A NOVEL APPROACH FOR FLUX WEAKENING SPEED CONTROL OF IPMSM DRIVES

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ABSTRACT

This paper presents a simplified algorithm for the speed control of an interior permanent magnet synchronous motor (IPMSM) above the base speed using flux-weakening method. Non-linear expressions of d-axis and q-axis currents have been derived and subsequently incorporated in the control algorithm in a practical form for the flux weakening strategy to operate the IPMSM above the base speed. In real-time implementation, derived non-linear expressions of d-axis and q-axis current can not be incorporated because of the calculation burden of the digital signal processor (DSP). In order to overcome this problem, simplified expressions of d-axis and q-axis currents have been derived using curve fitting method and used in the laboratory implementation. The efficacy of the proposed system is confirmed by simulation and successful implementation in the laboratory using DSP board DS1102 for a 1 hp IPMSM.

1. INTRODUCTION

Recent developments in microprocessors, high speed power electronic devices, magnetic materials and control algorithms have made it possible to use ac motors in a variety of drive applications. Among ac motors, IPMSMs are gaining wide recognition over other types of motors in drive system because of their inherent advantageous features [1]. Vector control technique in the IPMSMs drive offers a drive system which resembles the characteristics dc motor drives of decoupled torque and magnetizing characteristics [2]. Many researchers have focused their attention on the vector control of IPMSM drive by forcing the d-axis current equals to zero which essentially linearizes the motor model for speed control up to the base speed [2-5]. However, in real-time the electromagnetic torque and the flux producing d-axis current are non-linear in nature and the generated or back emf of an IPMSM is directly proportional to the rotor speed. As the rotor speed increases, the back emf increases in the linear fashion since excitation flux is constant due to the permanent magnets. Thus to reach a desired speed, the terminal voltage must be increased to overcome the back emf. It is the real time practice that the inverter should be capable of supplying the required voltage by PWM or any other suitable techniques up to the base or rated speed. For the drive operation above the base speed, an indirect flux control method of field weakening can be applied to the drive, so that the terminal voltage will remain constant after the base speed. This flux or field weakening strategy is very important from the limitation of IPMSM and inverter rating points of view, which optimizes the drive efficiency. However, owing to the permanent magnet construction of the rotor, nothing can be done on the rotor side from the control point of view. It is possible to weaken the field by controlling the stator current in such a way that a direct axis current component in the rotating frame axis can be generated which will oppose the main field produced by the permanent magnet. The problem associated with the flux weakening control technique is that its implementation in real time becomes complicated because there exists a complex non-linear relationship between d-axis current and speed and also among d- and q-axis currents. Some researchers have solved this problem by considering look-up table [6]. In this work, these non-linearties are incorporated in the laboratory drive system with a simpler expression of d-axis and q-axis current above the base speed. The simplified expressions of d-axis and q-axis currents have been derived using curve fitting method and used in the simulation as well as in real time implementation. Using a properly designed speed controller, the command torque and the d-axis current are calculated first and then the reference q-axis current is determined. Since q-axis current is a function d-axis current, the reference q-axis current is calculated readily. The proposed IPMSM drive system has been simulated using MATLAB SIMULINK [7] and implemented using DSPACE DSP controller board. The simulated and test results confirm the efficacy of the drive system.

2. IPMSM DYNAMICS

The mathematical model of an IPMSM drive can be described by the following equations in a synchronously rotating rotor d-q reference frame as,

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -P\omega_r L_q \\ P\omega_r L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ P\omega_r \psi_f \end{bmatrix} \tag{1}$$

$$T_e = T_L + J_m p\omega_r + B_m \omega_r \tag{2}$$

$$T_e = \frac{3P}{2}\left(\psi_f i_q + (L_d - L_q) i_d i_q\right) \tag{3}$$

where

v_d, v_q = d- and q-axis stator voltages;

i_d, i_q = d- and q-axis stator currents;

R = stator per phase resistance;

L_d, L_q = d- and q-axis stator inductances;

J_m = moment of inertia of the motor and load;

B_m = friction coefficient of the motor;

P = number of poles of the motor;

ω_r = rotor speed in angular frequency;

p = differential operator (=d/dt);

ψ_f = rotor magnetic flux linking the stator.

T_e, T_L = electromagnetic and load torques;

3. FLUX WEAKENING ALGORITHM

The steady-state voltage equations are derived from equation (1) :

$$v_q = R_s i_q + \omega_r L_d i_d + \omega_r \psi_f \tag{4}$$

$$v_d = -\omega_r L_q i_q + R_s i_d \tag{5}$$

For a limiting case of constant power of zero torque, the q-axis current is zero, therefore above equations (4) and (5) become

$$v_q = \omega_r L_d i_d + \omega_r \psi_f \tag{6}$$

$$v_d = -R_s i_d \tag{7}$$

Considering $V_s^2 = v_d^2 + v_q^2$ (8)

one can find the maximum value of speed for the maximum available inverter (also stator) voltage V_s from (6), (7) and (8) as

$$\omega_{r\max} = \frac{\sqrt{V_s^2 - R_s^2 i_d}}{\psi_f + i_d L_d} \tag{9}$$

The denominator of the above equation (8) must be positive giving condition of maximum stator current to be applied to counter the permanent magnet flux linkages as $i_{d\max} = I_s \langle \left(-\frac{\psi_f}{L_d} \right)$ (10)

Equations (9) and (10) are considered very important for real time implementation because these expressions provide upper limiting values of speed and d-axis current for a given IPMSM. By considering stator resistance $R_s = 0$, voltage limited ellipse equation can also be derived from (4), (5) and (9) as

$$\left(\frac{i_d + \frac{\psi_f}{L_d}}{\frac{V_s / \sqrt{2}}{\omega_r L_d}} \right)^2 + \left(\frac{i_q}{\frac{V_s / \sqrt{2}}{\omega_r Lq}} \right)^2 = 1 \tag{11}$$

Plots of q-axis vs. d-axis currents are shown in Fig.1 for speed range 200 rad/sec to 850 rad/sec (base speed 188 rad/sec) for a maximum inverter voltage of 250 volt.

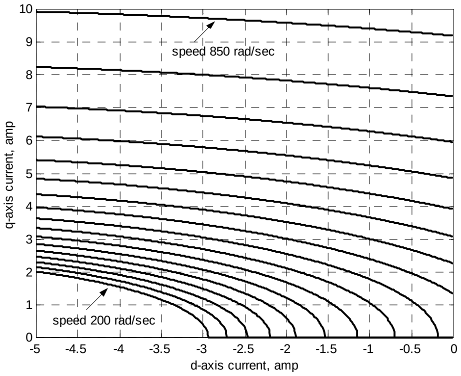

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Fig. 1 Voltage limited ellipses of IPMSM for flux weakening method of speed control

Considering

$$I_s = \sqrt{i_d^2 + i_q^2} \tag{12}$$

the expression of d-axis current can be derived from (6) and (7) as

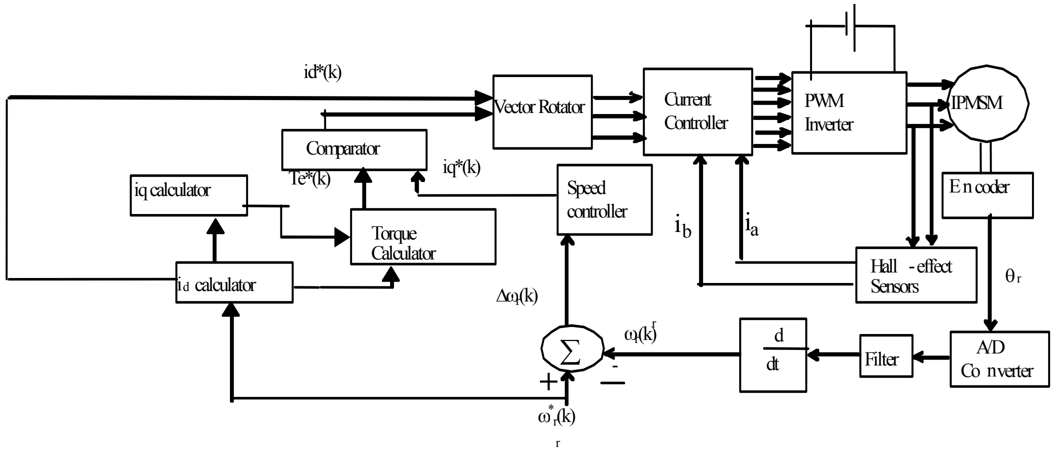

Fig. 2 Block diagram of flux weakening speed control of IPMSM drive

$$i_d = \frac{-L_d\psi_f \pm L_q\sqrt{\left[\left\{\left(L_d^2-L_q^2\right)\left(\frac{V_s}{\omega_r L_q}\right)^2 - I_s\right\}+\psi_f^2\right]}}{L_d^2-L_q^2} \quad (13)$$

Using the IPMSM data given in the Table-I, the expression of i_d in (13) has been simplified for the real time implementation using curve fitting method for a working range of speed of 188 rad/sec (base speed) to 276 rad/sec (doubling base speed) as

$$i_d = -0.000119\omega_r^2 - 0.080316\omega_r + 10.5269 \quad (14)$$

Using (12), the expression for q-axis current i_q has been obtained which is also simplified using curve fitting method and is given as

$$i_q = -0.260375 i_d^2 - 0.244651 i_d + 3.4422727 \quad (15)$$

Equations (14) and (15) are the key equations used for the flux weakening control of IPMSM. Block diagram in Fig. 2 shows the control scheme of the IPMSM drive. Using (14), the command d-axis current i_d^* is computed first, subsequently reference d-axis current i_q^* is calculated using equation (15). The command torque is obtained from a PI type speed controller. An estimated torque is calculated using (3), (14) and (15) and compared with the command torque. As long as the command torque is greater than the estimated torque, (14) and (15) are used to compute the three phase reference currents with the vector rotator. If the command torque is less than estimated torque, reference q-axis current is calculated using the command torque rather than the estmated torque. The hysteresis current controller compares the reference three phase currents with actual currents and generates base signals for the transistorized inverters.

4. RESULTS AND DISCUSSION

Several tests were performed to evaluate the performance flux weakening control based IPMSM drive. The speed and current responses are observed under different operating conditions, such as, various command speeds and loading conditions. Some of the sample results are presented in this paper. Before implementation, complete drive system for the flux weakening control have been simulated using Matlab/ Simulink software [7]. Some of the simulated results are also presented in this section.

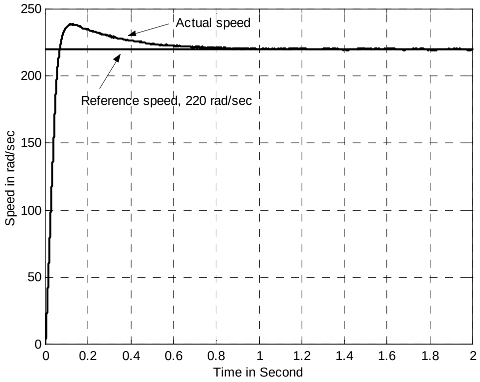

Fig. 3(a) Simulated speed of IPMSM drive for flux weakening control with reference speed 220rad/sec

Figures 3. (a) and (b) show the simulated speed and current responses, respectively for flux weakening control based IPMSM drive system under no-load condition with reference speed of 220 rad/sec. Figures 4.(a) and (b) show corresponding experimental speed, steady-state current responses, respectively for the flux weakening control under the same conditions.

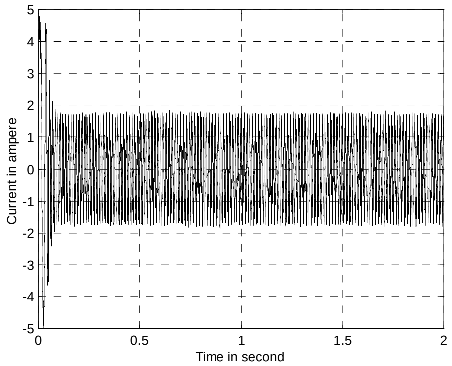

Fig. 3(b) Simulated current of IPMSM drive for flux weakening control with reference speed 220 rad/sec

The base speed of the IPMSM is 188 rad/sec, which corresponds 1800 rpm. From the above results of both simulation and experiment it is seen that the drive system is fully capable of operating at 220 rad/sec. For this operation stator voltage was not exceeded its rated value of 250 volt.

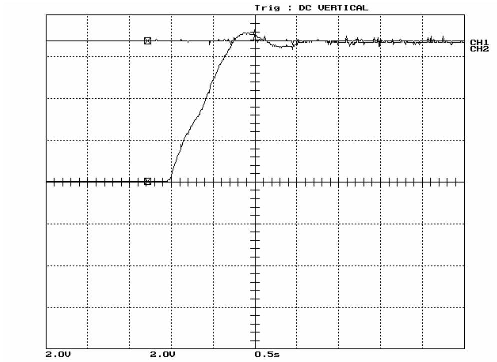

Fig. 4(a) Experimental speed of IPMSM drive for flux weakening control with reference speed 220 rad/sec. (Y-axis: 1div=65 rad/sec)

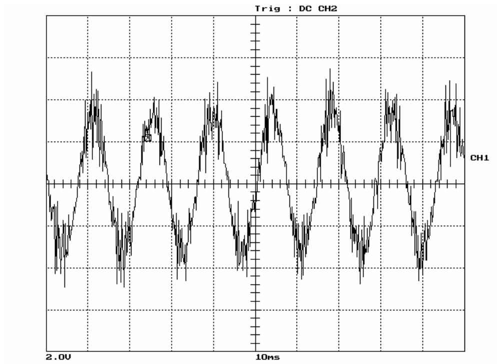

Fig. 4(b) Experimental current of IPMSM drive for flux weakening control with reference speed 220 rad/sec. (Y-axis: 1div=2 amperes)

5. CONCLUSIONS

In this paper a new approach of flux weakening method has been has been applied for the speed control of IPMSM drive above the base speed where relatively simpler expressions of d- and q-axis currents have been derived and incorporated in the IPMSM drive system. The IPMSM drive system is efficient enough to operate in no load and loading condition. Since in the flux weakening method, torque has to be decreased in the high speed range operation, therefore load has also been gradually removed when the reference speed was selected in higher range as for example double of the base speed. Derived equation of voltage limited ellipse, which has been plotted in Fig. 1 may dictate a new approach of flux weakening method for a optimum value of stator current which will provide better performance in terms of efficiency.

Table-I: Machine parameters

Motor rated power	3-phase, 1 hp
Rated voltage	250 V
Rated current	3 A
Rated frequency	60 Hz
Pole pair number (P)	2
d-axis inductance, L_d	42.44 mH
q-axis inductance, L_q	79.57 mH
Stator resistance, R	1.93 Ω
Motor inertia, J_m	0.003 kgm^2
Friction coefficient, B_m	0.001 Nm/rad/sec
Magnetic flux constant, ψ_f	0.311 volts/rad/sec

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