGBT inverter," *PCC-Yokohama 93*, pp. 206-212, 1993.



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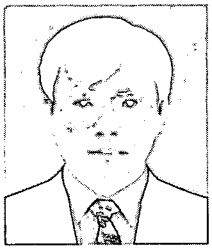

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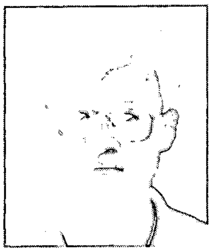

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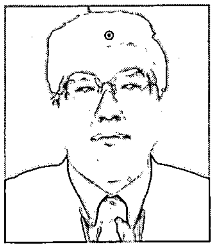

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