Adaptive Decoupling for IPM Machine(ICCAS 2005)

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Abstract: The current control for interior permanent magnet machines is more complicate than surface permanent magnet machine because of its torque characteristic depending on the reluctance. For high performance torque control, it requires state decoupling between the d-current and q-current dynamics. However the variation of the inductances, which couples the state dynamics of the currents, makes the state decoupling difficult. So some decoupling methods have developed to cope this variations and each current can be regulated independently. This paper presents a novel approach for fully decoupling the states cross-coupling using parameter adaptation. The adaptation method is based on the error between reference currents and the currents with state decoupling which have to follow the references. This method is more object-oriented than the other online parameter estimation methods in IPM machine and other electrical machines

Keywords: Adaptive decoupling , IPM machine

1. INTRODUCTION

When the AC machines model in the stationary frame is transformed into a synchronous frame, unwanted cross-coupling is produced[1-4]. So permanent magnet synchronous machines have state cross-coupling terms in their models. There are two types of motors in PMSM. One is surface permanent magnet machine and the other is interior permanent magnet machine which has magnets mounted inside the rotor. IPM machines have several advantages. First, The rotor is mechanically robust for high speed operation. Second, the different between d-axes and q-axis inductance can give additional torque. IPM and SPM have the same mathematical expression in their models but very different in control problems because of the second characteristic of the IPM. In SPM, zero d-axis current can produce maximum torque with nonzero q-axis current. This cancels the state cross-coupling and makes control easier. But, in IPM, maximum torque can be produced only when the two currents are controlled to whom are given look-up tables. So the state cross-coupling difficulty can not be avoided in there. For easy control of IPM machine, decoupling is needed and the accurate parameters are inevitable. However unfortunately, stator resistance and permanent magnet flux change with motor temperature [5]. In addition, magnetic saturation limits the air gap flux density and causes the varying inductance of IPM. So the parameter estimation of the inductances is highly desirable [6]. Several parameter estimation methods are developed in electric machine control. However they have not used decoupling. Their approaches are complicated and difficult in realization. The PI controllers are commonly used for AC machines. But this control method cannot work well in IPM because of the state cross-coupling. On-line parameter estimation method have been proposed in the decoupling problem[7][8]. However the method need the prior information of measured inductances as feed-forward term and has no guarantee for stability.

The purpose of this paper is to present a novel current controller based on decoupling and parameter estimation for IPM machine. The parameter estimation algorithm is derived from decoupled model using Lyapunov stability. Simulation results will be given.

2. IPM MACHINE MODELING AND DECOUPLING OF STATE CROSS-COUPLING

The IPM machine is represented by (1)

$$\begin{aligned} L_q \frac{di_q}{dt} &= -R_a i_q - L_d w i_d - K_e w + V_q \\ L_d \frac{di_d}{dt} &= L_q w i_q - R_a i_d + V_d \\ J \frac{dw}{dt} &= J K_t i_q - Bw - T_L \end{aligned} \qquad (1)$$

where L_q is a total d-axis inductance, L_d is a total d-axis inductance, K_e is a back-emf constant, i_q , i_d are q-axis and d-axis current respectively. Note that Lwi_d , Lwi_q are cross-coupling terms.

Typical IPM machine have the following maximum torque-current characteristic which is different from that of SPM machine.

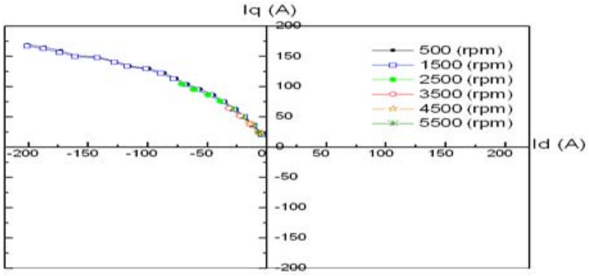

Fig.1 Typical maximum torque-current characteristic of IPM machine

From the above characteristic, it is clear that the currents have to be controlled independently. The following block diagram shows the current controlled IPM machine using state decoupling and PI controller.

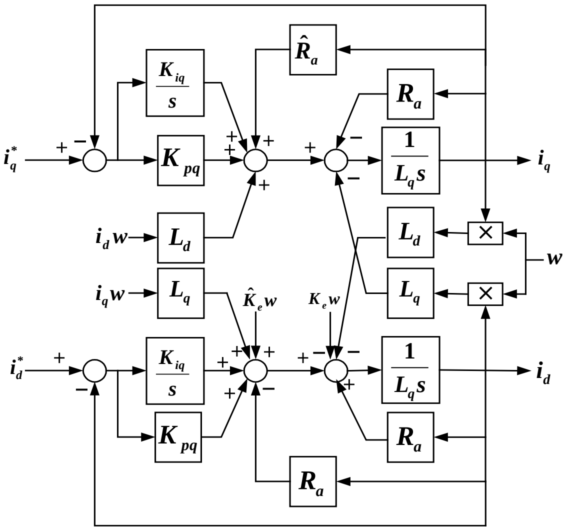

Fig.2 current controlled IPM machine using state decoupling and PI controller

Decoupling is a major factor which determine the control performance and depend on the accuracy of the parameter L_d, L_q. The following figures show the results of the PI control for IPM machine. They show that the parameter mismatches deteriorate control performance.

3. ON-LINE PARAMETER ESTIMATION

Under the assumption that other states cross-coupling have been decoupled, the q-axis current control system can be expressed as following block diagram. The d-axis current control system can also have the same expression. To apply the Lyapunov stability easily, proper states have to be chosen.

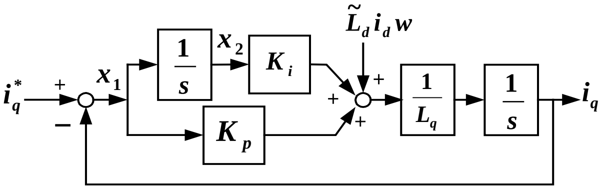

Fig.3 Q-axis current control system with states decoupling

From the fig.3 , the following equation is obtained.

$$L_q \dot{x}_1 = K_i x_2 + K_p x_1 + \tilde{L} i_d w \qquad \dot{x}_2 = x_1 \tag{2}$$

where $x_1 = e_q = i_q - i_q^*$ and $\dot{e}_q = \dot{i}_q$

In this paper, the following theorem has been obtained.

Theory: The estimated parameter using the following algorithm can make the overall system stable and parameter mismatches small.

$$\dot{\hat{L}}_d = -p_1 e_q i_d w \tag{3}$$

Proof.

Lyapunov candidate function is chosen as eq.(4).

$$V = \frac{1}{2}(L_q p_1 x_1^2 + p_2 x_2^2) + \frac{1}{2}\tilde{L}_d{}^2 \tag{4}$$

Its time derivative is

$$\dot{V} = L_q x_1 p_1 \dot{x}_1 + x_2 p_2 \dot{x}_2 + \tilde{L}_d \dot{\tilde{L}}_d$$
$$= (x_1 K_i p_1 x_2 + K_p p_1 x_1^2 + x_2 p_2 x_1) + (x_1 p_1 \tilde{L}_d i_d w + \tilde{L}_d \dot{\tilde{L}}_d)$$

W

e define $\dot{\tilde{L}}_d$ as follows.

$$\dot{\tilde{L}}_d = -p_1 x_1 i_d w$$

So following is obtained.

$$\dot{V} = x_1 K_i p_1 x_2 + K_p p_1 x_1^2 + x_2 p_2 x_1$$

This is negative because PI gains are chosen to make the system stable when uncertainties do not exist. The eq.(4) comes from the relation $\tilde{L} = \hat{L} - L^*$ under the assumption L^* is constant or slowly varying. Q.E.D.

4. SIMULATION AND EXPERIMENT RESULTS

The PI controller with decoupling and on-line parameter estimation was simulated for the IPM machine whose parameter are given in Table I

Table I. Motor Parameter

Parameter	Value
Max. Torque	7.66 Nm
Max. Speed	6200rpm
R	1.45Ω
Lq	11.04mH
Ld	3.74mH
λpm	0.0858Wb
J	99.6kg.$m^2 \times 10^{-6}$
Poles	4

The simulation results are shown as follows.

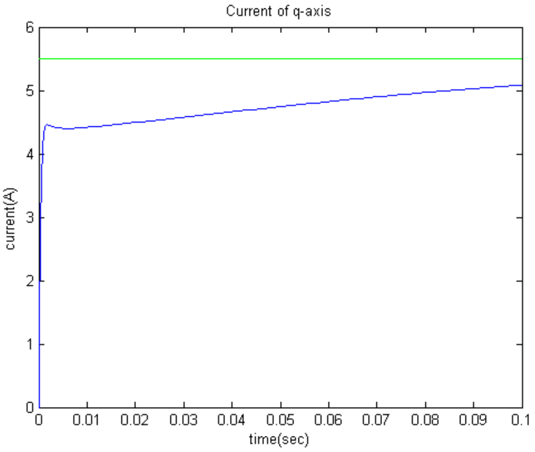

Fig.4 Q-axis current response controlled by existing method

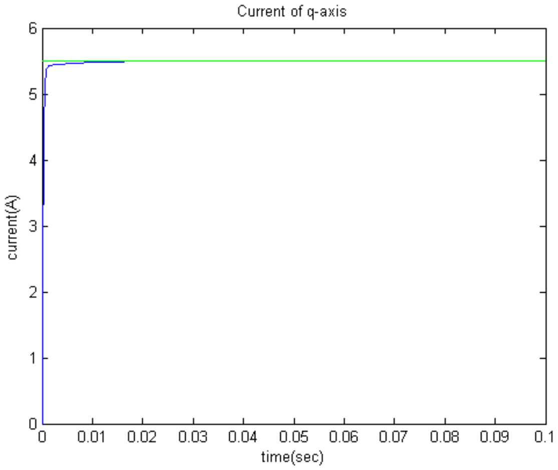

Fig.5 Q-axis current response controlled by proposed method

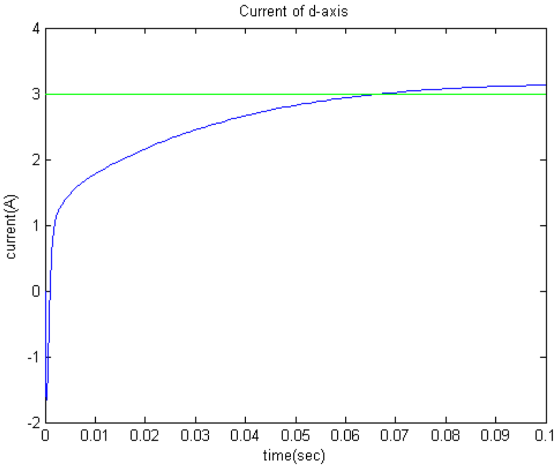

Fig.6 D-axis current response controlled by existing method

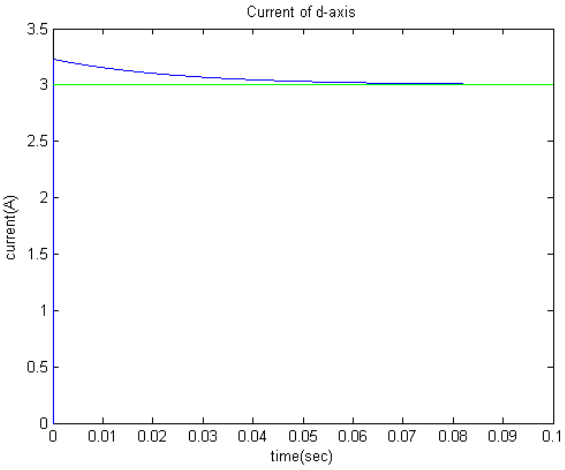

Fig.6 D-axis current response controlled by proposed method

5. CONCLUSIONS

A classical PI current controller cannot cope with cross-coupling which depends on the rotor speed and uncertain inductances. So On-line parameter estimation is required to mitigate this effect. A novel on-line parameter estimation was derived based on decoupling and Lyapunov stability. By using Lyapunov stability after applying decoupling method, the parameter estimation algorithm can be obtained more easily than other approaches. Simulation results show the coincident result with the theoretical assertion.

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