Adaptive Dead-Time Compensation of Voltage Source Inverter for Variable Speed Drives

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Keywords: voltage source inverter, dead-time, on-line identification, permanent magnet synchronous motor

This paper proposes an adaptive dead-time compensation strategy for VSI fed motor drives. In this method, a new reference frame (γ - δ) that is synchronized with commanded current vector is introduced. The relationship between pulsations of γ -axis current and γ -axis dead time compensation voltage (DTCV) with respect to the deviation of dead time compensation time (DTCT) is investigated. Then, the following evaluation index that consists of the product of γ -axis current with the sign of γ -axis DTCV is defined.

$$\lambda = i_\gamma \operatorname{sgn}(v_\gamma^{\text{com}}). \dots\dots\dots (1)$$

Fig. 1 shows the characteristic between evaluation index and the deviation of DTCT from its nominal value for various quadrant operations. Note that the symbol Δ denotes the filtered out value of index λ . It follows that the sign of evaluation index is practically same as that of the deviation of DTCT. Furthermore the magnitude of evaluation index corresponds to that of the deviation. Accordingly, evaluation index can measure the direction as well as magnitude of the deviation of DTCT. Note that the characteristic remains unchanged irrespective of any quadrant operation.

An optimum DTCT can be found by adjusting DTCT so as to reduce the magnitude of evaluation index. Fig. 2 shows on-line identification system for optimum DTCT.

Fig. 1. Simulation results for evaluation index versus deviation of DTCT: 1st (speed > 0, torque > 0), 2nd (speed > 0, torque < 0), 3rd (speed < 0, torque < 0), and 4th (speed < 0, torque > 0)

Fig. 3 shows the experimental result of adaptive dead-time compensation for two quadrant operation. In this experiment, load torque is set at 0.315 N·m at 600 rpm, i.e., the optimum value of DTCT for 600 rpm and/or -600 rpm is 3.1 μ s. The initial value of DTCT is set at 5 μ s. The on-line identification system for DTCT acts from 0.1 s. DTCT decreases quickly and reaches the optimum value at 600 rpm. Then, DTCT is again adjusted according to rotor speed. It follows that a significant pulsation of γ -axis current hardly arises even at the transition of rotor speed. As can be expected from the simulation result in Fig. 1, the adaptive dead-time compensator successfully performs in two quadrant operation.

Fig. 2. On-line identification system for DTCT

Fig. 3. Experimental result of adaptive dead-time compensation for two quadrant operation

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This paper presents an adaptive dead-time compensation of voltage source inverter for variable speed drives. An evaluation index is developed to determine the magnitude of dead-time compensation voltage on-line. The evaluation index offers exact and quick identification. Furthermore, motor parameters are never used in this method. Experimental results verify that the distortions of phase current and commanded voltage are suppressed by applying the proposed dead-time compensation strategy.

Keywords: voltage source inverter, dead-time, on-line identification, permanent magnet synchronous motor

1. Introduction

Voltage source inverter (VSI) fed motor drives have widely been used in industry applications. Several control strategies, such as rotor position sensorless drives and direct torque control drives, need information of fundamental stator voltage. Since fundamental stator voltage cannot be detected from the output terminal of VSI, commanded voltage is usually used instead of actual one. However, commanded voltage never agrees with actual fundamental stator voltage due to undesirable properties of VSI, such as dead-time, turn-on/off time, and on-state voltage of switching devices. Dead-time is vital to avoid short-circuit of inverter legs. Turn-on/off time and on-state voltages inevitably exist in actual devices. These properties also cause waveform distortion of stator voltage as well as fundamental voltage drop.

Generally undesirable properties of VSI are compensated by introducing a dead time compensation voltage (DTCV) along with current polarity⁽¹⁾. The magnitude of DTCV depends on the dead-time compensation time (DTCT) that is composed of dead-time, turn-on/off time, and on-state voltages. Since it is difficult to measure these parameters exactly and they can vary with operating condition, it is desirable to identify DTCT. For this reason, a startup identification of DTCT was developed⁽²⁾. Although this method provides good identification result, it cannot perform on-line because this method requires a particular q -axis current command. In order to adjust the magnitude of DTCV, a look-up table, in which the relationship between the magnitude of DTCV and the peak value of phase current is characterized, was developed⁽³⁾. In this method, the magnitude of DTCV is adjusted

on-line according to the peak value of phase current. However, this method is applicable to only the specified inverter. Kim et al. estimated DTCV directly by using a disturbance observer that is developed based on the mathematical model of motor⁽⁴⁾. Although this method performs on-line irrespective of inverter characteristic, it suffers from motor parameter variations.

This paper proposes an adaptive dead-time compensation strategy for VSI fed motor drives. In this method, a new reference frame (γ - δ) that is synchronized with commanded current vector is introduced. The relationship between γ -axis current and γ -axis DTCV with respect to the deviation of DTCT is investigated. Then, an evaluation index that consists of the product of γ -axis current with the sign of γ -axis DTCV is defined. The magnitude of evaluation index measures the magnitude of deviation of DTCT, while the sign of evaluation index measures the direction of deviation of DTCT. Based on the evaluation index, DTCT is adjusted on-line. The proposed method mainly has three advantages: 1) it adjusts DTCT on-line, 2) it never uses the information of any motor parameters and inverter characteristics, and 3) it performs under any operating conditions. Experimental results are given to confirm the validity of the proposed method.

2. Dead-Time Compensation Strategy

2.1 System Configuration Fig. 1 shows typical vector controlled permanent magnet synchronous motor (PMSM) drive system. Dead-time compensator is indicated by shadowed area. The block "DTCT Identification" stands for the proposed on-line identification system for DTCT. The detail of this block is discussed in Section 3.

2.2 Dead-Time Compensation Voltage Fig. 2(a) shows channel flow of positive a -phase current ($i_a > 0$) for VSI. When a -phase leg lies in on-state, a -phase current i_a flows through switching device S_a^+ . Then, inverter output

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where T_d , t_{on} , t_{off} , V_{on} , V_{dc} , and T_s are dead-time, turn-on time, turn-off time, average on-state voltage, dc-link voltage, and switching period, respectively. Average on-state voltage is defined as

$$V_{on} = \begin{cases} \frac{T_{on}}{T_s} v_S + \frac{T_{off}}{T_s} v_D & \text{for } i_a > 0 \\ \frac{T_{off}}{T_s} v_S + \frac{T_{on}}{T_s} v_D & \text{for } i_a < 0 \end{cases} \dots\dots\dots (2)$$

where T_{on} and T_{off} are on-period and off-period of a -phase leg of VSI, respectively. Fig. 4(a) shows the experimental result for the duty factor ($D_f = T_{on}/(T_{on} + T_{off})$) of a -phase inverter output voltage versus the instantaneous value of phase current for various power factors. It follows that duty factor varies with the instantaneous value of phase current in the region of 50 %. Duty factor also depends on power factor because it relates to phase voltage rather than phase current. Fig. 4(b) shows the average on-state voltage calculated from (2) in which on-stage voltages v_S and v_D are 1.9 V and 2.5 V, respectively. As can be seen from Fig. 4(b), average on-state voltage is not the same at positive and negative values of phase current in a precise sense. However, average on-state voltage is assumed to be the same irrespective of the polarity of phase current because the difference is negligible small (within 0.05 V). This assumption is valid as long as the duty factor of inverter output voltage remains around 50%.

In order to compensate undesirable properties of VSI, the DTCVs v_{abc}^{com} are added to the commanded voltages v_{abc}^* generated from current controller in the vector controlled PMSM drive system as shown in Fig. 1. The a -phase DTCV corresponds to the average value of Δv_{AN} during switching period T_s and is derived from the above analysis as

$$v_a^{com} = \frac{T_c}{T_s} V_{dc} \text{sgn}(i_a) \dots\dots\dots (3)$$

The polarity of DTCV depends on phase current. On the

Fig. 4. Duty factor of inverter a -phase output voltage and average on-state voltage in terms of the instantaneous value of phase current for various power factors (600 rpm, 1 A)

other hand, the magnitude of DTCV depends on DTCT T_c as long as switching period T_s and dc-link voltage V_{dc} are fixed value. Note that the DTCV can compensate the impact of turn-on/off time and voltage drop of switching devices as well as dead-time because DTCT contains these parameters. The b -phase and c -phase DTCVs are also derived in similar fashion.

3. On-Line Identification of Dead-Time Compensation Time

3.1 Definition of Coordinate Axes Fig. 5 shows the definition of four coordinate axes. “ a - b - c ” is defined as flux direction due to each phase current. “ α - β ” is a stationary reference frame. “ d - q ” is the rotor reference frame that is synchronized with the rotor position of motor. “ γ - δ ” is the current reference frame that is synchronized with commanded current vector. The position angle of γ - δ axes is expressed as

$$\theta_c = \phi - \frac{\pi}{2} \dots\dots\dots (4)$$

where ϕ is the position angle of commanded current vector and is expressed as

$$\phi = \tan^{-1} \left(\frac{i_\beta^*}{i_\alpha^*} \right) \dots\dots\dots (5)$$

where i_α^* and i_β^* are commanded α - β axes currents. When phase current is distorted due to dead-time effect, distortion component arises on γ -axis at right angles to commanded current vector. Then, this paper develops an on-line identification system for DTCT based on the pulsation of γ -axis current.

3.2 Evaluation Index To investigate the relationship between the deviation of DTCT and pulsation of phase current, computer simulations for vector controlled PMSM drive as shown in Fig. 1 are executed. Simulation program has been developed by FORTRAN. The mathematical model of PMSM is expressed by simultaneous first-order differential equation and is numerically solved by the Adams method. The specifications of tested PMSM are listed in Table 1. PWM-VSI with triangular wave carrier is also implemented in the simulation program. Table 2 lists simulation parameters. To incorporate dead-time into VSI model, calculation period T_{cal} is set at $0.1 \mu s$. Since individual setting of the

Fig. 5. Definition of coordinate axes

Table 1. Specifications of tested PMSM

rated power	P_n	160 W
rated torque	τ_n	0.5 N·m
maximum rated speed	N_n	3000 rpm
armature resistance	R	2.20 Ω
armature inductance	L	0.0065 H
emf constant	K_e	0.0658 V·s/rad
number of pole-pairs	P	2

Table 2. Simulation parameters

calculation period	T_{cal}	0.1 μ s
dc-link voltage	V_{dc}	200 V
carrier frequency	f_c	5 kHz
switching period	T_s	200 μ s
DTCT (nominal)	T_{cn}	3 μ s
control period	T_{ctl}	200 μ s
proportional gain for SC	K_{ps}	0.01
integral gain for SC	K_{is}	0.20
proportional gain for CC	K_{pc}	10
integral gain for CC	K_{ic}	1000

parameters, T_d , t_{on} , t_{off} , v_S , and v_D , complicates simulation program, the DTCT defined in (1) is directly installed into VSI model. In this simulation the nominal value of DTCT is set at 3 μ s. Both the speed controller (SC) and current controller (CC) are built up with PI controllers. Control period T_{ctl} is set at 200 μ s.

Fig. 6 shows simulation result of dead-time compensation for VSI fed PMSM drive under various DTCT conditions. Note that the block “DTCT identification” in Fig. 1 does not function in this simulation. The rotor speed of PMSM is controlled at 600 rpm (driving frequency is 20 Hz). Commanded d -axis current is set at 0 A. Fig. 6(a) shows dead-time compensation result for under-compensation ($T_c = 1 \mu$ s $< T_{cn}$). Phase currents (i_a , i_b , i_c) are distorted due to inappropriate compensation. The second trace of Fig. 6(a) shows phase currents transformed into γ - δ axes. Since δ -axis is synchronized with commanded current vector, δ -axis current corresponds to the fundamental component of phase currents. Thus, δ -axis current hardly pulsates under steady-state condition. On the other hand, the distortion component of phase currents appears as γ -axis current. When phase current is distorted by dead-time effect, γ -axis current pulsates with six times of driving frequency. It is important to notice that γ -axis current i_γ is almost opposite in sign to γ -axis DTCV v_γ^{com} . Fig. 6(b) shows dead-time compensation result for optimum compensation ($T_c = T_{cn} = 3 \mu$ s). It can be confirmed that phase currents are hardly distorted. As a result, γ -axis current seldom pulsates. Fig. 6(c) shows dead-time compensation result for over-compensation ($T_c = 5 \mu$ s $> T_{cn}$). As contrasted with Fig. 6(a), the sign of γ -axis current is almost same as that of γ -axis DTCV.

It follows from above inspection that the deviation of DTCT from its nominal value is measured from the magnitude of γ -axis current pulsation. Furthermore, the direction of deviation is determined from the relationship between signs of γ -axis current and γ -axis DTCV. To quantify the above feature, the following index is defined:

$$\lambda = i_\gamma \text{sgn}(v_\gamma^{com}). \quad (6)$$

Index λ is shown at the bottom trace in Fig. 6. As can be seen

(a) Under-compensation ($T_c = 1 \mu$ s) (b) Optimum compensation ($T_c = 3 \mu$ s) (c) Over-compensation ($T_c = 5 \mu$ s)Fig. 6. Simulation results of dead-time compensation for various DTCT conditions (600 rpm, 1 A, $T_{cn} = 3 \mu$ s)

from this figure, index λ is negative for under-compensation, but positive for over-compensation. Furthermore, the index becomes almost zero for optimum-compensation. Thus, DTCT can be identified based on index λ . Practically, the pulsation component of index λ is filtered out. The filtered value of index λ is referred to as the evaluation index Λ .

Fig. 7 shows the characteristic between evaluation index and the deviation of DTCT ($\Delta T_c = T_c - T_{cn}$) for various operating conditions. Fig. 7(a) shows the characteristic for various speed conditions. It follows that the sign of evaluation index is practically same as that of the deviation of DTCT. Furthermore, the magnitude of evaluation index corresponds to that of the deviation. Accordingly, evaluation index can measure the direction as well as magnitude of deviation of DTCT. This relation is maintained for any rotor speed. Fig. 7(b) shows the characteristic for various quadrant operations. It follows that the characteristic remains unchanged irrespective of any quadrant operation.

3.3 On-line Identification System for DTCT As can be seen from Fig. 7, an optimum DTCT can be found by adjusting DTCT so as to reduce the magnitude of evaluation

index. Fig. 8 shows on-line identification system for optimum DTCT. Firstly, the commanded d - q axes current are transformed into stationary reference frame. Then, position angel of γ - δ axes is calculated by using (4) and (5). Phase currents and phase DTCVs are transformed into γ -axis components by using position angle θ_c . Then, index λ is calculated by multiplying γ -axis current i_γ by the sign of γ -axis DTCV v_γ^{com} . To clear off the harmonics of index λ , a low-pass filter (LPF) is used. The fundamental frequency (f_λ) of index λ is six times of that of phase current. The cut-off frequency of LPF is set such that the gain of LPF at f_λ becomes -40 dB, i.e.,

$$f_{LPF} = f_\lambda \times 0.05. \dots\dots\dots (7)$$

Using the evaluation index Λ that is the filtered out value of index λ , DTCT is adjusted by the following adjustment rule.

$$T_{ck+1} = T_{ck} - K_{pt}\Lambda_k \dots\dots\dots (8)$$

where K_{pt} is the proportional gain. The adjustment rule is intuitive, that is, it means that DTCT is corrected up as far as evaluation index Λ becomes zero. The amount of correction depends on the evaluation index Λ_k and is adjusted by the proportional gain K_{pt} . Fig. 9 shows the simulation result for the convergence property of DTCT. Based on the trade-off between convergence rate and overshoot, the value of K_{pt} has been chosen at 0.01. The value is constant irrespective of operating condition.

The proposed adjustment method is superior to the method presented by Zhao et al. ⁽⁵⁾ in terms of convergence property.

(b) Characteristics for various quadrant operations: 1st (speed > 0, torque > 0), 2nd (speed > 0, torque < 0), 3rd (speed < 0, torque < 0), and 4th (speed < 0, torque > 0)

Fig. 7. Simulation results for evaluation index versus deviation of DTCT ($\Delta T_c = T_c - T_{cn}$)

Fig. 8. On-line identification system for DTCT

Fig. 9. Simulation result for the convergence property of DTCT. (initial value T_{c0} : 5 μs , nominal value T_{cn} : 3 μs)

The major difference between two methods is how to measure the deviation of DTCT. In Reference (5), the deviation is measured by the absolute value of harmonic current error. It cannot distinguish the direction of deviation. Actually, the adjustment of DTCT is based on the Hill Climbing method. In addition, the amount of correction does not directly depend on current error. These features make it difficult for smooth adjustment. In contrast, the evaluation index Λ in the proposed method can measure the direction as well as magnitude of deviation of DTCT. This leads to appropriate direction and size of correction. As a result, a smooth adjustment of DTCT is realized.

4. Experimental Results

4.1 Experimental Setup To confirm the validity of the proposed method, experimentations for dead-time compensation have been executed on the vector controlled PMSM drive system illustrated in Fig. 1. The SC, CC, and dead-time compensator are implemented on DSP TMS320C32. The block “DTCT Identification” stands for the on-line identification system for DTCT shown in Fig. 8. A gate driver generates PWM gate signal for VSI. Phase current and rotor position are incorporated into DSP via analog-digital converter (ADC) and counter board, respectively. The specification of VSI (IGBT module) is listed in Table 3. A tested PMSM with the specifications identical to those of computer simulation is utilized for this experimentation. A permanent magnet synchronous generator (PMSG) with same specifications of tested PMSM is utilized for load system. The electrical output power of PMSG is commutated by rectification circuit and consumed by an electronic dc load apparatus. Output torque τ is detected with the help of torque transducer (TT).

4.2 Comparison between adaptive and fixed DTCTs

Fig. 10 draws a comparison of the performance between dead-time compensator with fixed and adaptive DTCTs. The rotor speed of PMSM is set at 600 rpm. Commanded d -axis current is set at 0 A. A step load change ($\tau = 0.315 \text{ N}\cdot\text{m}$) is applied to PMSM.

Fig. 10(a) shows the experimental result for dead-time compensator with fixed DTCT ($T_c = 1.1 \mu\text{s}$). This is the optimum value for no-load condition at 600 rpm. Note that preliminary experiment has investigated evaluation index for various DTCTs with $0.1 \mu\text{s}$ step size to find an optimum value of DTCT at given operating condition. As can be seen from Fig. 10(a), evaluation index is almost zero under no-load condition. However it has negative value under load condition, i.e., the DTCT is less than the optimum one. As a result, the pulsation of γ -axis current increases during applying load torque to PMSM. Fig. 10(b) also shows the experimental result for fixed DTCT. In this case, the DTCT optimized at load

Table 3. Specifications of VSI

maximum rated voltage	$V_{\max}$	600 V
maximum rated current	$I_{\max}$	30 A
dead-time for IGBT	T_d	$5.0 \mu\text{s}$
turn-on time of IGBT	t_{on}	$0.6 \mu\text{s}$
turn-off time of IGBT	t_{off}	$2.0 \mu\text{s}$
on-state voltage of IGBT	v_S	1.9 V
on-state voltage of diode	v_D	2.5 V

Fig. 10. Experimental results of dead-time compensation for step load change at 600 rpm

(a) a-phase current

(b) a-phase commanded voltage

Fig. 11. Comparison of waveform of phase current and commanded voltage for various DTCTs under no-load condition

condition ($\tau = 0.315 \text{ N}\cdot\text{m}$) is utilized for dead-time compensation. In contrast with Fig. 10(a), evaluation index becomes almost zero under load condition. On the other hand, it has positive value under no-load condition, i.e., DTCT is greater than the optimum one. The pulsation of γ -axis current confirms that the setting value of DTCT is inappropriate under no-load condition. Fig. 10(c) shows the experimental result for adaptive DTCT. The DTCT successfully varies with step load change. As a result, evaluation index in steady state becomes zero irrespective of load condition. It can be also confirmed that γ -axis current hardly pulsates at any load condition.

Fig. 11 shows phase current and commanded voltage for various DTCTs under no-load condition. In this condition, the optimum value of DTCT is $1.1 \mu\text{s}$. As can be seen from Fig. 11(a), the dead time compensator with the optimum DTCT ($T_c = 1.1 \mu\text{s}$) suppresses the distortion of phase current. On the other hand, the inaccurate DTCT ($T_c = 3.1 \mu\text{s}$) causes an undesirous increase in the magnitude of DTCV. As a result, the distortion of phase current increases. It can be confirmed that the proposed dead-time compensator with adaptive DTCT successfully performs, i.e., the distortion of phase current is reduced at the same level as the optimum one. It follows from Fig. 11(b) that the commanded voltage for $T_c = 3.1 \mu\text{s}$ suffers fundamental voltage drop. Such a voltage error impact the control strategies that include the estimation of flux linkage.

(a) a-phase current

(b) a-phase commanded voltage

Fig. 12. Comparison of waveform of phase current and commanded voltage for various DTCTs under load condition ($\tau = 0.315 \text{ N}\cdot\text{m}$)

Fig. 12 shows phase current and commanded voltage under load condition ($\tau = 0.315 \text{ N}\cdot\text{m}$). The optimum value of DTCT in this condition is $3.1 \mu\text{s}$. Fig. 12(a) compares phase current for various DTCTs. There is few difference in the distortion of phase current. As can be seen from Fig. 10(a), γ -axis current for $T_c = 1.1 \mu\text{s}$ heavily pulsates during applying load torque to PMSM. Nevertheless, a noticeable distortion of phase current does not occur because γ -axis current is much less than δ -axis current under load condition. Note that a feedback controller also assists dead-time compensator in suppressing the distortion of phase current. Then, the effect of inaccuracy of DTCT on phase current can be compensated. Thus, the accuracy of DTCT is not important issue about the distortion of phase current as long as the magnitude of phase current is sufficiently large. In the mean time, the assist of feedback current controller causes undesirous commanded voltage. As can be seen from Fig. 12(b), the magnitude of commanded voltage for $T_c = 1.1 \mu\text{s}$ is greater than the optimum one (for $T_c = 3.1 \mu\text{s}$). In other words, commanded voltage increases so that a feedback current controller can make up for defective dead-time compensator.

It can be confirmed from experimental results that both the phase current and commanded voltage are hardly distorted irrespective of operating condition when the proposed dead-time compensator with adaptive DTCT is incorporated into vector controlled PMSM drive system.

4.3 Four Quadrant Operation Fig. 13 shows the

Fig. 13. Experimental result of adaptive dead-time compensation for two quadrant operation

Fig. 14. Simulation result of adaptive dead-time compensation for four quadrant operation

experimental result of adaptive dead-time compensation for two quadrant operation (1st: speed > 0, torque > 0 and 3rd: speed < 0, torque < 0). Because of the property of load system, load torque depends on rotor speed. This allows only two quadrant operation. In this experiment, load torque is set at 0.315 N·m at 600 rpm, i.e., the optimum value of DTCT for 600 rpm and/or -600 rpm is 3.1 μs. The initial value of

DTCT is set at 5 μs. The on-line identification system for DTCT acts from 0.1 s. DTCT decreases quickly and reaches the optimum value at 600 rpm. Then, DTCT is again adjusted according to rotor speed. It follows that a significant pulsation of γ-axis current hardly arises even at the transition of rotor speed. As can be expected from the simulation result in Fig. 7(b), the adaptive dead-time compensator successfully performs in two quadrant operation. Fig. 14 shows the simulation result for four quadrant operation. The initial value of DTCT is set at 5 μs while the optimum value is 3 μs. The on-line identification system starts from 2 s. DTCT is smoothly adjusted in spite of the change of quadrant. It can be confirmed that the pulsation of γ-axis current is immediately reduced after 2 s. This simulation result validates that the proposed dead-time compensation performs in four quadrant operation.

5. Conclusions

This paper has proposed an adaptive dead-time compensation strategy for VSI fed motor drives. An evaluation index has been defined in this paper, then it is used for adjusting the magnitude of DTCV, i.e., DTCT on-line. In the proposed method, DTCT can be adjusted without any knowledges of both inverter characteristics and motor parameters. Furthermore, the proposed strategy successfully performs under any operating condition. Experimental results of dead-time compensation for PMSM drive confirm that the proposed method provides appropriate adjustment of DTCT. Also, the experimental results indicate the following analyses: 1) an accuracy of DTCT has a significant impact on phase current under light load condition. The effect under heavy load condition is reduced with the aid of a feedback current controller. 2) On the other hand, an impact of the accuracy of DTCT on commanded voltage is important issue irrespective of load condition.

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