Microprocessor-based and Modified Hysteresis Current Controller Design for BLDCM Drive

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Abstract

This paper is to study a modified hysteresis band current control technique for keeping the fixed switching frequency. The control technique is applied to an brushless DC motor(BLDCM). This paper gives an analysis of the modified hysteresis band with isolated neutral case and the PI controller with current limiter in forward loop; their characteristics are studied by simulation. The proposed control technique is implemented by using a microprocessor-based system.

1. Introduction

The hysteresis band current control has been widely used for AC machine drive. The advantages of hysteresis band current control are its simplicity of hardware, inherent current limit capability and fast response. For the reason of these merit, various techniques of current control have been studied and reported in the literature. These control schemes can be classified into two large groups. One is on-off control, the other is predictive control. On-off control provides a fast response but the current ripple is relatively large according to the hysteresis band width and causes additional machine heating. On the other hand predictive control is characterized by forwarding the balance between instantaneous command and feedback currents. Although this method inclines to give optimum performance with respects to the response time, accuracy and current ripple, this is very complicate to implement.

For these reasons, this paper proposes a modified hysteresis band current control in which switching frequency can be held nearly constant. And acoustic noise causes problem when machines are driven by power transistor. So, this disappears by using power MOSFET over audio frequency 20[KHz]. This technique is implemented by using microprocessor-based system. And a way of obtaining controller parameter is discussed.

2. Modified Hysteresis Band Analysis

2-1 Modeling of BLDCM

The performance of BLDCM with sinusoidal back emf is described by the standard d,q transform of synchronous machine model. Modeling of BLDCM in Fig.1 is given

$$pi_{qs} = -\frac{r_s}{L_q}i_{qs} - \frac{L_d}{L_q}\omega_r\left(\frac{\lambda_f}{L_d} + i_{ds}\right) + \frac{V_q}{L_q} \quad (1)$$

$$pi_{ds} = -\frac{r_s}{L_d}i_{ds} + \frac{L_q}{L_d}\omega_r i_{qs} - \frac{V_d}{L_d} \quad (2)$$

$$p\omega_r = \frac{3n^2}{8J_m}\left(\lambda_f i_{qs} + L_d\left(1 - \frac{L_q}{L_d}\right)i_{ds}i_{qs}\right) - \frac{nT_L}{2J_m} \quad (3)$$

V_{qs}, V_{ds} : q, d axis voltage
i_{qs}, i_{ds} : q, d axis current
L_q, L_d : q, d axis inductance
r_s : stator resistance
ω_r : rotor speed
J_m : rotor inertia
p : d/dt
n : number of poles
λ_f : mutual flux linkage
T_L : load torque

2-2 Formulation of Hysteresis Band

In most case of BLDCM drive, it operates with isolated neutral. Such case, the phase voltages are given below.

Mode	$Q_1(Q_4)$	$Q_3(Q_6)$	$Q_5(Q_2)$	V_{an}	V_{bn}	V_{cn}
0	0 (1)	0 (1)	0 (1)	0	0	0
1	1 (0)	0 (1)	0 (1)	⅔Vdc	-⅓Vdc	-⅓Vdc
2	0 (1)	1 (0)	0 (1)	-⅓Vdc	⅔Vdc	-⅓Vdc
3	1 (0)	1 (0)	0 (1)	⅓Vdc	⅓Vdc	-⅔Vdc
4	0 (10	0 (1)	1 (0)	-⅓Vdc	-⅓Vdc	⅔Vdc
5	1 (0)	0 (1)	1 (0)	⅓Vdc	-⅔Vdc	⅓Vdc
6	0 (1)	1 (0)	1 (0)	-⅔Vdc	⅓Vdc	⅓Vdc
7	1 (0)	1 (0)	1 (0)	0	0	0

1:on 0:off

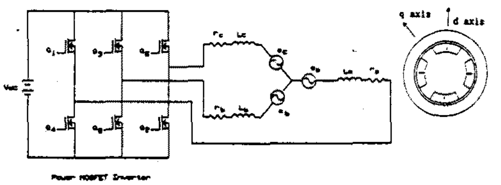

Fig. 1. Three phase inverter scheme for BLDCM drive

When power MOSFET Q_1 is on, the phase 'a' current will rise or fall, depending on phase voltage and back emf. But the phase 'a' current will fall during the power MOSFET Q_4 on interval. During Q_1-on period, small current rise δh is expressed by

$$\delta h = (\frac{\alpha V_{dc}}{L} - \frac{di_{ar}}{dt} - \frac{e_a}{L})\delta t_r \qquad (4)$$

α = 0, ⅓, or ⅔

e_a : phase 'a' back emf
i_{ar} : phase 'a' reference current
δt_r : time of arbitrary mode of Q_1-on

The hysteresis band can be determined by summing small current rise at Q_1-on state.

$$2H = \Sigma\delta h = -(\frac{di_{ar}}{dt} + \frac{e_a}{L})t_r + \frac{1}{L}\Sigma\delta t_r \alpha V_{dc} \qquad (5)$$

t_r : Q_1 - on period

Also, when Q_4-on period, small current fall δh is given by

$$\delta h = (\frac{\alpha V_{dc}}{L} + \frac{di_{ar}}{dt} + \frac{e_a}{L})\delta t_f \qquad (6)$$

δf : time of arbitrary mode of Q_4-on

Therefore, the total fall is given by

$$2H = \Sigma\delta h = (\frac{di_{ar}}{dt} + \frac{e_a}{L})t_f + \frac{1}{L}\Sigma\delta t_f \alpha V_{dc} \qquad (7)$$

t_f : Q_4 - on period

The average fall or rise of current is determined by α. From the equations (5), (7)

$$\Sigma\delta t_r \alpha V_{dc} = t_r \beta_1 V_{dc}$$
$$\Sigma\delta t_f \alpha V_{dc} = t_f \beta_2 V_{dc}$$

$$\beta_1 = \Sigma\delta t_r \alpha / t_r \qquad (8\text{-}1)$$
$$\beta_2 = \Sigma\delta t_f \alpha / t_f \qquad (8\text{-}2)$$

We assume the average applied voltage in the t_r, t_f period is nearly the same, and then $\beta_1 = \beta_2$. The parameter α, β_1 and β_2 will vary between ⅓ to ⅔ and ⅔ is the worst case. This assumption will cause some inaccuracy. Combining (5), (7), (8-1) and (8-2), we can express as follows.

$$2H = -(\frac{di_{ar}}{dt} + \frac{e_a}{L})t_r + \frac{1}{L}\beta_1 t_r V_{dc} \qquad (9)$$
$$2H = (\frac{di_{ar}}{dt} + \frac{e_a}{L})t_f + \frac{1}{L}\beta_1 t_f V_{dc} \qquad (10)$$

Through some computation, modified hysteresis band H is given by

$$H = \frac{\beta_1 V_{dc}}{4Lf_s}\{1 - \frac{L^2}{\beta_1^2 V_{dc}^2}(\frac{di_{ar}}{dt} + \frac{e_a}{L})^2\} \qquad (11)$$

f_s : $1/(t_r + t_f)$

Applying some mathematical formula, and considering relations between d, q axis value and three phase value, H is expressed by

$$H = C - D\sin^2(\theta_e + \gamma) \qquad (12)$$

$$C = \frac{\beta_1 V_{dc}}{4f_s L} \qquad \gamma = \frac{Li_{qs}}{\sqrt{2}\lambda_f - i_{ds}}$$

$$D = \frac{0.25\omega_e^2}{f_s\beta_1 V_{dc} L}\{(\sqrt{2}\lambda_f - i_{ds})^2 + L^2 i_{qs}^2\}$$

θ_e : angle between stator phase 'a' and the rotor
ω_e : synchronous speed

Modified hysteresis band H is dependent on f_s (switching frequency) in equation (12). Then BLDCM can operate the fixed switching frequency by changing the hysteresis band H.

3. Controller Parameter Determination

It is difficult to attain the sampling time and controller parameter because of the nonlinear dynamics of BLDCM. So the nonlinear system model needs to be linearized. The linearized system equations is described

$$p i_{qs} = (V_{qs} - r i_{qs} - K_T \omega_r)/L_q \qquad (13)$$
$$p \omega_r = (K_T i_{qs} - T_L) \qquad (14)$$

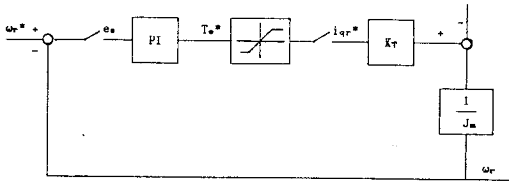

Fig. 2. Block diagram for speed control system

Fig.2 shows the simplified block diagram of PI controller considering saturation type current limiter in the feedforward loop. First of all, speed error $e_s(z)$ must be minimized. This condition is achieved by the sum square error criterion for sampled-data systems. The sum square error J can be described below.

$$J = \sum_{k=0}^{\infty} e_s(kt) \qquad (15)$$

The following conditions are required to obtain system parameter K_P, K_I which minimize error.

$$\frac{\partial J}{\partial K_P} = 0, \qquad \frac{\partial J}{\partial K_I} = 0 \qquad (16)$$

It is necessary to analyze the case that considered the current limiter because the system parameter obtained in the above method didn't include it.

Considering the effect of current limiter, transfer function ω_r^*/ω_r in the bilinear w-domain becomes

$$G(w) = \frac{(K_T/J_m)\ T\ \{-(K_I + 2K_P)w^2 + 2K_P w + K_I\}}{4w^2} \qquad (17)$$

The current limiter can be approximated by its describing function.

$$N(T_e^*) = \frac{2}{\pi}\left[\frac{T_e^*{}_{max}}{T_e^*}\cos\left(\sin^{-1}\frac{T_e^*{}_{max}}{T_e^*}\right) + \sin^{-1}\frac{T_e^*{}_{max}}{T_e^*}\right] \qquad (18)$$

If $G(j\omega)$ and $-1/N(T_e^*)$ intersect, the closed-loop response will exhibit limit cycles. The gain margin for the system to be stable is positive and less than 1. The gain margin is approximately expressed

$$|G(j\omega_c)| \cong \frac{(K_T/J_m)\ T\ (2K_P + K_I)}{4} \qquad (19)$$

As mentioned above, for the system to be stable the following inequality requires

$$0 < |G(j\omega_c)| < 1 \qquad (20)$$

The K_P, k_I, T, are selected by equation (16) and (20). The gain-phase plot shown in Fig.3.

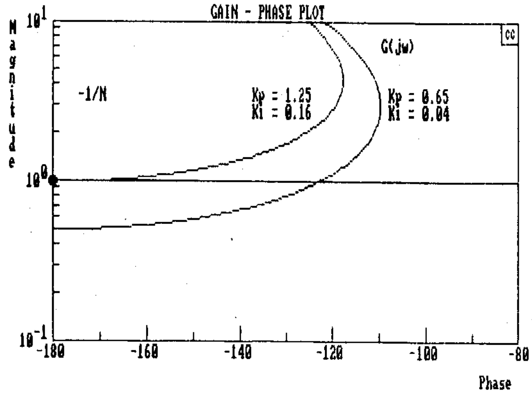

Fig. 3. Gain-phase plot

4. SYSTEM DESCRIPTION

The construction of modified hysteresis band current controller is similar to the common fixed hysteresis current controller but for modified band generator. The modified band generator will calculate the band for holding the inverter frequency constant. Current reference generator is made by EP-ROM which address is made by resolver to digital converter. Fig.4 shows the system block diagram.

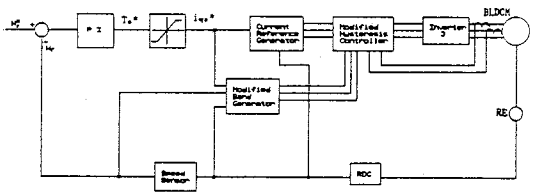

Fig. 4. Block diagram for the digital speed control system with the modified current controller

5. Simulation and Result

Using fourth order Runge-Kutta algorithm, A modified hysteresis band current control for BLDCM and an fixed hysteresis band current control are simulated with attaining system parameter in the paragraph 3. The simulation result is shown in Fig. 5-1 and Fig. 5-2. The fixed hysteresis band is chosen by calculating the value when power MOSFET inverter operates at the maximum switching frequency 25[KHz]. The modified hysteresis band is changed with phase 'a' current reference. In this case the parameter for calculating band width is f_s = 25[KHz], V_{dc} =120[V], β_1 = ⅔(worst case). The inverter frequency changes a little because of inaccuracy of β_1. The case of modified hysteresis band is shown to lessen current ripple.

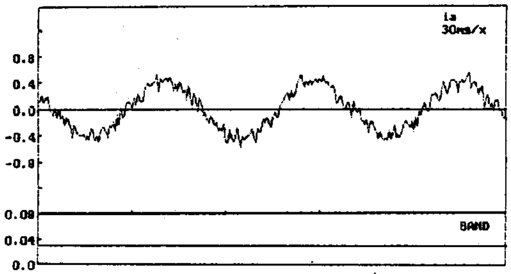

Fig. 5-1. Simulated phase 'a' current i_a with the fixed hysteresis band

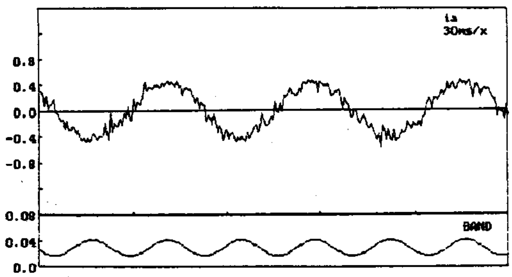

Fig. 5-2. Simulated phase 'a' current i_a with the modified hysteresis band

6.Conclusion

In this paper, an modified hysteresis current control is studied and a way of determination of system parameter for BLDCM with the current limiter is discussed. This enables to design the better current control system for BLDCM drive that is simple and causes relatively small current ripple. In addition to this, acoustic noise can be lessened.

7. Reference

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