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영구자석 동기전동기용 전압원 인버터의 전압왜곡 분석 및 On-line 보상

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Voltage Distortion Analysis and On-line Compensation of VSI for Permanent Magnet Synchronous Motor

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ABSTRACT

In a PWM VSI, the voltage distortion exists between the reference and output voltage. This distortion is caused by the intended blanking time and the inherent characteristics of the switching devices which are function of the operating condition. In this paper, the dead-time effects are analysed and a new on-line estimation method for a PMSM is proposed to compensate time varying dead-time effects .

1. Introduction

In a PWM VSI, the voltage distortion exists between the reference voltage and output voltage. This distortion is partly caused by the blanking time which is inevitable to prevent the shoot-through phenomenon. The other reasons are the inherent characteristics of the switching devices such as voltage drops, turn on/off time, and output voltage transition time. These non-ideal characteristics of the devices vary with the operating conditions such as the temperature, DC bus voltage, and phase current level. This distortion affects machine current distortion, torque pulsations, degradation of control performance, and observer performance. To compensate this distortion, these non-ideal characteristics of the power devices have been considered in some papers [1]-[4]. Some approaches require off-line experiments and the compensation is based on these off-line experiments [1],[2]. However, it is difficult to compensate perfectly the time varying voltage distortion using these methods. The other approach requires the terminal voltage sensing hardware [3]. In [4], the on-line observing method for the voltage distortion due to the blanking time and non-ideal characteristics has been proposed. In this method, the voltage distortion is estimated by a time delay control observer. However, because this voltage distortion is abruptly changed at some instant, the phase delay exists between the real distortion voltage and observed voltage. This delay originates from a low-pass filter of the observer and causes a degradation of compensation characteristics. To overcome this problem, a new indirect distortion voltage observing algorithm is proposed in this paper.

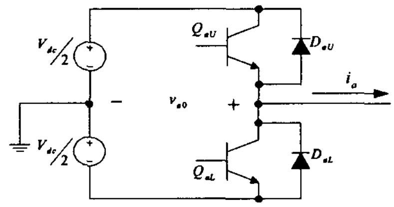


Fig. 1 Leg of 3 phase inverter

2. Analysis of Dead-time Effects

Fig. 1 shows a leg of a 3 phase inverter, in which there are two active switches, Q_{aU} and Q_{aL}, and two anti-parallel diodes, D_{aU} and D_{aL}. To turn on and turn off these active switches, the gate drive signal is needed. The ideal gate drive signals are represented in Fig. 2 as G^*_{aU} and G^*_{aL} for two active switches. The practical

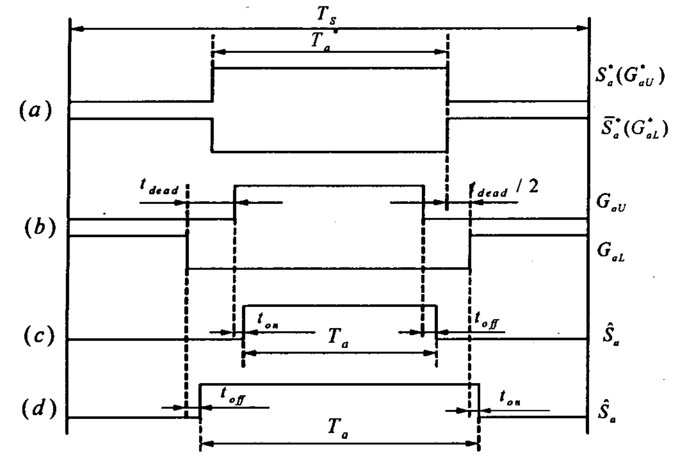


Fig. 2 Ideal and practical gate drive signal and switching function

gate drive signal which includes a dead-time period are represented as G_{aU} and G_{aL} in Fig. 2. The switching functions which include the turn-on delay and the turn-off delay of the switches for the conditions of $i_a \geq 0$ and $i_a \leq 0$ are represented in Fig. 2(c) and (d), respectively. The switching function is 1 when terminal voltage of a phase, v_{a0}, is equal to $V_{dc}/2$ and the switching function is 0 when $v_{a0} = -V_{dc}/2$. From the switching function considering the dead-time effect, the instantaneous terminal voltage, $v_{a0}(t)$, can be calculated as follows:

$$v_{a0}(t) = V_{dc}(\hat{S}_Q - 0.5) \tag{1}$$

where V_{dc} is DC bus voltage and $\hat{S}_Q$ is switching function in which dead-time effect is considered. However, in (1) the voltage drops of switches are ignored. The effects of voltage drops are represented in Fig. 3. If the effects of voltage drops are considered, $v_{a0}(t)$ can be represented as follows:

$$v_{a0}(t) = (V_{dc} - V_{ce} + V_d)(\hat{S}_Q - 0.5) - 0.5sgn(i_a)(V_{ce} + V_d) \ . \tag{2}$$

where V_{ce} is the saturation voltage of the active switch and V_d is the forward voltage of the anti-parallel diode. The average voltage during the k[th] PWM step can be derived from (2) and the results is

$$v_{a0}(k) = (V_{dc} - V_{ce} + V_d)(\frac{T_a(k)}{T_S} - 0.5) - 0.5sgn(i_a)(V_{ce} + V_d) \ . \tag{3}$$

Considering the switching function at the dead-time period, the effective on-time of the active switch Q_{aU} in (3) can be represented as follows:

$$T_a(k) = T_a^*(k) - sgn(i_a)(t_{dead} + t_{on} - t_{off}) \tag{4}$$

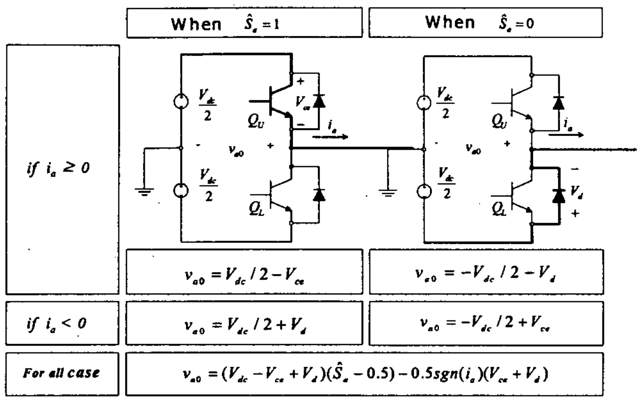


Fig. 3 Effects of saturation and forward voltage

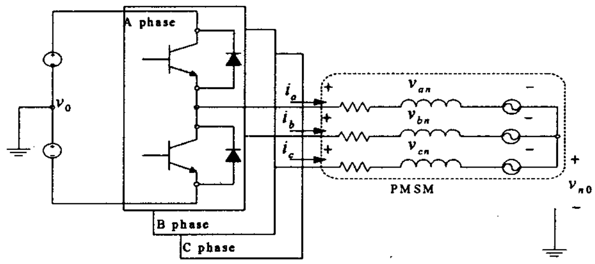


Fig. 4 Relation between terminal and phase voltage

where $T_a^*(k)$ is ideal on-time command at kth PWM period of Q_{aU}, t_{dead} is dead-time period, t_{on} is turn-on time, t_{off} is turn-off time of active switch, and $sgn(.)$ is sign function.

3. Voltage Distortion Analysis

Now, let we calculate the phase voltage distortion. To calculate the average phase voltage, consider the following equation:

$$v_{a0} = v_{an} + v_{n0}, \ v_{b0} = v_{bn} + v_{n0}, \ v_{c0} = v_{cn} + v_{n0} \tag{5}$$

where v_{an}, v_{bn}, and v_{cn} are phase voltage and v_{n0} is the neutral to center voltage as shown in Fig. 4. In a three-phase three-wire motor, following conditions is satisfied:

$$i_a + i_b + i_c = 0. \tag{6}$$

Also, if the air-gap magnetic flux distribution is sinusoidal, the sum of each phase back EMF is equal to 0. From the previous equation and assumption, the following condition is satisfied for any balanced PMSM,

$$v_{an} + v_{bn} + v_{cn} = R_S(i_a + i_b + i_c) + L_S\frac{d}{dt}(i_a + i_b + i_c) + (e_a + e_b + e_c) = 0 \tag{7}$$

where R_S is a stator resistance, L_S is a stator

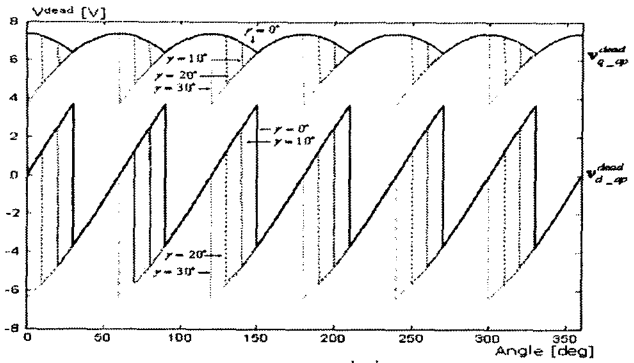


Fig. 5 *Voltage distortion* $v_{qd-ap}^{dead}(k)$ *according to* γ

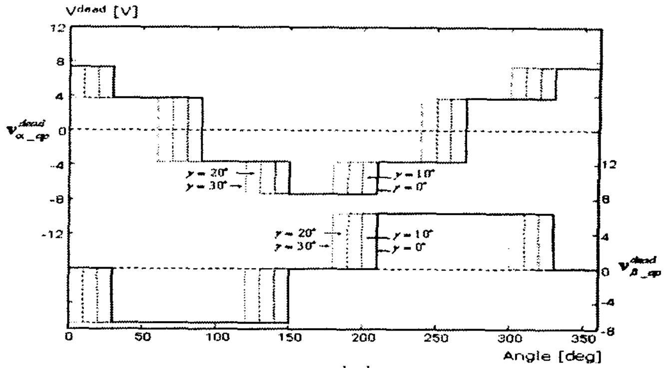


Fig. 6 *Voltage distortion* $v_{\alpha\beta-ap}^{dead}(k)$ *according to* γ

inductance, and e_a, e_b, and e_c represent respective phase back EMFs. From (5) and (7), the following equation can be derived.

$$v_{n0} = \frac{v_{a0} + v_{b0} + v_{c0}}{3} \tag{8}$$

From (3) and (8), the average phase to neutral voltage can be calculated as follows:

$$v_{n0}(k) = \frac{(V_{dc} - V_{ce} + V_d)}{3}\left(\frac{T_a(k)+T_b(k)+T_c(k)}{T_S} - 1.5\right) - \frac{(sgn(i_a)+sgn(i_b)+sgn(i_c))(V_{ce}+V_d)}{6} \tag{9}$$

A phase voltage also can be calculated from (3), (5), and (9) and the result is

$$v_{an}(k) = \frac{(V_{dc} - V_{ce} + V_d)}{3}\left(\frac{2T_a(k)-T_b(k)-T_c(k)}{T_S}\right) - \frac{(2sgn(i_a)-sgn(i_b)-sgn(i_c))(V_{ce}+V_d)}{6} \tag{10}$$

Through the same procedure, the required phase reference voltages can be calculated as follows:

$$v_{an}^*(k) = \frac{V_{dc}}{3}\frac{(2T_a^*(k) - T_b^*(k) - T_c^*(k))}{T_S}. \tag{11}$$

Finally, a phase voltage distortion from the dead-time effects can be derived as follows from the difference between (10) and (11):

$$\begin{aligned} v_{an}^{dead}(k) &= v_{an}^*(k) - v_{an}(k) = (2sgn(i_a) - sgn(i_b) - sgn(i_c))A_p \\ &+ \frac{(V_{ce}-V_d)(2T_a^*(k) - T_b^*(k) - T_c^*(k))}{3T_S} \\ &= v_{an-ap}^{dead}(k) + v_{an-nap}^{dead}(k) \end{aligned} \tag{12}$$

where $A_p = (2(V_{dc} - V_{ce} + V_d)(t_{dead} + t_{on} - t_{off})/T_S + (V_{ce} + V_d))/6$

The voltage distortion can be divided into two parts as shown in (12). The first part of RHS, $v_{an-ap}^{dead}(k)$, is an abruptly changed part by the zero-cross point of phase currents and proportional to A_p. On the other hand, the second part of RHS, $v_{an-nap}^{dead}(k)$, is not an abruptly changed part. Similarly, the voltage distortions of other phase can be calculated.

Table 1 Voltage distortion in stationary frame

Mode	$sgn(i_a)$	$sgn(i_b)$	$sgn(i_c)$	V_α^{dead}	V_β^{dead}
0	1	-1	-1	$4A_p$	0
1	1	1	-1	$2A_p$	$-2\sqrt{3A_p}$
2	-1	1	-1	$-2A_p$	$-2\sqrt{3A_p}$
3	-1	1	1	$-4A_p$	0
4	-1	-1	1	$-2A_p$	$2\sqrt{3}A_p$
5	1	-1	1	$2A_p$	$2\sqrt{3}A_p$

The voltage distortion in the synchronous reference frame can be calculated from the *abc* frame variable using following equation.

$$\begin{bmatrix} v_q^{dead}(k) \\ v_d^{dead}(k) \end{bmatrix} = \begin{bmatrix} v_{q\_ap}^{dead}(k) + v_{q\_nap}^{dead}(k) \\ v_{d\_ap}^{dead}(k) + v_{d\_nap}^{dead}(k) \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta_e & \cos(\theta_e - \frac{2\pi}{3}) & \cos(\theta_e + \frac{2\pi}{3}) \\ \sin\theta_e & \sin(\theta_e - \frac{2\pi}{3}) & \sin(\theta_e + \frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} v_{an}^{dead}(k) \\ v_{bn}^{dead}(k) \\ v_{cn}^{dead}(k) \end{bmatrix}. \tag{13}$$

The voltage distortion in the synchronous reference frame also can be represented as two parts. The first part can be represented as follows:

$$v_{d\_ap}^{dead} = 4A_p\left(\sin\left(\theta_e - Mode\frac{\pi}{3}\right)\right)$$
$$v_{q\_ap}^{dead} = 4A_p\left(\cos\left(\theta_e - Mode\frac{\pi}{3}\right)\right), \tag{14}$$

where *Mode* is an integer that is greater than or equal to 0 and less than 6 and obtained using $Mode = \text{int}\left(\frac{6(\theta_e + \gamma + \pi/6)}{2\pi}\right)$. The first part of the voltage distortion is shown in Fig. 5, according to the γ. In this Fig. γ is the angle between the stator current angle and q-axis in the synchronous reference frame as represented in (15).

$$\gamma = atan(-i_d/i_q) \tag{15}$$

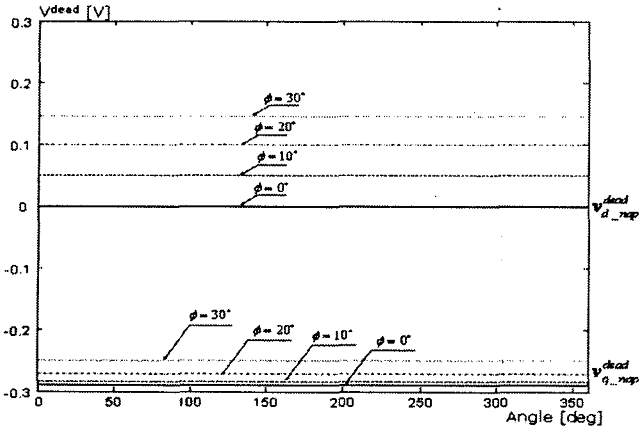


Fig. 7 *Voltage distortion* $v^{dead}_{qd-nap}(k)$ *according to* ϕ

The first part of the voltage distortion in the stationary frame, $v^{dead}_{\alpha\beta-ap}(k)$, is shown in Fig. 6 and table 1. This value can be derived from (12) using the park transformation for the stationary frame. The conditions for Fig. 5 and 6 are set as follows: T_S is 200μsec, V_{dc} is $310V$, V_{ce} is $2.25V$, V_d is $2.75V$, t_{on} is 1.4μsec, t_{off} is 2.45μsec, and t_{dead} is 3μsec.

The second part of the voltage distortion in the synchronous reference frame can be calculated from (12) and (13) as follows:

$$\begin{bmatrix} v^{dead}_{q\_nap}(k) \\ v^{dead}_{d\_nap}(k) \end{bmatrix} = \frac{2}{3}\frac{(V_{ce}-V_d)}{T_s}\begin{bmatrix} \left(T^*_a(k)\cos\theta_e + T^*_b(k)\cos(\theta_e - \frac{2\pi}{3}) + T^*_c(k)\cos(\theta_e + \frac{2\pi}{3})\right) \\ \left(T^*_a(k)\sin\theta_e + T^*_b(k)\sin(\theta_e - \frac{2\pi}{3}) + T^*_c(k)\sin(\theta_e + \frac{2\pi}{3})\right) \end{bmatrix}. \quad (16)$$

If the carrier-comparison PWM methods[5] is used, $T^*_a(k)$, $T^*_b(k)$, and $T^*_c(k)$ can be calculated as follows:

$$T^*_a(k) = \frac{T_S}{V_{dc}}(v^*_{an}(k) + v^*_{zs}), T^*_b(k) = \frac{T_S}{V_{dc}}(v^*_{bn}(k) + v^*_{zs})$$
$$, T^*_c(k) = \frac{T_S}{V_{dc}}(v^*_{cn}(k) + v^*_{zs}), \quad (17)$$

where $v^*_{an} = |v^*_s|cos(\delta(k))$, $v^*_{bn} = |v^*_s|cos(\delta(k) - \frac{2\pi}{3})$, $v^*_{cn} = |v^*_s|cos(\delta(k) + \frac{2\pi}{3})$. From (16) and (17), the second part of voltage distortion can be derived as follows:

$$\begin{bmatrix} v^{dead}_{q\_nap}(k) \\ v^{dead}_{d\_nap}(k) \end{bmatrix} = \frac{|v^*_s|(V_{ce}-V_d)}{V_{dc}}\begin{bmatrix} \cos\phi \\ -\sin\phi \end{bmatrix}. \quad (18)$$

where $\phi = \delta(k) - \theta_e(k)$. This voltage distortion according to ϕ is shown in Fig. 7. The conditions are identical with that of Fig. 5. To get the worst case voltage distortion, it is assumed that the maximum value under the linear modulation region is applied to PMSM, that is $|v^*_s| = V_{dc}/\sqrt{3}$.

4. Dead Time Effects Observer and On-line Compensation

The voltage distortion can be divided into two parts as can be seen in the previous section. The first part, v^{dead}_{qd-ap}, is abruptly changed at the zero-cross point of a phase current and this abruptly changed characteristic makes difficult to employ a low-pass filter. In [4], the on-line observing method for the voltage distortion due to the blanking time and non-ideal characteristics has been proposed. In this method, the voltage distortion is estimated based on time delay control. However, because the voltage distortion is fast changed value, and moreover abruptly changed at some instant, the phase delay exists between the real distortion voltage and observed voltage. This delay originates from a low-pass filter of the observer and causes a degradation of compensation characteristics. To overcome this problem, a new indirect distortion voltage observing algorithm is proposed in this paper. Although the voltage distortion is abruptly changed at the zero-cross point of a phase current, the intermediate value A_p is not abruptly changed but slowly varied by the operating conditions. In the proposed observing method, the second part of the voltage distortion, v^{dead}_{qd-nap}, is neglected since this is very small in comparison with v^{dead}_{qd-ap} as shown in previous section. If v^{dead}_{qd-nap} can be negelected, the voltage distortion is a function of A_p. Therefore, by observing A_p, the voltage distortion can be calculated from table 1.

Since the voltage distortion is equal to the difference between the reference voltage and supplied voltage, the voltage distortion at the k-1 step in the stationary frame can be calculated as follows:

$$\check{v}^{dead}_{\alpha}(k-1) = v^*_{\alpha}(k-1) - R_S i_{\alpha}(k-1) - \frac{L_S}{T_S}(i_{\alpha}(k-1) - i_{\alpha}(k-2)) - \lambda_m w_e \cos\theta_e(k-1)$$
$$\check{v}^{dead}_{\beta}(k-1) = v^*_{\beta}(k-1) - R_S i_{\beta}(k-1) - \frac{L_S}{T_S}(i_{\beta}(k-1) - i_{\beta}(k-2)) - \lambda_m w_e \sin\theta_e(k-1). \quad (19)$$

However, these values cannot be directly used to compensate the voltage distortion, because the high frequency noise in the stator current may be amplified owing to the numerical differentiation of the measured

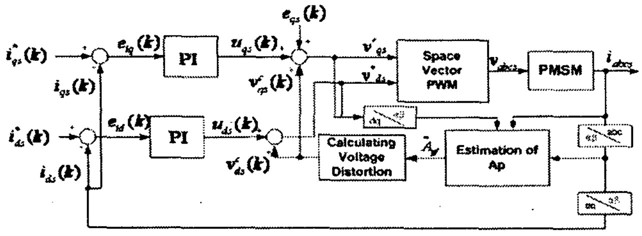


Fig. 8 Proposed Compensation Method

Table 2. Specifications of Test Motor

Rated power	750[W]	Number of poles	8
Rated torque	2.4[Nm]	Rated speed	3000[rpm]
Stator resistance	0.49[Ω]	Rated current	6.0[A]
Linkage flux	0.0667[Wb]	Stator inductance	6.9[mH]

Table 3. Specification of Drive System

DC link voltage(V_{DC})	310[V]	Switching period	200[μSec]
Dead time	3[μSec]	Switching device	IGBT
Turn-on time*	0.8-2.0[μSec]	Turn-off time*	2.0-2.9[μSec]
Saturation voltage*(V_{ce})	1.8-2.7[V]	Forward Voltage*(V_d)	2.2-3.3[V]

*: Mitsubishi data sheet(PM50RSA060)

current. Furthermore, k^{th} compensation using $k\text{-}1^{th}$ calculated data of (19) make the problem of incorrect compensation if k^{th} PWM is in the abruptly changed instant. Nevertheless, the observed value for $A_p(k-1)$, $\hat{A}_p(k-1)$, can be calculated from (19) and table 1 according to the respective current mode. It is also necessary to employ a low-pass filter for $\hat{A}_p$, because of the numerical differentiation in (19). Using the low-pass filter, the filtered $\hat{A}_p$ can be obtained as follows:

$$\hat{A}_{pf}(k-1)=\frac{1}{1+a_1T_S}\hat{A}_{pf}(k-2)+\frac{a_1T_S}{1+a_1T_S}\hat{A}_p(k-1) \quad (20)$$

where a_1 is the cut-off frequency of the low-pass filter. From (14) and (20), the observed voltage distortion according to the individual current mode can be obtained. The overall block diagram of the compensation for the proposed dead-time effects observer is represented in Fig. 8. In Fig. 8, the voltage command for the dead-time effects compensation is represented as follows:

$$v^*_{qd}(k)=u_{qd}(k)+e_{qd}(k)+v^c_{qd}(k)$$

$$v^c_q(k)=\hat{v}^{dead}_q(k)=4\hat{A}_{pf}(k-1)(\cos(\theta_e(k)-\mathrm{mode}(k)\frac{\pi}{3}))$$

$$v^c_d(k)=\hat{v}^{dead}_d(k)=4\hat{A}_{pf}(k-1)(\sin(\theta_e(k)-\mathrm{mode}(k)\frac{\pi}{3})) \quad . (21)$$

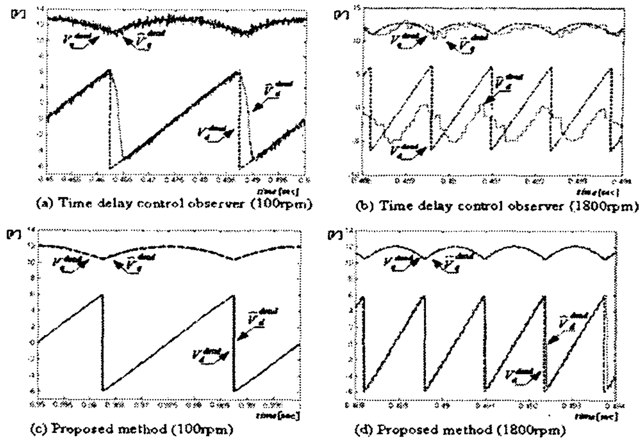
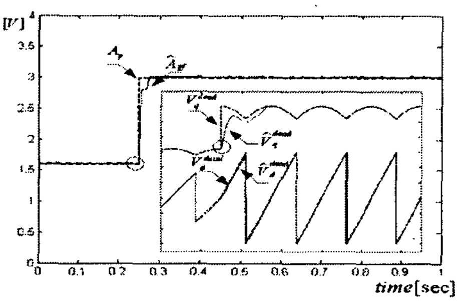


Fig. 9 Comparison of Observed Voltage Distortion



Fig, 10 Observing Performance of Proposed Method

5. Simulation Results

In this section some simulation results will be shown to prove the effectiveness of the proposed dead-time effects observer and compensation method. The parameters related to the PMSM and Inverter are represented in Table 2 and Table 3, respectively. The simulation results for the voltage distortion observer are shown in Fig. 9. The simulation parameters are set as follows: T_S is 100μsec, V_{DC} is 311V, V_{ce} is 1.8V, V_d is 2.2V, t_{on} is 0.8μsec, t_{off} is 2.9μsec, and t_{dead} is 3μsec. The observed distortion voltages of the previous method using time delay control are shown in Fig 9(a) and (b). The operating rpm of PMSM are 100rpm and 1800rpm, respectively. The cut-off frequency of low-pass filter for this observer is 800Hz. As can be seen in Fig. 9(a) and (b), phase delay exists between real voltage distortion v^{dead}_{qd} and observed voltage distortion $\hat{v}^{dead}_{qd}$. The observed distortion voltages of proposed method are shown in Fig 9(c) and (d). It is obvious that the observed voltage distortion is nearly equal to the real distortion and has no phase delay. Fig. 10 shows the simulation

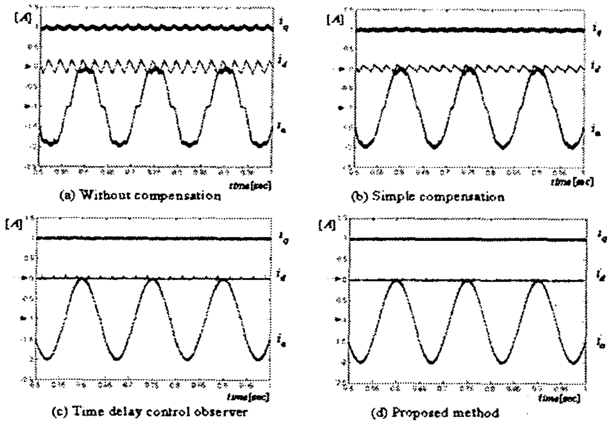


Fig. 11 Current waveform comparison at 100rpm

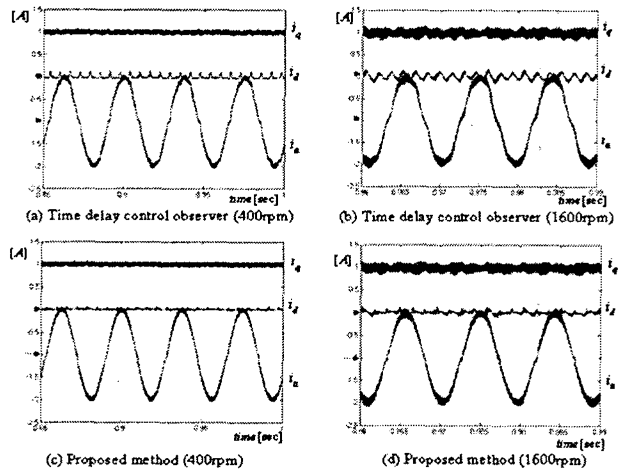


Fig. 12 Current waveform comparison between time delay control and proposed compensation

results for the proposed dead time effects observer under the assumption that the real A_p is changed at 0.25sec. The results show that the observed value well follows the real one within 0.05sec. Fig. 11 shows current waveforms of the several dead-time effects compensation methods at 100rpm. The current command is $i_q^* = 1A$ and $i_d^* = 0A$. In this figure, the simple compensation method represents the compensation method of only the known blanking time. The compensation method of the time delay control shows that i_d current error exists at the zero-cross point of the phase current. It is originate from the phase delay shown in Fig. 9(a) and (b). Fig 12 shows current waveforms of the compensation methods by time delay control and proposed method at 400rpm and 1600rpm. Fig 12(a) and (b) show motor currents using time delay control compensation. The current error range of i_d expands with the increasing speed. However, the current waveforms of the proposed method nearly equal to the current command.

6. Conclusions

In this paper, voltage distortion of PWM VSI is analyzed with the several operating condition in the synchronous frame and in the stationary reference frame and a new on-line voltage distortion observing method for a PM synchronous motor is presented. In the analysis section, it is shown that the voltage distortion caused by the dead-time effects can be divided into two parts and the second part can be ignored for compensation because this value is very small. From the analysis results, the voltage distortion observing method is proposed using the intermediate value, A_p, instead of a direct observing voltage distortion. Using this intermediate value, the voltage distortion is observed indirectly without the phase delay of the low-pass filter. Any hardware and off-line experiments is not required for the proposed method. The simulation results show that the proposed observing and compensation method has good performance with the wide operation speed region.

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