Paper

Position Estimation System for PMSM Position Sensorless Control in Inverter Overmodulation Drive

Kosuke Kondo[*]   Student Member,   Shinji Doki[*]   Senior Member

This study investigates compensation methods for harmonic components to realize PMSM position sensorless control in inverter overmodulation drive. While applying PMSMs as traction motor motors in an EV or HEV, operating PMSM in inverter overmodulation drive is an effective method to widen high-speed drive region of PMSM and achieve fast torque response when voltage saturates because it enable to utilize 27% higher fundamental voltage as compared to linear drive. In addition, position sensorless control is regarded as an important technique for adding a fail-safe function and downsizing of the drive system. However, the harmonic components which are inevitably generated in inverter overmodulation drive have negative effects on closed current control and position estimation systems.

The key to realize position sensorless control in inverter overmodulation drive is an appropriate compensation for the harmonic components in the input voltage and input current of a the position estimator. There are several methods to achieve this, and differences in position estimation performance possibly exist among these methods.

In this study, the compensation methods for harmonic components in overmodulation drive are compared, and a suitable compensation method for sensorless control is investigated through an experiment.

Keywords: PMSM, position sensorless control, overmodulation drive, harmonics compensation

1. Introduction

In recent years, Permanent Magnet Synchronous Motors (PMSMs) are successfully being applied to various fields such as railway vehicle, electric vehicle (EV), hybrid electric vehicle (HEV), electric appliance or industry fields for their compactness, high power density and high efficiency [1][2].

Vector control is a most commonly used control method to operate PMSMs for accurate torque control and fast torque response. Rotor position information is required to operate current vector control system, therefore, position sensor is generally needed. However, position sensor increases the axial length of the PMSM, resulting in the reduction of torque density per unit volume. In addition, it can deteriorate the robustness of the drive system, both electrically and mechanically. Therefore, position sensorless control methods have been attracting a great interest and have been widely studied [3]–[7].

Upon the application of PMSMs as traction motor of EV or HEV, power output/torque density per unit volume is being an important requirement [8]. To widen the speed drive region of PMSMs, higher DC link voltage is needed. A simple solution is the expansion of the battery unit. However, this is an undesirable way from the aspect of cost, weight and installation space. From these background, inverter overmodulation drive has widely been studied [9]–[15]. Overmodulation drive enables to utilize 27% higher inverter output voltage compared to linear drive without expanding the system hardware.

Position sensorless control technique in the overmodulation

drive is, of course, a important requirement upon the various application of PMSM drive for adding fall-safe function and downsizing of the drive system. Hence it have already been considered as a suitable solution to satisfy these requirements and several researches are already reported that harmonic voltage and harmonic current unavoidably generated in the overmodulation drive has negative effect to the closed current control system [16]–[18]. However, the harmonic components included in voltage and current caused by overmodulation has negative effect to not only the closed current control system but also the position estimation system in case of position sensorless drive.

So far, we revealed the problem of conventional position estimation system in the overmodulation drive, and presented one solution for improving position estimation [16][19]. The facts revealed in the previous study is summarized as follows.

(a) Performance of conventional position estimation system based on the electromotive force, is deteriorated in the overmodulation drive.

(b) Low-order harmonics caused by overmodulation, which are included in voltage and current, leads to the position estimation error.

(c) Appropriate compensation of the harmonic components effectively works to improve the position estimation performance in overmodulation drive.

Namely, the key to realize position sensorless control in inverter overmodulation drive is an appropriate compensation to the harmonic components in the input voltage and current to the position estimator. Based on these concepts, we have proposed a position sensorless control system for over modulation drive [16]. To realize the concept, however, other approaches are possible and some differences in the

* Nagoya University
 Fro-cho, Chikusa-ku, Nagoya 464-8603, Japan

position estimation performance possibly exist among those. This paper shows those methods and make a comparison between those compensation methods of low-order harmonics included in voltage and current caused by overmodulation. This paper is organized as follows. Firstly, the problems of conventional position sensorless system in overmodulation drive and previous work [19], which is able to improve the position estimation performance in overmodulation drive by compensating low-order harmonics included in voltage and current caused by overmodulation, is described. Next, some compensation methods of the low-order harmonics for position estimation system are shown and the difference between them are discussed. Lastly, experimental results for comparing the harmonics compensation methods are presented and the suitable method for sensorless control in overmodulation drive is discussed.

2. The Problems of Conventional Position Estimation System in the Overmodulation Drive

Firstly, the problems of vector control with position sensor in the overmodulation range and methodologies for operation in the overmodulation drive is reviewed. Then the problems of position sensorless control system, which consists of the vector control improved for overmodulation drive and a conventional position estimator are presented.

2.1 Vector Control with Position Sensor in Overmodulation Drive As mentioned in the introduction, in the overmodulation drive, it is possible to use 27% higher inverter output voltage than the linear range with same DC link voltage at the maximum. However, harmonic voltage and current unavoidably generated in the overmodulation drive has negative effect to the closed current control system.

The harmonic components affect the current control system as follows:

(1) Low-order harmonic current generated by the harmonic components in the output voltage is fed back to the current controller.

(2) Conventional current controller which has wide band works to suppress the low-order harmonics current.

(3) As a result, keeping high modulation rate is being difficult and limited voltage can not be effectively used for driving a motor in a wider operating range and then become unstable in the worst case.

To deal with these problems, a current control system with compensator for the harmonic components (harmonic current estimator) has been proposed in Ref. (14). This system has harmonic current estimator which estimates low-order harmonics voltage and current. The harmonic current estimator is composed of inverter model and harmonic current model to estimate low-order harmonics voltage and current. By subtracting the estimated harmonic current from the feedback current, the inverter works as if there were no harmonic current so as not to suppress it. Hence this system enables PMSM to use the voltage generated in the overmodulation range effectively.

2.2 Problems of Applying Conventional Position Estimation System in Overmodulation Drive [19] This section discusses the position sensorless control system which consists of the vector control improved for overmodulation drive shown in Ref. (14) and a conventional position
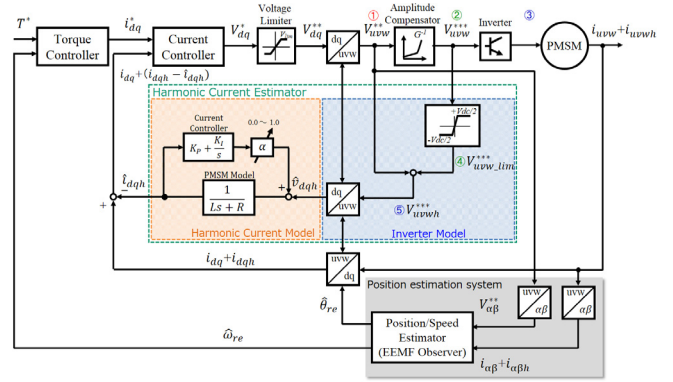

Fig. 1. System diagram of the conventional position sensorless vector control system
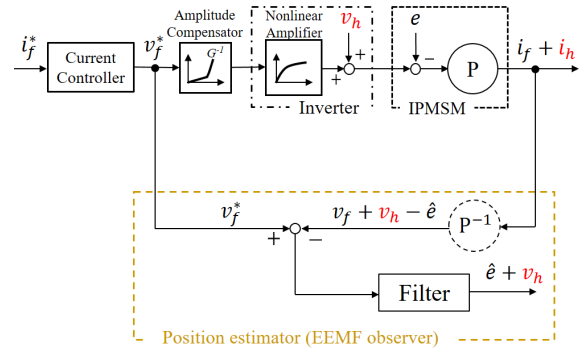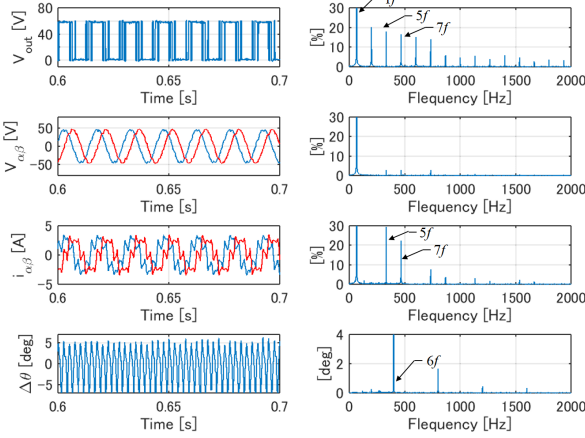

Fig. 2. Conventional position estimation system for overmodulation drive

estimator. The system diagram is shown in Fig. 1. Because the input-output relation of inverter becomes non-linear in overmodulation drive, amplitude compensator is given to the control system as shown in Fig. 1. Extended electromotive force(EEMF) observer [3][4] is assumed for the position estimation system since overmodulation drive is utilized at the voltage saturation region.
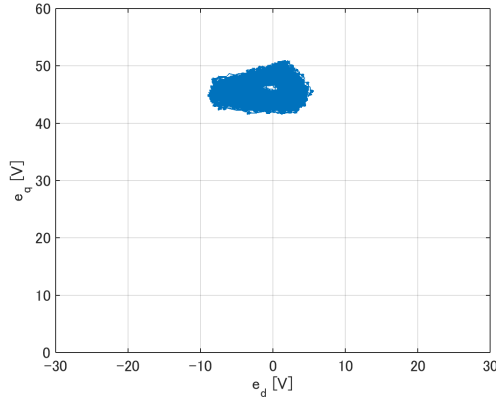
Figure 2 shows the system diagram of the conventional position estimation system in overmodulation drive. Voltage and current are defined as v_f and i_f for fundamental components and v_h and i_h for harmonic components respectively in Fig. 2. v_f in Fig. 2 is equivalent to the voltage command value to the amplitude compensation (V_{uvw}^{**}) in Fig. 1. In this system, the voltage command value is simply used for the input voltage value of the position estimator.

In linear drive, the inverter output voltage in the linear range mainly consists of fundamental components and carrier components because the inverter can be regard as a linear amplifier. On the other hand, carrier components does not include in voltage command value. Therefore, the frequency components of the input voltage and current to the position estimator do not correspond. However, it's actually not a significant difference to the estimation of EEMF and the rotor position since the frequency components of the carrier components is higher enough compared to the control band of position estimator.

On the other hand, as mentioned in the previous section, in overmodulation drive, the inverter characteristic become nonlinear, consequently generating the low-order harmonic components. As in linear drive, the frequency components

(a) Waveforms & Frequency spectrum

(b) Locus of estimated extended-EMF vector

Fig. 3. Various quantities of EEMF observer and the position estimation error (conventional method: system A)

Table 1. Parameters of test IPMSM

pole pairs	P_n	2
EMF. constant	K_e	0.0912 V/(rad/s)
winding resistance	R	0.45 Ω
d-axis inductance	L_d	4.15 mH
q-axis inductance	L_q	16.74 mH

Table 2. Condition of experimental set

Inverter carrier frequency	f_c	10000 Hz
DC link voltage	V_{DC}	60 V
Current limit	I_{max}	5 A
Dead time		4 μs
Bandwidth of current controller	ω_{cc}	3000 rad/s
Current control period	T_{cc}	100 μs
Voltage limiter method		constant d-axis voltage
Antiwindup calculation method		stop integration
Modulation method		Triangle-wave PWM

3. Compensation Methods of the Low-order Harmonics for Position Estimation System in Overmodulation Drive

As in the previous section, the main cause of the position estimation error in overmodulation drive is the difference of harmonic components of input voltage and current for position estimator which comes with in the control band, namely the low-order harmonic components. This section discusses about some different compensation methods of the low-order harmonics for position estimation system and the differences between them.

3.1 Compensation Methods of the Low-order Harmonics for Position Estimation System Table 3 shows the constitutions of the position estimation system being discussed in this paper. As shown in Table 3, there are some compensation methods to make input signal corresponding.

System *A* is the conventional position estimation system (incorrespondence harmonic components between input signals). As system B and C make harmonic components between input signals corresponding, both of them can have superior performance to system A. One of aims in this paper is to clarify and compare the performance of those position estimation systems.

Note that these two systems differs in harmonic components corresponding between input signals, they, therefore, lead to the difference in the EEMF estimation results. In the next section, a discussion about the EEMF estimation characteristics of system B and C are presented.

3.2 Relations between Input Signals for EEMF Observer and the Estimation Characteristics In this section, the estimation characteristics of EEMF in the overmodulation drive are discussed, focusing on the harmonic components of the input voltage and current to position estimator.

The EEMF[3] are represented by

$$\boldsymbol{e} = \{\omega_{re}K_E - (L_q - L_d)(\omega_{re}i_d - \dot{i}_q)\}\begin{bmatrix} -\sin\theta_{re} \\ \cos\theta_{re} \end{bmatrix} \cdots (1)$$

where, i_d, i_q, L_d and L_q are the d- and q-axis current, and inductances, R is the stator winding resistance, ω_{re} is the electric angular velocity, K_e is the back EMF constant and then $\dot{i}_q$ is q-axis current differential value. As you can see from Eq. (1), the amplitude of the EEMF has current differential

of the input voltage and current to the position estimator do not correspond. However, the difference arises from the low-order harmonic components. The problem is that the frequency components of the low-order harmonic components generally comes within the control band of position estimator. Therefore, in this case, the difference may lead to a significant estimation error of EEMF and the rotor position.

Experimental result to confirm the fact about the conventional system in overmodulation drive is shown in Fig. 3. In this experiment, torque command value were set to $0.6Nm(10\%)$ at $1800min^{-1}$. Operation point belongs to overmodulation drive. V_{out}, $V_{\alpha\beta}$, $i_{\alpha\beta}$ and $\Delta\theta$ in Fig. 3(a) represents the output voltage, input voltage, input current, position estimation error, respectively. The parameters of the test motor and the setting condition are shown in Table 1 and Table 2. The DC link voltage is set to 60 V to make voltage saturation likely to occur. As shown in Fig. 3(a), input current components contain fundamental component and harmonic components. On the other hand, input voltage components contain fundamental components. Figure 3(b) shows the locus of the estimated EEMF vector on the d-q coordinate. As in Fig. 3(b), the locus of the estimated EEMF which is ideally pointing to the direction of q-axis is vibrating to the direction of d-axis. Consequently, the position estimation error in Fig. 3(a) arose.

Table 3. Position estimation systems discussed in this paper

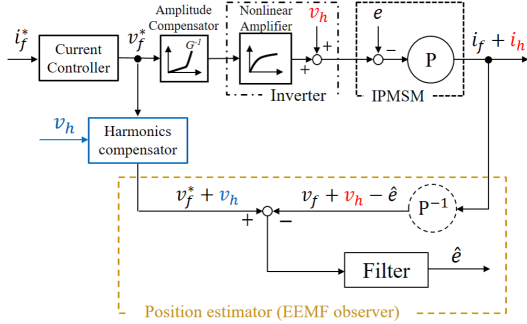| Position estimation system	Input voltage signal	Input current signal	Correspondence of harmonic components between input signals
System *A* (Fig. 2)	Command value	Measured value	×
System *B* (Fig. 4)	Compensated value	Measured value	○ (Fundamental + low-order harmonic components)
System *C* (Fig. 5)	Command value	Compensated value	○ (Fundamental components)

Fig. 4. The position estimation system with harmonics voltage compensator (System B)
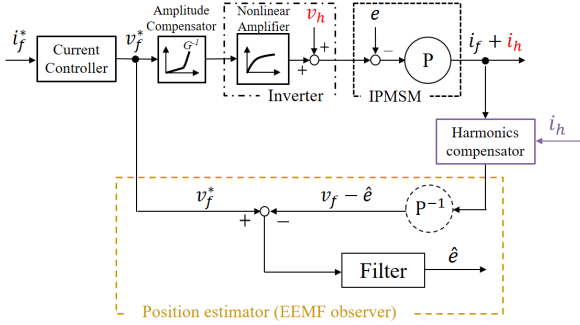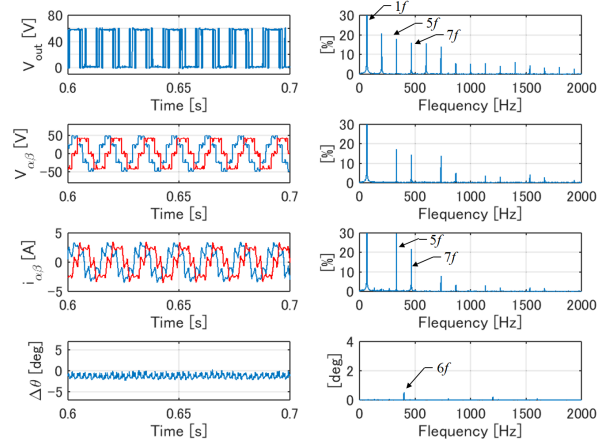

Fig. 5. The position estimation system with harmonics current compensator (System C)

(a) Waveforms & Frequency spectrum

(b) Locus of estimated extended-EMF vector

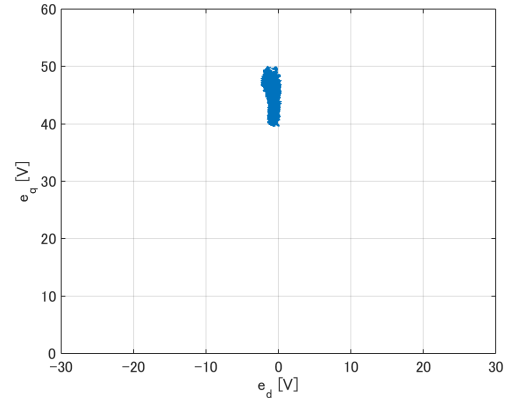Fig. 6. Various quantities of EEMF observer and position estimation error (System B)

terms. Thus the amplitude of the EEMF is a variable which behaves quite differently depending on the inverter drive region. In overmodulation drive, the amplitude of the EEMF changes depending on the harmonics current generated.

In system B, as EEMF observer input contains the low-order harmonic components, the amplitude of the EEMF vibrates due to the current differential terms in Eq. (1). On the other hand, in system C, input signals are corresponded to as only fundamental components for the EEMF observer input as in linear drive. As a result, both the amplitude and the phase of the EEMF does not vibrate as in linear drive. Experiments were carried out to confirm the discussion in the previous section, under the same conditions as Fig. 3. Figure 6 and Fig. 7 show the position estimation results by each method to make the harmonic components between input signals corresponding. In this experiment on Fig. 7, Filter method which extract fundamental components were applied as compensation method.

As you can see from Fig. 6(a) and Fig. 7(a), each method made the harmonic components corresponding. Compared to the conventional method, the vibration of the estimated EEMF in the direction of d-axis is suppressed as in Fig. 6(b) and Fig. 7(b). Consequently, rotor position estimation became stable compared to the conventional method (Fig. 3(a)). Therefore, it can be said that correspondence of harmonic

components between the input signals is effective for improving the position estimation performance in the overmodulation range. And, as shown in Fig. 6(b) and Fig. 7(b), the loci of estimated EEMF vector behaved differently. From the above, the discussion in the previous section was confirmed to be a fact experimentally.

4. Study on Compensation Method for Correspondence of Harmonic Components between Input Signals for the Position Estimator

In the previous section, it is confirmed that correspondence of harmonic components between input signals for the position estimator is necessary for improving the position estimation performance in overmodulation drive. This section presents a comparison of compensation methods for harmonic components, that make harmonic components between the input signals corresponding (summarized in Table 4).

Table 4. Each constitution of the position estimation system

	Position estimation system			Characteristics	
	Correspondence of components between input signals	Voltage compensation	Current compensation	Steady state	Transient state
System A	-	-	-	-	-
System B	Fundamental + low-order harmonic components	○	-	○	○
System C1	Fundamental components	-	○：**Filter-based**	○	Phase delay
System C2	Fundamental components	-	○：**Model-based**	Modeling error	

(a) Waveforms & Frequency spectrum

(b) Locus of estimated extended-EMF vector

Fig. 7. Various quantities of EEMF observer and position estimation error (System C)

(a) Actual inverter output voltage (b) Estimated inverter output voltage

Fig. 8. Comparison of output voltage and frequency spectrum in overmodulation drive

4.2 Compensation Method for Correspondence of Input Signals Components without Low-order Harmonic Components (System C)　　This section describes the method, that eliminates incorresponding harmonic components from input signals (Fig. 5). As in Fig. 5, current sensor value ($i_f + i_h$) is processed through the harmonics compensator. Harmonics compensator eliminate i_h and extract i_f, thus frequency components of the input current is corresponding to the one of the input voltage, without low-order harmonics. It can be solved by applying the compensation, which eliminates harmonics components i_h, in position estimation system. There are following two compensation methods for eliminating harmonics components.

(a) Filter-based compensation (System C1)
Elimination of the harmonics current (i_h) and extraction of the fundamental current (i_f) by Low Pass Filter (LPF) or Band Pass Filter (BPF) [20]

(b) Model-based compensation (System C2)
Elimination of the harmonics current (i_h) and extraction of the fundamental current (i_f) by subtraction of the estimated harmonics current [14]

This process is similar to the compensation of the feedback current described in section 2.1. The effect of LPF or BPF of System C1 are similar to that of filter in the EEMF observer. However changing bandwidth of filter, which means change of pole assignment of the observer may cause the deterioration of transient response and robustness [19]. In this paper, authors distinguished between the two methods and executed the evaluation under same design of EEMF observer, focusing to methods for corresponding to input signal.

4.3 Comparison with the Characteristics of Each Compensation Method　　This section presents a brief discussion about System B and C (C1 and C2) from the aspect of the procedure for position estimation.

As described in section 4.1, System B estimates inverter output voltage using the voltage command value and the inverter model. The objective of the inverter model emulates the voltage saturation at the voltage limit value, and this process is independent from the motor model/parameter.

4.1 Compensation Method for Correspondence of Input Signals Components Including Low-order Harmonic Components (System B)　　This section describes the method, that compensates input signals for incorresponding harmonic components (Fig. 4). As in Fig. 4, voltage command of the current controller v_f^* is processed through the harmonics compensator. Harmonics compensator estimates the inverter output voltage containing harmonics voltage v_h using the inverter model. Thus frequency components of the input voltage is corresponding to ones of the input current ($i_f + i_h$). Figure 8 shows waveforms of the inverter output voltage and the estimated voltage by inverter model on the upper and frequency spectrum on the lower. As can be seen in Fig. 8, the inverter output voltage containing low-order harmonics current is accurately estimated by the inverter model. This is the position estimation system the authors have proposed in Ref. (16).
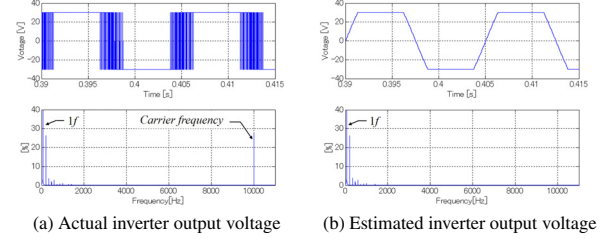
(a) System A: Conventional method (No compensation)

(b) System B: Voltage compensation method

(c) System C1: Filter-based current compensation method

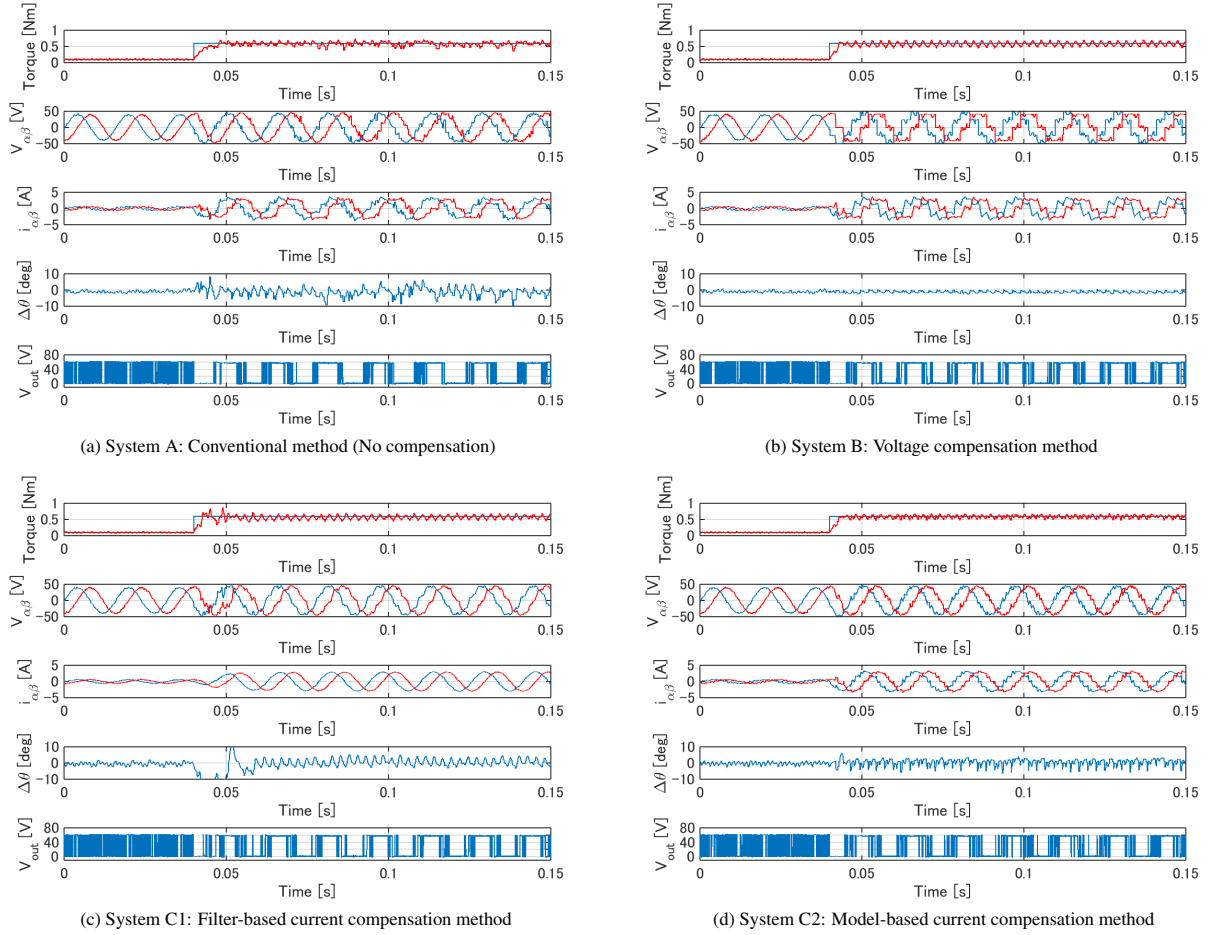(d) System C2: Model-based current compensation method

Fig. 9.   Results of torque step experiment

Accordingly, deterioration of position estimation performance due to the modeling error of the motor does not occur in System B.

The discussion about System C is quite similar to that of the signal separation techniques for low speed sensorless control performed in Ref. (21). Although filter-based compensation method (System C1) is a suitable solution in steady state, phase delay due to the filter characteristics is an unavoidable problem in transient state. Model-based compensation method (System C2) does not have a concern about transient characteristics. However, modeling error is an unavoidable problem since this method utilizes the motor model and the current controller model, possibly result in position estimation error.

The constitution and the characteristic of each position estimation system is summarized in Table 4.

5.   Evaluation of Compensation Methods for Harmonic Components

Experiments were carried out to evaluate the static/transient characteristics of compensation methods discussed in the previous section (see Table 4). The test motor and the setting condition were the same as the previous experiment (Table 1 and Table 2). Torque command value were stepwise given as $0.1Nm$ (10%) to $0.6Nm$ (50%) at $1800min^{-1}$ at the rotor position of $0deg$. Operation point after change belongs to overmodulation drive.

Figure 9 shows the experimental results: torque, input voltage and current to position estimator ($V_{\alpha\beta}$ and $i_{\alpha\beta}$), position estimation error ($\Delta\theta$) and inverter output voltage (V_{out}) from top to bottom. As in Fig. 9(a) (System A: Conventional method), large position estimation error arose in overmodulation drive both in the steady state and the transient state due to the uncorrespondence of input voltage/current frequency.

On the other hand, as in Fig. 9(b) (System B: Voltage compensation method [16]), position estimation was stably realized in both state, just as discussed in the previous section.

In Fig. 9(c) (System C1: Filter-based current compensation method), position estimation is stably realized in the steady state, however, the phase lag due to the application of LPF can be seen, resulting in the deterioration of the transient characteristics. Estimation error in transient state is reduced in Fig. 9(d) (System C2: Model-based current compensation method) compared to Fig. 9(c). However, the estimation error arose in the steady state due to the remaining harmonics current, probably caused by the modeling error caused by the magnetic saturation [14]. The modulation index at operation point after change were 1.19 (Fig. 9(a)), 1.20 (Fig. 9(b)), 1.20 (Fig. 9(c)) and 1.19 (Fig. 9(d)).

From the above, System B proposed by the authors in Ref. (16) is confirmed to be the most suitable compensation method, that harmonic components of input signals corresponding to the position estimator from the aspect of the position estimation performance.

6. Conclusions

For improving the position estimation in overmodulation drive, this paper discusses compensation methods of low-order harmonics included in voltage and current caused by overmodulation.

This paper is concluded as follows:

(1) Presented two methods to improve position estimation performance in overmodulation drive

(2) Discussed a comparison of compensation methods for harmonics components, which makes harmonic components of input signals for position estimator corresponding from the aspect of improvement of position estimation in overmodulation drive

(3) Confirmed that the methods by authors in Ref. (16) is suitable compensation methods through experiments

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Appendix

In appendix, details of harmonic current compensator for system C are described.

1. Details of Harmonic Current Compensator

1.1 Filter-based Harmonic Compensation The transfer function of BPF and LPF represent below.

$$G_{BPF}(s) = \frac{\dfrac{\omega_0}{Q} s}{s^2 + \dfrac{\omega_0}{Q} s + \omega_0^2} \cdots\cdots\cdots\cdots\cdots (A1)$$

where, ω_0 is the center frequency and ω_0 is the center frequency. ω_0/Q represents pass-band of BPF. The center frequency is set to frequency which extract only fundamental components. Eq. (A1) is a frequency variable band-pass-filter, and the center frequency is set to the fundamental frequency.

$$G_{LPF}(s) = \frac{1}{s + \omega_n} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (A2)$$

where, ω_n represent cut-off frequency, and is set to frequency which extract only fundamental components.

1.2 Model-based Current Compensation The model-based current compensation is calculated by substituting the harmonic voltage estimated into the harmonic current model below [14].

$$
\begin{bmatrix} \dot{\widehat{i}}_{dh} \\ \dot{\widehat{i}}_{qh} \\ \dot{\widehat{e}}_{dh} \\ \dot{\widehat{e}}_{qh} \end{bmatrix} =
\begin{bmatrix}
-\left(\dfrac{R + aK_{pd}}{L_d}\right) & 0 & \dfrac{aK_{id}}{L_d} & 0 \\
0 & -\left(\dfrac{R + aK_{pq}}{L_q}\right) & 0 & \dfrac{aK_{iq}}{L_q} \\
-1 & 0 & 0 & 0 \\
0 & -1 & 0 & 0
\end{bmatrix}
$$

$$
\times \begin{bmatrix} \widehat{i}_{dh} \\ \widehat{i}_{qh} \\ \widehat{e}_{dh} \\ \widehat{e}_{qh} \end{bmatrix} +
\begin{bmatrix} 1/L_d & 0 \\ 0 & 1/L_q \\ 0 & 0 \\ 0 & 0 \end{bmatrix}
\begin{bmatrix} \widehat{v}_{dh} \\ \widehat{v}_{qh} \end{bmatrix} \cdots\cdots\cdots\cdots (A3)
$$

$$0 \le a \le 1$$

where, $[\hat{i}_{dh}, \hat{i}_{qh}]^T$ and $[\hat{v}_{dh}, \hat{v}_{qh}]^T$ represent the estimated harmonic current and the harmonic voltage, and $[\hat{e}_{dh}, \hat{e}_{qh}]^T$ represents the estimation error. K_{pq}, K_{pd}, K_{iq} and K_{id} are d- and q-axis proportional gain and integral gain of current controller. a works as a factor to adjust the time constant of the harmonic current model. Harmonic current model extracts fundamental components by subtracting the estimated harmonic current from the feedback current.

Kosuke Kondo (Student Member) was born in Aichi, Japan, in 1991. He received the B.E. and M.E. degrees in electrical engineering from Nagoya University in 2014 and 2016. Since 2016, he has been a Researcher with DENSO Corporation. His research interests include control, power electronics and motor drive.

Shinji Doki (Senior Member) was born in Nagoya, Japan, in 1966. He received the B.E., M.E. and Ph.D. degrees in Electronic-mechanical Engineering from Nagoya University, Japan in 1990, 1992 and 1995, respectively. Since 2012, he has been a Professor at Nagoya University, Japan. His research interests include control, modeling, signal/information processing and their application to motor drive systems. Prof. Doki was a recipient of the IEEE IECON 92 best paper award and paper awards from the Japan Society for Precision Engineering and the Institute of Electrical Engineers of Japan.