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On-line Torque Estimation Using Flux Approximation Surfaces for Torque Feedback MTPA Control

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ABSTRACT: IPMSM deviates from the optimal operating point for vector control due to magnetic saturation of inductance and magnet flux variation with magnet temperature change. Therefore, torque feedback MTPA control, one of the control methods of IPMSM that is resistant to parameter fluctuations, is used. The accuracy of torque estimation, which is a problem in this process, is improved by an approximation method that calculates the estimated torque from the values of current and magnet flux during drive.

KEY WORDS: IPMSM, Torque Feedback Control, Magnet Temperature, Magnetic Flux Estimation, MTPA Control

1. INTRODUCTION

IPMSM (Interior Permanent Magnet Synchronous Motor) are often used to drive electric vehicles because of their compact size and high efficiency. In IPMSM, the drive condition may cause fluctuations in the inductance value due to magnetic saturation and fluctuations in the electromotive force coefficient of the permanent magnet due to the rise in magnet temperature of the rotor. When these magnetic motor constant variations occur, the controller is unable to determine the minimum required current command value for the desired torque, resulting in wasted current and increased copper losses. To account for these variations in magnetic motor constants, conventional research has proposed the following methods: creating a magnetic flux model of IPMSM that accounts for magnetic saturation [(1)]; estimating the d-axis magnetic flux using a magnetic flux observer and measuring the magnet temperature by referring to MAP data created through magnetic field analysis [(2)]. All of these methods can account for parameter variations with high accuracy, but they require complex analyses, such as magnetic field analysis and thermal analysis, and require large computational costs. Therefore, torque feedback MTPA control has been proposed as a method to compensate for such changes without complex analysis [(3)]. This control requires more accurate torque estimation because the correction of the current amount depends only on the estimated value of torque.

The authors proposed a method to calculate torque by the outer product of current and magnetic flux which is calculated by partial differentiation of voltage by angular velocity [(4)]. This method can estimate magnetic flux and torque with high accuracy. However, this calculation requires past data, which takes time for torque estimation and reduces the response speed of torque feedback control.

Therefore, this paper proposes a method for accurate torque estimation that considers parameter variations and does not depend on past data. In the proposed method, an approximate formula for the magnetic flux that considers magnetic saturation and parameter variations due to temperature is obtained in advance. Then, the torque is calculated as the outer product of the magnetic flux obtained from this formula and the actual current. This is expected to provide highly accurate and fast-response torque estimation that is considered parameter variations. Torque estimation accuracy under steady-state conditions and response to current step input were measured, confirming the superiority of this method.

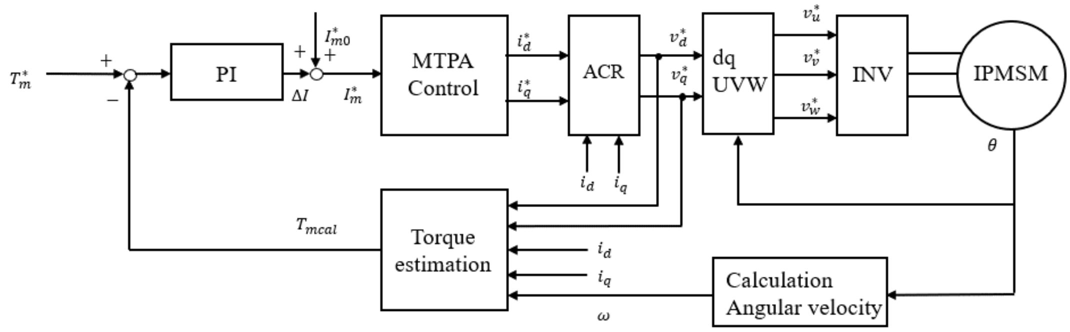

Fig. 1. Block diagram of Torque Feedback MTPA Control

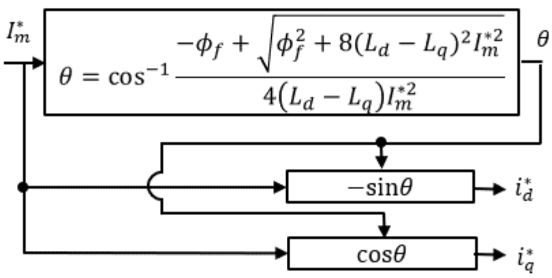

Fig. 2. Block diagram of MTPA Control

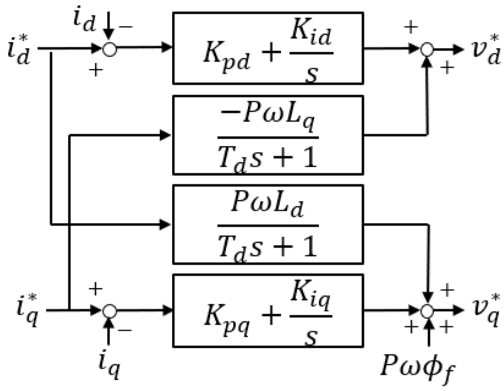

Fig. 3. Block diagram of Current control (ACR: Automatic Current Regulator)

2. Torque feedback MTPA control

Fig.1 shows a block diagram of torque feedback MTPA control. This control system is constructed by applying MTPA control (Fig.2) to the current control system [5] (ACR: Automatic Current Regulator) (Fig.3) and combining torque feedback control to the major loop. In the current control system of the PMSM, the effect of the motor flux variation is expressed in the inverter output voltage. The estimated torque is calculated using this voltage command value, and the deviation from the torque command value is used as a current correction value to determine the current vector length. Then, the current phase angle that allows maximum torque output is determined by MTPA control, and d-q axis current command values are generated. This control enables highly efficient vector control with the minimum amount of current required for the desired torque command.

3. Conventional torque estimation method

In torque feedback MTPA control, the estimated torque is feedback to determine the current correction amount. Therefore, accurate torque estimation is required. The following sections describe three torque estimation methods that are conventional and will be compared to the proposed method in this paper.

3.1. Current type torque estimation method

In this paper, equation (1) is called the current-type torque estimation equation.

$$T_{mcal} = P\{(L_d - L_q)i_d + \phi_f\}i_q \tag{1}$$

L_d: d axis inductance L_q: q axis inductance

ϕ_f: Electromotive force coefficient

This torque estimation formula is not subject to copper loss or inverter output voltage errors because voltage values are not used in the calculation. Therefore, if the motor parameters are correct, accurate torque estimation is possible over the entire speed range. However, because motor parameters are used as fixed values, the accuracy of torque estimation deteriorates when these fluctuations occur. In addition, because voltage values are not used for torque estimation, the feedback torque is not expected to compensate for the current caused by magnetic flux fluctuations.

3.2. Voltage type torque estimation method

Equation (2) [3] is called the voltage-type torque estimation equation.

$$T_{mcal} = \frac{P\sum_{k=u,v,w}\left\{v_k^* - \left(\frac{T_{dt}}{T_{sw}}V_{dc} + V_{fd}\right)sign(i_k) - Ri_k\right\}i_k}{\omega} \tag{2}$$

ω: angular velocity T_{dt}: dead time v_k^*: Voltage reference

T_{sw}: witching cycle V_{dc}: Supply voltage i_k: phase current

V_{fd}: Voltage drop at element R: Winding resistance

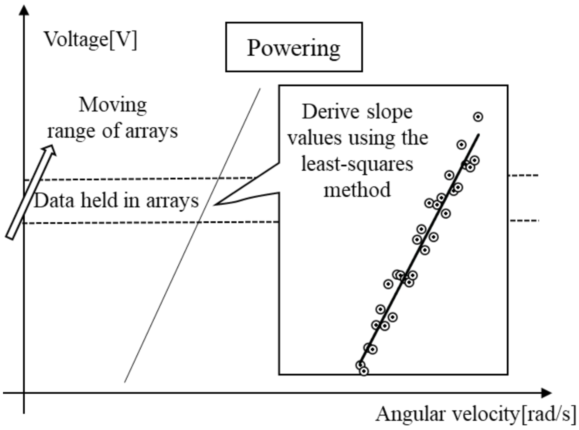

Fig. 4. Flux calculation method

In this torque estimation equation, the variation of the magnetic flux is reflected in the variation of the voltage vector, so the torque estimation can consider the variation of the motor parameter. However, at low speeds, the ratio of loss to input power is large, making it difficult to determine the effective power contributing to the machine output. Furthermore, since the power is divided by the angular velocity, the lower the speed, the larger the error. As a result, torque estimation is possible with high accuracy at high speeds, but torque estimation is subject to large errors at low speeds.

3.3. Flux type torque estimation method

In this paper, equation (3) is called the flux-type torque estimation equation.

$$T_{mcal} = P\left(\phi_d i_q - \phi_q i_d\right) \tag{3}$$

The magnetic flux vector is calculated by the following equation.

$$\begin{cases} \phi_q = -\dfrac{\partial v_d^*}{\partial \omega} \\ \phi_d = \dfrac{\partial v_q^*}{\partial \omega} \end{cases} \tag{4}$$

The flux-type torque estimation formula is the same as the current-type torque estimation formula in that the torque is calculated by the outer product of the flux vector and current vector. However, it differs in that the magnetic flux is calculated by the partial differentiation of the voltage during power operation by the angular velocity, without using the inductance value or electromotive force coefficient for the magnetic flux calculation.

The feature of this method is that the voltage is differentiated by angular velocity to eliminate voltage errors that are not a function of angular velocity, and the magnetic flux can be calculated from the induced voltage only. This mechanism enables highly accurate estimation of magnetic flux and torque independent of rotation speed and considering variations in motor parameters.

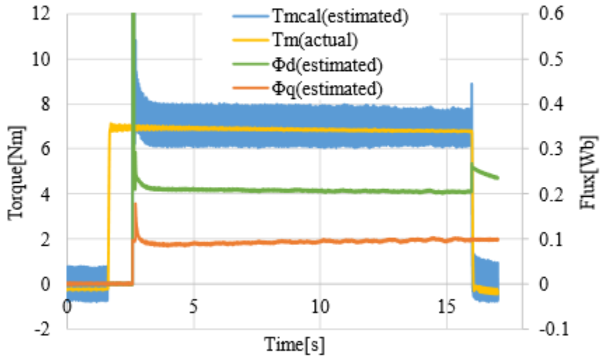

Fig. 5. Estimation results by flux-type torque estimation method.

The specific magnetic flux calculation method is shown in Fig 4. The voltage and angular velocity data for 10,000 carrier cycles are stored in a two-dimensional array. Then, a linear approximation is performed using the least-squares method for each cycle, and the slope is the magnetic flux.

Fig.5 shows an example of the flux and torque estimation results of this method. As can be seen from Fig.5, the calculation of the magnetic flux requires 10,000 carrier cycles of past data for partial differentiation, which causes a delay and does not provide fast dynamic characteristics for the estimated torque.

4.Torque estimation method using flux approximation

To solve the problems of error and response in the torque estimation formula of the conventional method, this paper proposes a method to obtain an approximate formula for magnetic flux that considers magnetic saturation and parameter variations due to temperature in advance, and to calculate torque by the outer product of magnetic flux calculated from this formula and actual current. The structure of this method is explained below.

The first step is to acquire d-q axis flux data dependent on d-q axis currents. The target motor is driven by current control, and the q-axis current command i_q^* value and d-axis current command i_d^* value are changed in steps to obtain the d-q axis magnetic flux during power operation with a combination of multiple current command values. The magnetic flux is calculated using the method described in Section 3.3. Next, the acquired magnetic flux data in the d-q axis at multiple points are approximated to a surface of second order in the i_q^* and i_d^* directions using the fit function in MATLAB, as shown in the following equation (5).

$$\phi_k\left(i_d, i_q\right) = p00_k + \left(p10_k * i_d\right) + \left(p01_k * i_q\right) + \left(p20_k * i_d^2\right) + \left(p11_k * i_d * i_q\right) + \left(p02_k * i_q^2\right) \tag{5}$$

$$p00_k, p10_k, p01_k, p20_k, p11_k, p02_k (k = d, q)$$

: Coefficients constituting the magnetic flux surface

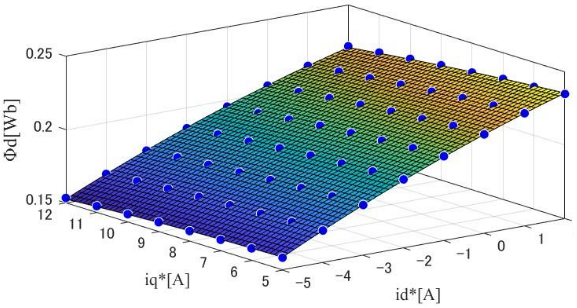

Fig. 6. Measured data of d-axis magnetic flux and approximate surface (ex.)

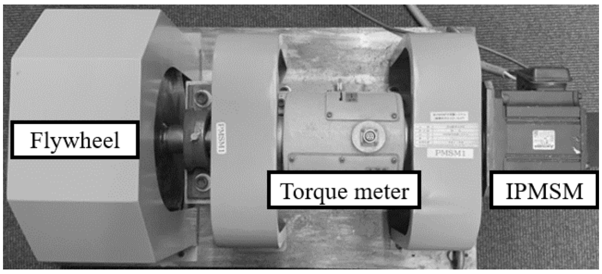

Fig. 7. Appearance of experimental equipment

Fig.6 shows an example of d-axis magnetic flux overlaid on a plot of acquired data and an approximate surface. By this approximation, the d-q-axis magnetic flux, considering magnetic saturation, can be obtained by substituting the actual currents during the drive. However, as the rotor magnet temperature rises, the electromotive force coefficient of the permanent magnet fluctuates, and the magnetic flux cannot be accurately estimated using this approximate surface. Therefore, multiple magnetic flux surfaces are obtained in succession, and the coefficients constituting each surface are obtained as a function of the electromotive force coefficient ϕ_f,as in the following equation.

$$\begin{aligned} p00_k &= a_{p_{00_k}}\phi_f + b_{p_{00_k}} & p10_k &= a_{p_{10_k}}\phi_f + b_{p_{10_k}} \\ p01_k &= a_{p_{01_k}}\phi_f + b_{p_{01_k}} & p11_k &= a_{p_{11_k}}\phi_f + b_{p_{11_k}} \\ p20_k &= a_{p_{20_k}}\phi_f + b_{p_{20_k}} & p02_k &= a_{p_{02_k}}\phi_f + b_{p_{02_k}} \end{aligned} \quad (6)$$

$a_{p_{00_k}}, a_{p_{10_k}}, a_{p_{01_k}}, a_{p_{11_k}}, a_{p_{20_k}}, a_{p_{02_k}} (k = d, q)$: coefficient slope

$b_{p_{00_k}}, b_{p_{10_k}}, b_{p_{01_k}}, b_{p_{11_k}}, b_{p_{20_k}}, b_{p_{02_k}} (k = d, q)$: coefficient intercept

The electromotive force coefficient ϕ_f is treated as a variable that varies only with temperature and is measured from the d-axis magnetic flux during no-load drive (coasting) using the same method (described in Section 3.3) as the d-q axis magnetic flux.

With the above approximation, the magnetic flux can be calculated instantaneously, taking into account magnetic saturation and rotor temperature variation, using the actual current and electromotive force coefficient as arguments. Then the torque can be calculated from the outer product of the calculated magnetic flux and current.

Table 1. Experimental conditions

Parameter	Value	Units
DC link Voltage V_{dc}	300	V
Pole Pairs P	4	Pole Pairs
d-axis inductance L_d	10.4	mH
q-axis inductance L_q	12.8	mH
Winding resistance R_m	1.1	Ω
Switching frequency f_{sw}	8	kHz
Dead time T_{dt}	3.5	μs

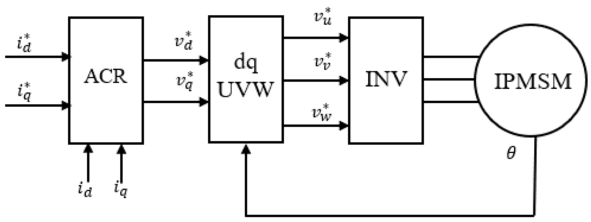

Fig. 8. Block diagram of current control in IPMSM

5. Validation through mini-model experiments

Experiments on the mini model confirmed the accuracy of torque estimation and response in the proposed method.

5.1. Experimental system configuration and conditions

Fig.7 shows the appearance of the mini-model experimental apparatus, and Table.1 shows the motor parameters and other experimental conditions. The mini-model experimental apparatus consists of an IPMSM rated at 1kW driving a flywheel via a shaft with a torque meter.

5.2. Verification of torque estimation accuracy

The accuracy of the torque estimation in steady state of the proposed method was verified. The motor was driven by a current control system (Fig.8), and the q-axis current command value i_q was changed from 5A to 12A and the d-axis current command value i_d was changed from -5A to 2A in increments of 1A, for a total of 64 magnetic flux data points. Four sets of this data were obtained consecutively, and four flux surfaces were obtained, varying with increasing rotor temperature, and approximated by the procedure of the proposed method. In other words, the approximation is 8 points on the i_d axis, 8 points on the i_q axis, and 4 points on the ϕ_f axis for each temperature.

The evaluation was made by the error between the actual torque acquired by the torque meter and the torque estimate by the proposed method. The error used here as an index for evaluation is the average of the torque estimation errors in the 64 current command value patterns obtained. As a comparison, the same

Table 2. Average error of measured torque and estimated torque

	Current type[%]	Voltage type[%]	Proposal type[%]
1.low temp.	2.2	4.3	1.7
2 ↓	3.4	5.2	2.5
3	3.8	5.4	2.3
4.high temp.	3.1	4.6	1.7

evaluation was performed with the current-type torque estimation formula and voltage-type torque estimation formula of the conventional method. Table 2 shows the experimental results. The current-type torque estimation equation shows that the accuracy of torque estimation deteriorates when the temperature rises due to parameter variation. In addition, the voltage type torque estimation formula is also affected by the inverter output error, resulting in an error of about 5%. On the other hand, the proposed method calculates the magnetic flux considering magnetic saturation and temperature variation, so that torque estimation can be done with high accuracy, with an error of about 2% even when the temperature rises.

5.3. Verification of estimated torque response during transient response

Current was input in steps to verify the response of the estimated torque during current transient response. As in the previous section, the motor was driven by the current control system and the estimated torque was compared with the actual torque obtained by the torque meter. An example of the results obtained (i_q=6A, i_d=-1A, ω =400rad/s) is shown in Fig. 9. The figure shows that the estimated torque follows the actual torque even during the current step response.

In addition, the accuracy of torque estimation during transient state under various driving conditions is shown.

Fig.10 shows the torque estimation results during current step response in various speed ranges, and Fig.11 shows the torque estimation results during current step response in various current values. The results show that the torque in the transient state can be accurately estimated in various speed ranges and current command values. The above results confirm that this method can accurately estimate torque not only in steady state but also in transient response and can be sufficiently used as a correction amount in torque feedback.

6. Conclusion

IPMSM deviates from the operating point of optimal drive of vector control due to magnetic saturation of inductance and magnet flux fluctuation caused by magnet temperature change. Therefore, torque feedback MTPA control, which is robust to parameter fluctuations, is used, but the estimated torque, which is the only compensation quantity, must be highly accurate and fast.

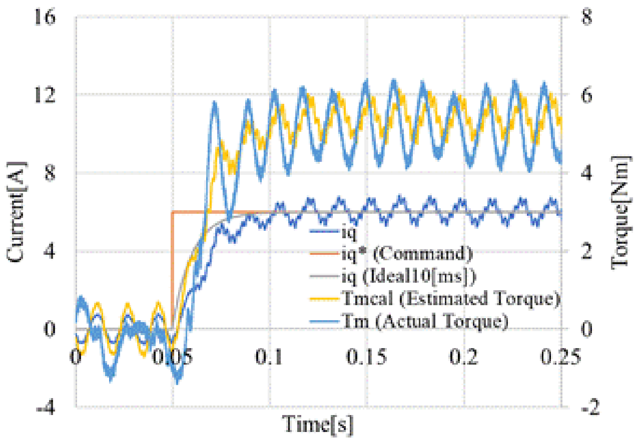

Fig. 9. Response of torque estimation by the proposed method

Therefore, this paper proposes a method to calculate the torque by the external product of the magnetic flux and the current by obtaining an approximate formula for the magnetic flux in advance, which considers parameter fluctuations due to magnetic saturation and temperature.

Mini-model experiments show that the proposed method can accurately estimate the torque at steady state and transient response, and that the proposed method can estimate the torque with high accuracy and fast response considering the parameter fluctuation.

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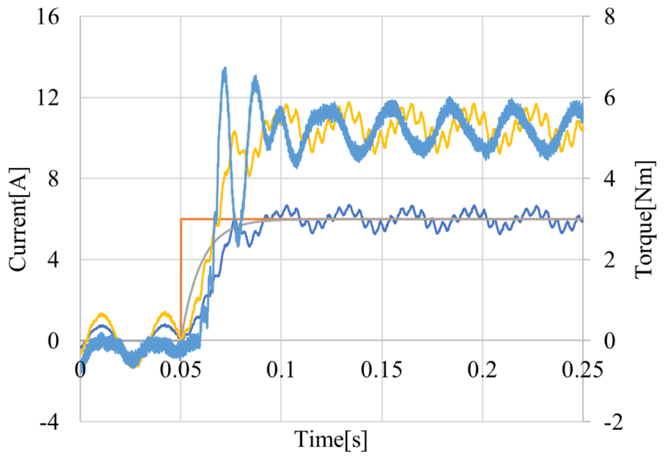
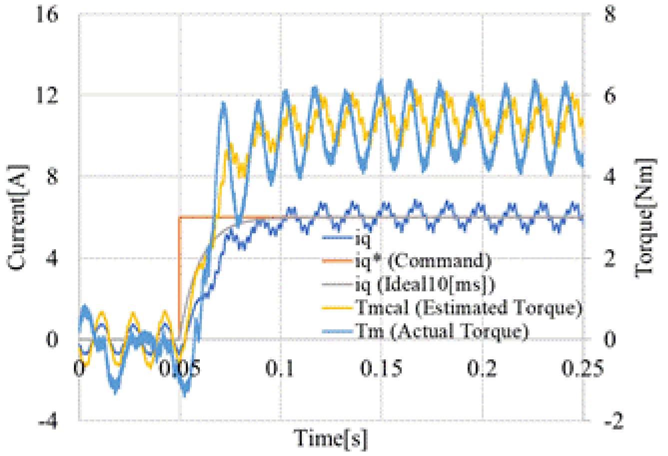
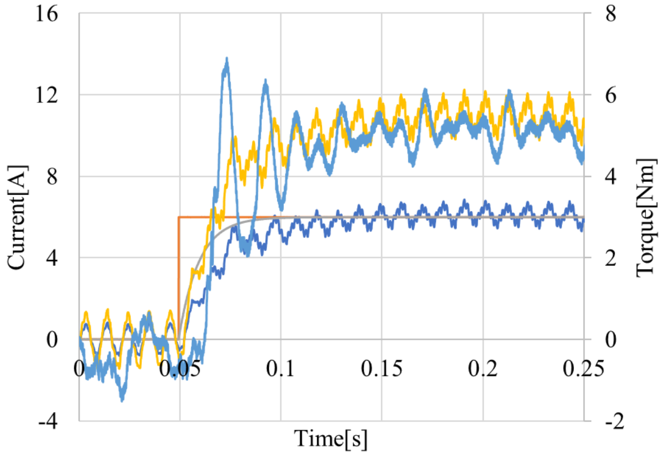


$\omega = 200[rad/s]$

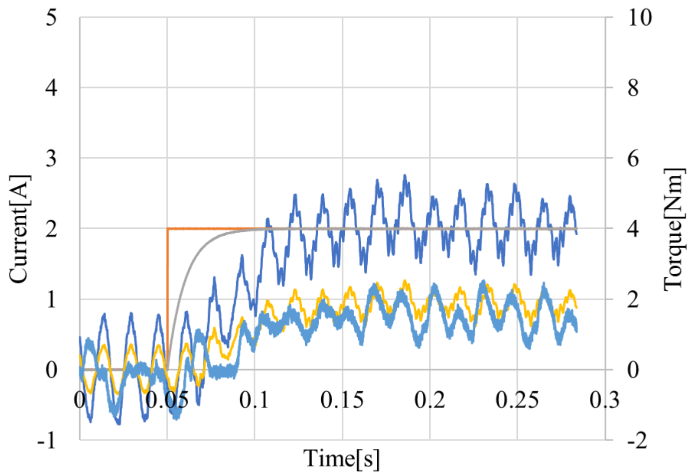


$\omega = 400[rad/s]$

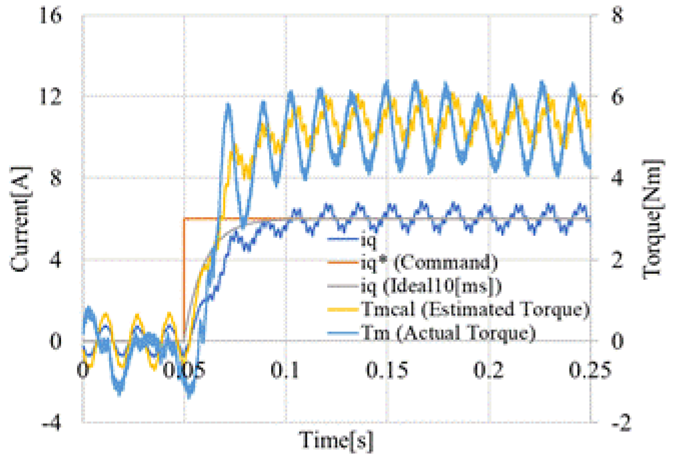


$\omega = 600[rad/s]$

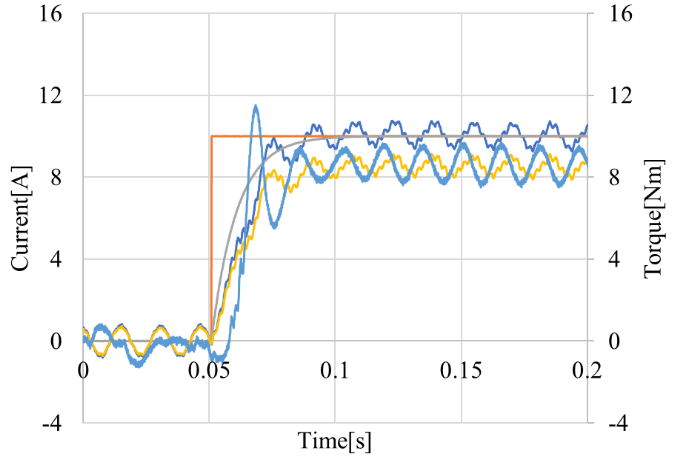
Fig. 10. Response of torque estimation by the proposed method
(Step input at each angular velocity)
$i_q^* = 6[A] \quad i_d^* = -1[A]$



$i_q^* = 2[A] \quad i_d^* = -1[A]$



$i_q^* = 6[A] \quad i_d^* = -1[A]$



$i_q^* = 10[A] \quad i_d^* = -1[A]$

Fig. 11. Response of torque estimation by the proposed method
(Step input at each current)
$\omega = 400[rad/s]$