Speed Control of High-Performance Brushless DC Motor Drives by Load Torque Estimation

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Abstract—**This paper presents a novel robust speed control method based on the load torque observer of high-performance brushless DC(BLDC) motor. Recently, high-performance BLDC motor drives are widely used for variable speed drive systems of the industrial applications. In case of the control of robot arms and tracking applications with lower stiffness, we cannot design the speed controller gain to be very large from the viewpoint of the system stability. Thus, the feedforward compensator with disturbance torque observer was proposed. This method can improve the servo stiffness without increasing the speed controller gain. The enhanced speed control performance can be achieved and the speed response against the disturbance torque can be improved for high-performance BLDC motor drive systems in which the bandwidth of the speed controller cannot be made large enough. The load disturbance is compensated by detected load torque through the observer. The compensation current is made through q-axis current. The d-q transform of phase currents were possible by the Fourier series summation method.**

Consequently, the speed control for high-performance BLDC motor drives become improved. The simulation results for BLDC motor drive systems confirm the validity of the proposed method.

I. INTRODUCTION

Recently, the DC motors have been gradually replaced by the BLDC motors since the industrial applications require more powerful actuators in small sizes. Elimination of brushes and commutators also solves the problem associated with contacts and gives improved reliability and enhances life. The BLDC motor has the low inertia, large power to volume ratio, and low noise as compared with the permanent magnet DC servo motor having the same output rating [1]-[3]. Therefore, high-performance BLDC motor drives are widely used for variable speed drive systems of the industrial applications. In case of the control of robot arms and tracking applications with lower stiffness, we cannot design the speed controller gain to be very large from the viewpoint of the system stability. The PI controller is usually employed in a BLDC motor control, which is simple in realization. But it is difficult to obtain the sufficiently high-performance applications. Thus, the feedforward compensator using disturbance torque observer was proposed [4]. This method can improve the servo stiffness without increasing the speed controller gain [5].

In this paper, the proposed method is used a feedforward compensation method through load torque estimation. The estimated load disturbance by the state observer is compensated as the equivalent current [6]. When the bandwidth of the speed controller cannot be made large enough, the enhanced speed control performance can be achieved and the speed response of high-performance BLDC motor drive systems can be improved. Moreover, the proposed method has robust characteristic against parameters variation and disturbance torque. And, in the proposed method, the d-q transform of phase currents were possible by the Fourier series summation method [7]. This current control method was used to get compensation current of BLDC motor.

The validity of the proposed control scheme is verified through the simulated results in comparison with the uncontrolled method.

II. MODELING OF THE BLDC MOTOR AND CURRENT CONTROL METHOD

A. Modeling of BLDC Motor

The BLDC motor is an AC synchronous motor with permanent magnet mounted on the rotor and stator windings. The voltage equation can be expressed as shown in Fig.1. The BLDC motor has three stator windings and permanent magnets on the rotor.

The modeling is based on the following assumptions:

(1) The motor is not saturated.

(2) Stator resistances of all windings are equal and self and mutual inductances are constant.

(3) Power semiconductor devices in the inverter are ideal.

(4) Iron Losses are negligible.

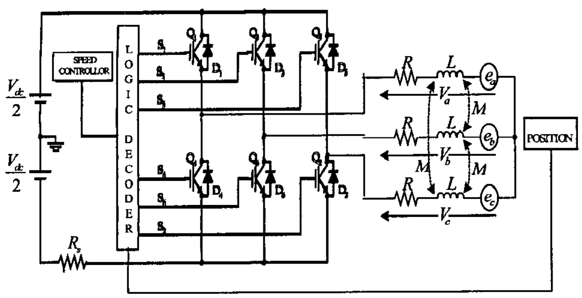

Fig. 1. Block diagram of BLDC motor drive.

Under the above assumptions, a BLDC motor can be represented as

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

where i_a, i_b, and i_c are rectangular shaped phase currents and e_a, e_b, and e_c are trapezoidal shaped back-EMFs.

The electromagnetic torque is expressed as

$$T_e = \frac{1}{\omega_m}(e_a i_a + e_b i_b + e_c i_c) \tag{2}$$

where, ω_m is mechanical speed.

B. Current Control Method

As shown in Fig. 2, input current reference value was calculated from the summation method of the Fourier series. Phase current is rectangular shape, and then, it's Fourier series is expressed as

$$i(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cdot \cos n\omega t + b_n \cdot \sin n\omega t) \tag{3}$$

where $a_0 = 0$ and $a_n = 0$.

And, because it is odd function, (3) is followed as (4)

$$i(t) = \sum_{n=1}^{\infty} (b_n \sin n\omega t) \tag{4}$$

where $b_n = \frac{4}{n\pi}\cos\left(\frac{n\beta}{2}\right)$ $\quad n = 1,\ 5,\ 7,\ 11,\ 13,\ 17,\ 19.$

A period of commutation ; $\beta = \frac{\pi}{3}$

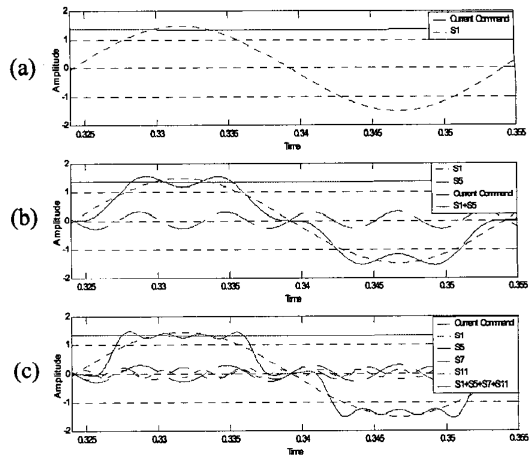

Fig. 2. Current reference summation of each harmonics.
(a) Wave form of reference current and Fundamental current.
(b) Summation wave form of fundamental current and 3 harmonic current.
(c) Summation wave form of fundamental current, 3, 5, 7, and 11 harmonic current.

The third harmonic and its multiples are cancelled out in the output, because the motor is wound Y winding. Rectangular phase currents of 120° conduction are made by summation of each harmonic current waveform.

Then, using above (4) d-q transform of phase current can be done. The harmonic order up to the nineteenth order is considered. Since, the amplitude of harmonics more than nineteenth order is small, it was not considered.

Consequently, the electromagnetic torque of (2) is rewritten as

$$T_e = \alpha \lambda_m i_q \tag{5}$$

where α is proportional constant for feedforward compensation, λ_m is linkage flux of permanent magnet, and i_q is q axis stator current.

This is represented as

$$T_e = k_\alpha i_q \tag{6}$$

where k_α is $\alpha\lambda_m$.

The interaction of T_e with the mechanical dynamics determines how the motor speed is built up

$$T_e = T_L + J\frac{d\omega}{dt} + B\omega \tag{7}$$

where T_L is the load torque, J is the inertia, ω is the rotor speed, and B is the viscous damping.

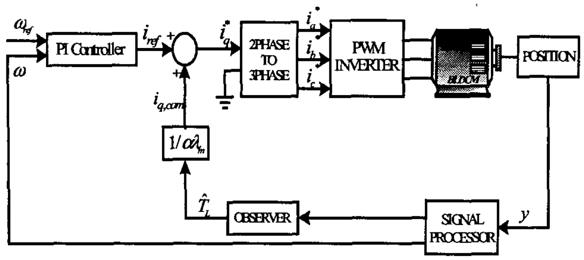

Fig. 3. Block diagram of proposed control algorithm.

III. LOAD TORQUE OBSERVER

The proposed speed control method requires information of the load torque for feedforward compensation. A direct measurement of the load torque is difficult because other high cost equipment is required. Therefore, this paper used to estimate value by the state observer. Input value of the state observer is position information of rotor.

The system equations of a motor can be described as

$$\dot{\omega} = (T_e - T_L - B\omega)/J \tag{8}$$

and

$$y = \int \omega dt \tag{9}$$

where the y is rotor position .

The dynamic equation of a given system can be expressed as follows

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{10}$$

and

$$y(t) = Cx(t) \tag{11}$$

where $x = \begin{bmatrix} \omega \\ y \\ T_L \end{bmatrix}$, $A = \begin{bmatrix} -\frac{B}{J} & 0 & \frac{1}{J} \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$,

$C = [0 \quad 1 \quad 0]$, and u = the electromagnetic torque.

where the dimensions of the matrices A, B, and C are 3×3, 3×1, and 1×3, respectively.

A state observer for the load torque estimation can be represented follows as (12)

$$\begin{bmatrix} \dot{\hat{\omega}} \\ \dot{\hat{y}} \\ \dot{\hat{T}}_L \end{bmatrix} = \begin{bmatrix} -\frac{B}{J} & 0 & \frac{1}{J} \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{\omega} \\ \hat{y} \\ \hat{T}_L \end{bmatrix} + \begin{bmatrix} T_e \\ 0 \\ 0 \end{bmatrix} + L\left[y - (0 \quad 1 \quad 0) \begin{bmatrix} \hat{\omega} \\ \hat{y} \\ \hat{T}_L \end{bmatrix} \right] \tag{12}$$

where $\hat{\omega}$, $\hat{y}$, and $\hat{T}_L$ are the estimated state vector.

A state observer for the system described by (12) can be constructed as follows

$$\dot{\hat{x}} = A\hat{x} + Bu + L(y - C\hat{x}) \tag{13}$$

where (13) is the estimated state vector, and $L = [l_1 \quad l_2 \quad l_3]^T$ is the proportional gain vector to be chosen so as to determine the error dynamics of the observer.

Fig. 3 shows the overall control strategy proposed for controlling the speed and torque of a BLDC motor drives. Estimated outputs of the observer are rotor position, speed, and load torque. Estimated load torque is used for feedforward compensation. Reference current i_q^* is compensated as $i_{q,com}$ by estimated $\hat{T}_L$.

IV. SIMULATION RESULTS

In order to verify the proposed control algorithm simulation is performed. The parameters of a BLDC motor used in this simulation are given in Table I. The switching operation of the inverter is modelled by using ideal six-switches.

TABLE I
PARAMETERS OF BLDC MOTOR

Item	Symbol	Data
Rated Voltage	V	310 (V)
Moment of Inertia	J_0	0.0036 (kg·m²)
Viscous Damping	B_0	0.0001(N·m·sec/rad)
Resistance	R_s	7.3 (Ω)
Inductance	L_s	20.3 (mH)
Back-EMF Constant	K_e	0.3 (V/(rad/sec))
Poles	P	4
Rated Torque	T_e	2(N·m)

The load disturbance is compensated by the feedforward compensation method. The compensated current command comes from the load torque observer. The simulation results of the proposed method depicted in Fig. 4 to Fig. 9 show that the motor speed quickly converges the reference shortly after startup and recovers very well from the load torque disturbance as well as parameters variation. Fig. 4 and 5 show the simulation results of the uncontrolled system and the proposed system when the speed reference 1000 (*rpm*) at t = 0.1 (sec), $J = J_0$, $B = B_0$, and the external load torque $2(N \cdot m)$ at 2.0 (sec).

Fig. 5 shows robust speed characteristic of BLDC motor drives with feedfoward compensation. The secondly, Fig. 6 and 7 show the simulation results of the uncontrolled system and the proposed system when the speed reference 1000 (*rpm*) at t = 0.1 (sec), $J = 2J_0$, $B = 2B_0$, and the external load torque 2 $(N \cdot m)$ at 2.0 (sec). The speed response in Fig. 7 shows a good dynamic performance. As explained before, the proposed control method has robust speed characteristic under the parameters variation of $J = 2J_0$ and $B = 2B_0$.

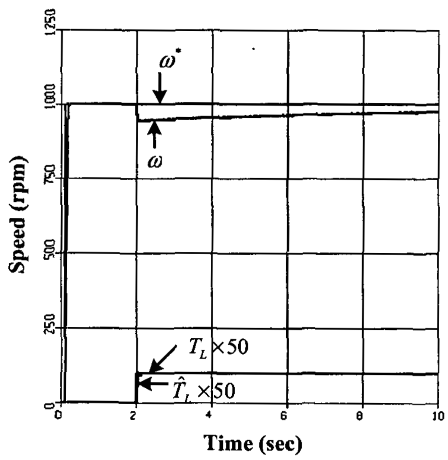

Fig. 4 Speed response and estimated load torque of uncontrolled method. $J = J_0$, $B = B_0$, $T_L = 2(N \cdot m)$.

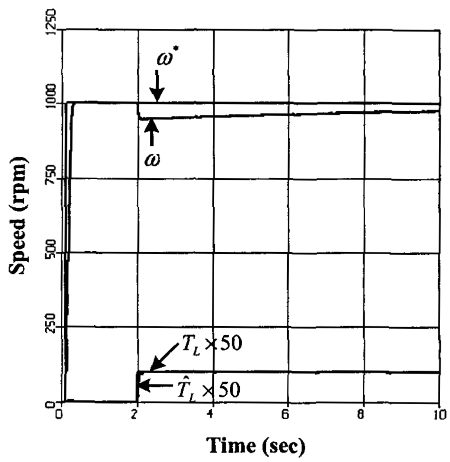

Fig. 6 Speed response and estimated load torque of uncontrolled method. $J = 2J_0$, $B = 2B_0$, $T_L = 2(N \cdot m)$.

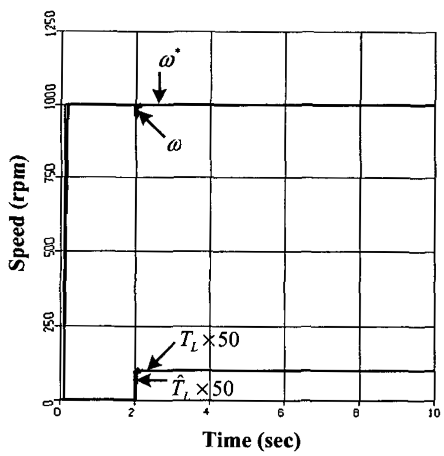

Fig. 5 Speed response and estimated load torque of proposed method. $J = J_0$, $B = B_0$, $T_L = 2(N \cdot m)$.

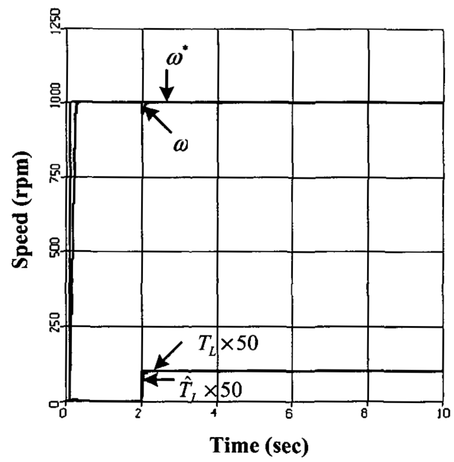

Fig.7 Speed response and estimated load torque of proposed method. $J = 2J_0$, $B = 2B_0$, $T_L = 2(N \cdot m)$.

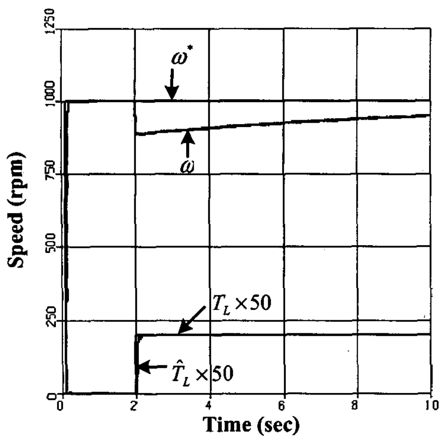

Fig. 8 Speed response and estimated load torque of uncontrolled method. $J = J_0$, $B = B_0$, $T_L = 4(N \cdot m)$.

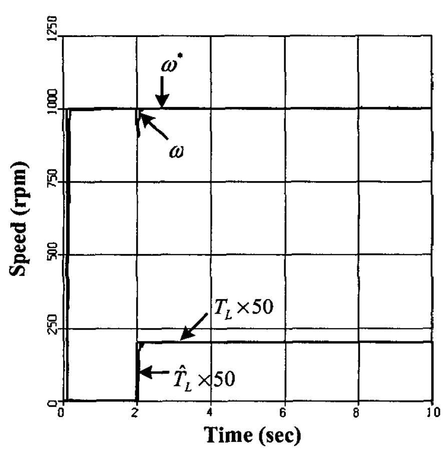

Fig. 9 Speed response and estimated load torque of proposed method. $J = J_0$, $B = B_0$, $T_L = 4(N \cdot m)$.

Finally, Fig. 8 and 9 show the simulation results of the proposed method when the speed reference $1000\,(rpm)$ at t = 0.1(sec), $J = J_0$, $B = B_0$, and the external load torque $4(N \cdot m)$ at $2.0\,(\mathrm{sec})$. As shown in Fig. 9, proposed method shows a better dynamic performance about incremental load torque.

V. CONCLUSION

In the applications of servo control, we cannot design the speed controller gain to be very large. However, the feedforward compensation control improves the overall speed control performance in low speed controller gain. It is regarded as the best control method to get fast and accuracy speed response. The compensated current is made by the q-axis current through Fourier series summation. Simulation result is described the detail speed characteristic.

Consequently, the proposed method has robust speed characteristics against parameters and disturbance torque variations. Therefore, it can be adapted speed control for high-performance BLDC motor without increasing the speed controller gain.

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