# 상전류센서 없는 새로운 방식의 공간 전압 벡터 PWM 인버터

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## A New Space-Vector PWM Inverters without Phase Current Sensors

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*Abstract* - A method for detecting the three-phase currents of a voltage-fed pulsewidth modulated(PWM) inverter is proposed by utilizing only one current sensor placed on the dc-link. The proposed space vector PWM technique is two phase modulated PWM, this enables to detect the phase currents from only one DC link current sensor. The proposed method is simple, reduces the cost, and provides the 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 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. Therefore, 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 dc link current-steps was studied[4]. This method requires two sampled values of $i_{dc}$ for one detection of phase current and has some difficulties for determining the sample points and sensing the dc link current-steps with short pulse.

In this paper, a new method of detecting the three-phase currents from dc link current is proposed by using the modified space-vector PWM technique. The proposed method has the constant sampling time by employing the space-vector PWM technique generating the rearranged switching pattern so that it is simple to implement using a microprocessor. This proposed method is simple and has the small detection error.

### II. DETECTION TECHNIQUE OF THREE-PHASE CURRENTS

Figure 1 shows the 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[2] and the equivalent PWM inverter, shown in Fig. 2, can be used to analyze the waveform of the dc-link current regardless of the direction of the output currents. It is assumed that an AC motor is Y-connected and it has no neutral connection.
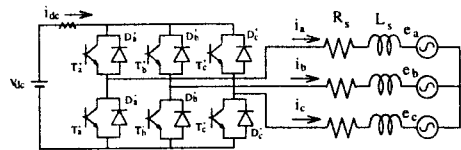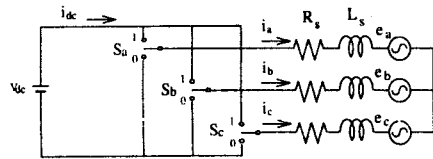


Fig. 1. Voltage-Fed PWM inverter



Fig. 2. Equivalent PWM inverter

One of the three-phase current waveforms appears in the dc-link current depending on the switching functions as shown in Table 1. When one switching function $S_m$ ($m \in \{a,b,c\}$) 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 $i_m$. Similarly, when one 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 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 $\upsilon$ is defined as a combination of the phase voltages $\upsilon_a, \upsilon_b$, and $\upsilon_c$ as follows[1]:

$$\upsilon \equiv \begin{bmatrix} \upsilon_\alpha \\ \upsilon_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \upsilon_a \\ \upsilon_b \\ \upsilon_c \end{bmatrix} \quad (1)$$

where $\upsilon_\alpha$ and $\upsilon_\beta$ 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 $\mathbf{V}_a, \mathbf{V}_b, \mathbf{V}_c$ and the zero voltage vector is denoted by $\mathbf{V}_0$.

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

$$i_m(k) = \operatorname{sgn}(\mathbf{v}_s(k)) \cdot i_{dc}(k) \qquad (2)$$

where the subscript $m \in \{a, \ b, \ c\}$ denotes the subscript of the selected $\mathbf{v}_s(k)$ and $\operatorname{sgn}(\cdot)$ is a signum function. In case that $\mathbf{v}_s(k)$ 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 phase currents depending on $\mathbf{v}_s(k)$.

Therefore, one phase current 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 $i_{dc}$. Two of three phase currents can also be detected with sufficient accuracy if each of $i_{dc}(k-1)$ and $i_{dc}(k)$ alternately indicates a different phase current depending on $\mathbf{v}_s(k-1)$ and $\mathbf{v}_s(k)$, respectively. The remaining phase current can be derived by using the equation that $i_a + i_b + i_c = 0$.

To satisfy the above conditions, the switching sequence of the space vector PWM method will be rearranged in the followings. It is noted that one phase current can be exactly detected from the dc-link current at each sampling instant but the remaining two-phase currents may have the maximum errors with the current displacement during the sampling interval $T_s$ because of using previously sampled one-phase current.

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

| $(S_a, S_b, S_c)$ | $\mathbf{v}_s(k)$ | $i_{dc}(k)$ | Mode | Circuit Connection |
|---|---|---|---|---|
| (1, 0, 0) | $\mathbf{V}_a$ | $i_a(k)$ | active | $i_{dc}(k)$  $i_m(k)$ |
| (0, 1, 0) | $\mathbf{V}_b$ | $i_a(k)$ | active | |
| (0, 0, 1) | $\mathbf{V}_c$ | $i_a(k)$ | active | |
| (0, 1, 1) | $-\mathbf{V}_a$ | $-i_a(k)$ | active | $i_{dc}(k)$ |
| (1, 0, 1) | $-\mathbf{V}_b$ | $i_a(k)$ | active | |
| (1, 1, 0) | $-\mathbf{V}_c$ | $-i_a(k)$ | active | $i_m(k)$ |
| (0, 0, 0) | $\mathbf{V}_0$ | 0 | free-wheeling | $i_{dc}(k) = 0$ |
| (1, 1, 1) | $\mathbf{V}_0$ | 0 | free-wheeling | |

### III. SWITCHING PATTERNS OF SPACE VECTOR MODULATION

In the space vector PWM method, a desired inverter voltage vector $\upsilon^*$ is approximately generated by using the two adjacent voltage vectors $\mathbf{V}_r, \mathbf{V}_l$, and a zero voltage vector $\pm\mathbf{V}_0$ during a sampling interval, where $\mathbf{V}_r$ and $\mathbf{V}_l$ are determined according to a sector in which $\upsilon^*$ 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:

$$V_r = |\upsilon^*(k)|\cos\varphi - 0.5V_l, \qquad V_l = 2|\upsilon^*(k)|\sin\varphi/\sqrt{3}$$
$$T_r = 2V_r T_s/3V_{dc}, \ T_l = 2V_l T_s/3V_{dc}, \ T_0 = T_s - T_l - T_r \qquad (3)$$

The switching sequence is newly rearranged in a way that the PWM inverter generates a nonzero voltage vector at the sampling instant of the dc-link current. Assume that the dc-link current is
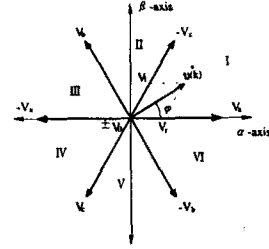


Fig. 3. Inverter output voltage space vector

sampled at the beginning of a sampling interval. Then, three switching patterns are available during a sampling interval as follows:

$$\text{P1:} \ \ \mathbf{V}_r \to \mathbf{V}_0 \to \mathbf{V}_l$$
$$\text{P2:} \ \ \mathbf{V}_l \to \mathbf{V}_0 \to \mathbf{V}_r$$
$$\text{P0:} \qquad \mathbf{V}_0 \qquad \text{if } T_l = T_r = 0.$$

The pattern P0 may occur when the no-operation of the inverter is 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 a 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 for detecting a phase current from the dc-link current.

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 of $\upsilon^*(k-1)$, the $k$-th sequence pattern different from the $(k-1)$-th pattern is 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 is 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. Fig.4 shows the flow chart of a switching pattern generation in a modified space-vector PWM technique. Fig.5 shows space voltage vector pattern at the $(k-1)$-th sampling instant and the $k$-th. In this case, space voltage vector $\mathbf{v}_s(k)$ exists in Sector I, the switching pattern is P1. Therefore, c-phase current is obtainable from $i_{dc}(k)$. At next instant, the switching pattern is P2, a-phase current is obtainable.
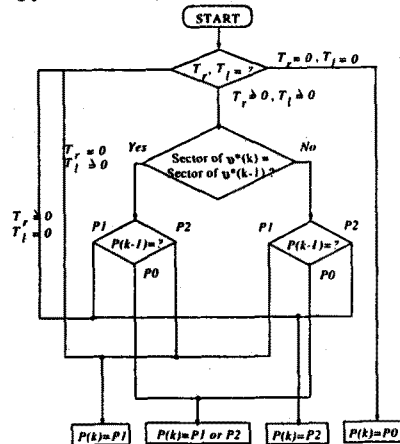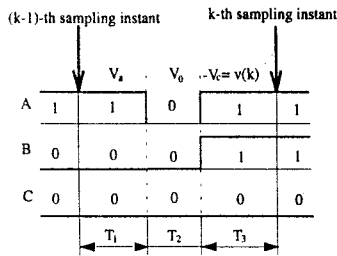


Fig. 4 Flow Chart of Switching Pattern Generation

(k-1)-th sampling instant     k-th sampling instant

Fig. 5 Space voltage vector pattern

**Table 2 Mode of Voltage Vector Generation**

| $k$ -th Pattern | | $v_s(k)$ ( sector of $v^*(k)$ ) |
|---|---|---|
| P1 | $(v_t)$ | $-v_c(I),\ v_b(II),\ -v_a(III)$ |
| | | $v_c(IV),\ -v_b(V),\ v_a(VI)$ |
| P2 | $(v_r)$ | $v_a(I),\ -v_c(II),\ v_b(III)$ |
| | | $-v_a(IV),\ v_c(V),\ -v_b(VI)$ |

## IV. SIMULATION AND EXPERIMENTAL RESULTS

To verify the usefulness of the proposed method for detecting the phase currents, the predictive current control[2] is employed with the proposed modulation sequence. The data used in the simulation are $R_s = 6.192[\Omega]$, $L_s = 46[mH]$ and $V_{dc} = 50[V]$. The proposed method starts to detect the phase currents after the current control reaches the steady state. Fig.6a shows the transient responses of the real and detected phase currents from the pre-data hold method, when $e_a = 40\cos(100\pi t - \pi / 2)[V]$ and $i_a = 1\cos(100\pi t)[A]$. The sampling time is 0.5[ms]. It is noted that the detected three-phase currents can have the maximum error with the current displacement during one sampling interval. The solid line is a detected phase current obtained from $i_{dc}$ and the estimated value, and the dotted line is a real phase current. As shown in Fig.6, a detected current is in accordance with a real current at each sampling instants. Fig. 7 shows the experimental result of detected and real a-phase current. From this result, a detected current obtained from the proposed scheme is almost same as real current.
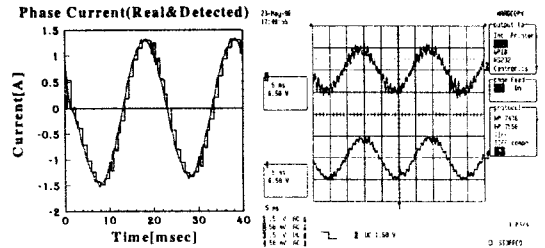


Fig.6 Detected and Real Phase Current    Fig.7 Detected and Real Phase Current
(Experiment)

## V. CONCLUSIONS

A method for detecting the three-phase currents with one current sensor placed at the dc-link is proposed. 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. The proposed method has constant sampling time by applying the modified space-vector PWM technique generating the rearranged switching pattern so that it is simple to implement using a microprocessor. In conclusion, the proposed detection method is simple to implement and is able to cut down the cost.

## VI. REFERENCES

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