Research on Vector Decoupled system of the Machine based on Internal Model Current Control

WENXIANG ZHANG, XIANHONG KAN, AIMIN YANG
Junior College ,Computer Science and Information Technology College
Zhejiang Wanli University
No.8, South Qian Hu Road Ningbo, Zhejiang Province
CHINA
http://www.computer.zwu.edu.cn

Abstract: - On the basis of the dynamic asynchronous motor model in the *d—q* reference frame rotating at synchronous speed, the article, taking alternating current machine as example, introduces internal model control into current control on basis of the alternating inductive machine mathematical models under synchronous rotating coordinate, and designs the parameters of adjustor. Considering the machine magnetism saturation to different extent caused by load change in real course and so-caused nonlinear change of machine parameters,Internal Model Control method was introduced, based on which and rotor flux oriented vector control, the stator current controllers were detailedly designed. Considering the parameters nonlinearity caused by different extent flux saturation along with the variations of torque load in the real experimental systems, robustness of the current internal model controller to such nonlinear parameters was analyzed. Based on the model, a whole Vector Control simulation system and experiment setup were established, and subsequently the simulation and experimental studies were carried out respectively with and without flux saturation. It was indicated that, from the results, the current internal model controllers could provide good steady-state and dynamic decoupled performance under both model matching and model mismatching.

Key-Words: - asynchronous, vector transformation, decoupled control, field-orientation, internal model current control, Systematic modeling

1 Introduction

Alternating current asynchronous induction machine is a system of multi variable, strong couple, nonlinear and time varying. Its instantaneous torque is hard to control. So it's difficult to gain the same high dynamic timing performance as direct current machine. The technology [1][2] of vector transformation control, no matter it's rotor field-orientation[2], air interspaces field-orientation[3] , or stator linkage-orientation[4] and stator pressure-orientation[5], its basic conception is to decompose stator current into vertical direct current excitation (without power) current and torque (with power) current through the changes of rotating coordinate, and go on independent closed loop adjustment on them separately to realize the decoupled control on alternating current asynchronous machine.

The existing methods of current control include current blocked loop control and PI adjustment control under stator coordinate and synchronous coordinate. Of which, the current PI adjustment control under synchronous coordinate can especially earn good steady performance. While this method will directly decouple the dynamic effect because of the couple between d and q introduced by coordinate change. In addition, the parameters adjustment of PI controller on d , q axis is traditionally debugged and got by experiment. On that, literature [6][7] bring in the internal model control (IMC) in industry process control to the current control of alternating machine, and gave the design process of current loop control parameters and results of relevant simulation and experiments by taking eternal-magnetic synchronous machine as example. References [13] and [13] presented a nonlinear internal-model control (IMC) combining the feedback linearization control and IMC. The control system has strong robustness under the conditions of modeling uncertainties, inside and outside disturbances. It can effectively compensate for the nonlinearity of the plant. Moreover, by using the error between the plant and model outputs as a feedback signal, the nonlinear IMC has an inside integral action, which ensures the convergence of the plant output to the constant reference of the steady state. However, analysis on the decoupled effect and robustness research of internal current control methods under the condition of parameters nonlinear caused by load change is seldom seen in the existing literature.

In view of that, the article, taking alternating current machine as example, introduces internal model control into current control on basis of the alternating inductive machine mathematical models under synchronous rotating coordinate, and designs the parameters of adjustor. Considering the machine magnetism saturation to different extent caused by load change in real course and so-caused nonlinear change of machine parameters, the writer theoretically analyzes the dynamic decoupled effect and robustness from internal current control methods to parameter nonlinear. Based on that, he composed alternating asynchronous machine dynamic model which consider the effect of magnetism saturation in MATLAB/SIMULINK, and set up the magnetic test-type alternating inductive machine vector control system based on rotor field-orientation and internal current model control and stimulated and researched it on conditions of considering whether the magnetism is saturation or not. Results prove the correctness and effectness of current controller and adjustor based on internal current model control methods and the robustness and good dynamic decoupled effect of machine parameters nonlinear change. To further verify the proposed method, the experimental bench is also been setup base on TI DSP controller, and the experimental results also show the good performance using the proposed method.

2 Problem Formulation

2.1 Asynchronous machine model under synchronous rotating $d-q$ coordinate system

Alternating current asynchronous induction machine is a system of multi variable, strong couple, nonlinear and time varying system. According to the theory of the electric machine, the asynchronous induction machine mathematical model under the synchronous coordinate system can be expressed in a space vector form as [6][7]

$$\begin{cases} \dfrac{d}{dt}\vec{\psi}_s(t) = -R_s\vec{i}_s(t) - j\omega_1\vec{\psi}_s(t) + \vec{v}(t) \\ \dfrac{d}{dt}\vec{\psi}_r(t) = -R_r\vec{i}_r(t) - j\omega_2\vec{\psi}_r(t) \end{cases} \quad (1)$$

$$\begin{cases} \vec{\psi}_s(t) = L_s\vec{i}_s(t) + L_m\vec{i}_r(t) \\ \vec{\psi}_r(t) = L_r\vec{i}_r(t) + L_m\vec{i}_s(t) \end{cases} \quad (2)$$

In the formula, $\vec{i}_s, \vec{\psi}_s$ and $\vec{i}_r, \vec{\psi}_r$ are the current and the flux linkage vector of stator and rotor, respectively. $\vec{v}$ is the vector of stator voltage. R_s, R_r and L_s, L_r are the resistance and the self-induction of stator and rotor. L_m is the mutual induction. ω_1 and $\omega_2 = \omega_1 - \omega_r$ are stator frequency and slip frequency, respectively.

From formula (1) and (2), we can get the following equation

$$\begin{aligned} &L_\sigma \frac{d\vec{i}_s(t)}{dt} + [R_s + (\frac{L_m}{L_r})^2 R_r]\vec{i}_s(t) + j\omega_1 L_\sigma i_s(t) \\ &= \vec{v}(t) + \frac{L_m}{L_r}(\frac{R_r}{L_r} - j\omega_r)\vec{\psi}_r(t) \end{aligned} \quad (3)$$

where $L_\sigma = L_s[1 - L^2{}_m/(L_s L_r)]$

Therefore, under the rotor field orientation (d-q reference frame), we can get that $\psi_{rd} = \psi_r, \psi_{rq} = 0$, hence, the asynchronous inductive machine model can be expressed in the rotor reference frame as

$$\begin{cases} v_d(t) = v'_d(t) - \dfrac{L_m}{L_r^2} R_r \psi_{rd} \\ v_q(t) = v'_q(t) + \omega_r \dfrac{L_m}{L_r} \psi_{rd} \end{cases} \quad (4)$$

In the formula, $R'_s = R_s + (\frac{L_m}{L_r})^2 R_r$

and

$$\begin{cases} v'_d(t) = R'_s i_{sd}(t) + L_\sigma \dfrac{di_{sd}(t)}{t} - \omega_1 L_\sigma i_{sq}(t) \\ v'_q(t) = R'_s i_{sq}(t) + L_\sigma \dfrac{di_{sq}(t)}{t} + \omega_1 L_\sigma i_{sd}(t) \end{cases} \quad (5)$$

Transform formula (5) of Laplace, we can get

$$\boldsymbol{U}(s) = \boldsymbol{G}^{-1}(s)\boldsymbol{Y}(s) \quad (6)$$

Therefore it comes that

$$\boldsymbol{U}(s) = \begin{bmatrix} V'_d(s) \\ V'_q(s) \end{bmatrix}, \boldsymbol{Y}(s) = \begin{bmatrix} I_{sd}(s) \\ I_{sq}(s) \end{bmatrix} \quad (7)$$

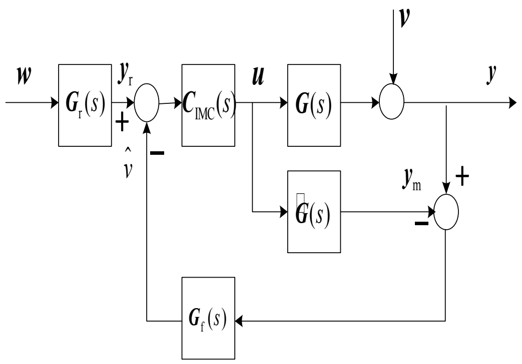

Fig.1 IMC structure

$$\boldsymbol{G}(s) = \begin{bmatrix} sL_\sigma + R'_s & -\omega_1 L_\sigma \\ -\omega_1 L_\sigma & sL_\sigma + R'_s \end{bmatrix}^{-1} \quad (8)$$

2.2 Design of internal current controller

The well-known internal model control scheme is based on a particular structure, in which the controller explicitly includes a model of the plant to be controlled. This structure has been and continues to be very popular in process control applications since it allows to the designer to tune a single parameter to achieve an interesting trade-off between closed loop performance and robustness to model inaccuracies. However the application of internal model to the electric machine is not popular.

In this paper, we introduce the internal model control of process control on industry course into the design of current loop controller parameters for synchronous induction machine. Internal model control and its equivalent structural chart are the same as Fig.1 and Fig.2[6] . In these figures, $\hat{G}(s)$ is the internal model, G(s) is the model of the plant, $C_{IMC}(s)$ is the internal model controller, $\boldsymbol{u}, \boldsymbol{y}$ are voltage vector and current vector of the vector control system and $\boldsymbol{w}$ is the reference current vector.

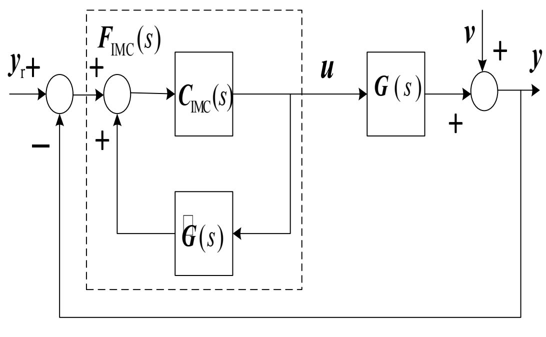

Fig.2 Equivalent diagram of IMC

From chart 2, we can get

$$\boldsymbol{F}_{IMC}(s) = [\boldsymbol{I} - \boldsymbol{C}_{IMC}(s)\hat{\boldsymbol{G}}(s)]^{-1}\boldsymbol{C}_{IMC}(s) \quad (9)$$

From formula 8, we can get the minimum phasic system of $\hat{G}(s)$. Then we can get

$$C_{IMC}(s)=\hat{G}^{-1}(s)f(s) \quad (10)$$

$$f(s)=\frac{\alpha}{s+\alpha}I \quad (11)$$

In the formula, α is the band width of current loop. And $\alpha=2.2/t_r$. t_r is the ascending time of current.

From (9) - (11) , the current controller can be derived as

$$F_{IMC}(s)=[I-\frac{\alpha}{s+\alpha}I]^{-1}\hat{G}^{-1}(s)\frac{\alpha}{s+\alpha}$$
$$=\frac{\alpha}{s}\hat{G}^{-1}(s)=\alpha\begin{bmatrix}\hat{L}_\sigma(\frac{\hat{R}'_s}{s\hat{L}_\sigma}+1) & -\frac{\omega_1\hat{L}_\sigma}{s}\\ \frac{\omega_1\hat{L}_\sigma}{s} & \hat{L}_\sigma(\frac{\hat{R}'_s}{s\hat{L}_\sigma}+1)\end{bmatrix} \quad (12)$$

In the formula, $\hat{R}'_s$, $\hat{L}_\sigma$ are estimated value of R'_s and L_σ.

It is obvious that we can confirm the exact design parameters of the current loop controller so long as we know the control band width of current loop and machine parameters.

Generally speaking, the machine model will mismatch the real objective because of the estimation error of parameters.

But, we know

$$C_{IMC}(0)=\hat{G}^{-1}(0)f(0)=\begin{bmatrix}\hat{R}'_s & -\omega_1\hat{L}_\sigma\\ \omega_1\hat{L}_\sigma & \hat{R}'_s\end{bmatrix}I=\hat{G}^{-1}(0) \quad (13)$$

And

$$\frac{d}{dt}[C_{IMC}(s)\hat{G}(s)]|_{s=0}=\frac{d}{dt}[\hat{G}^{-1}(s)f(s)\hat{G}(s)]$$
$$=\frac{d}{dt}[\frac{\alpha}{s+\alpha}]|_{s=0}=-\frac{1}{\alpha}\neq 0 \quad (14)$$

We can see that that there's no steady state errors under the step reference input and constant value disturbance for the inductive machine current control system based on internal model control while model parameters mismatch the real model.

3 Systematic modeling

MATLAB program is a powerful tool for simulation, and the SIMULINK is a toolbox extension of the MATLAB program, it is a program for simulating dynamic systems. According to the above analysis on the induction motor model and the internal model controller, the writer composed the alternating asynchronous machine dynamic model of different magnetic saturation effect caused by different load by adopting the S function in MATLAB and established the simulation system of magnetism test-type alternating inductive machine vector control based on rotor field-orientation and internal current model control using SIMULINK module.

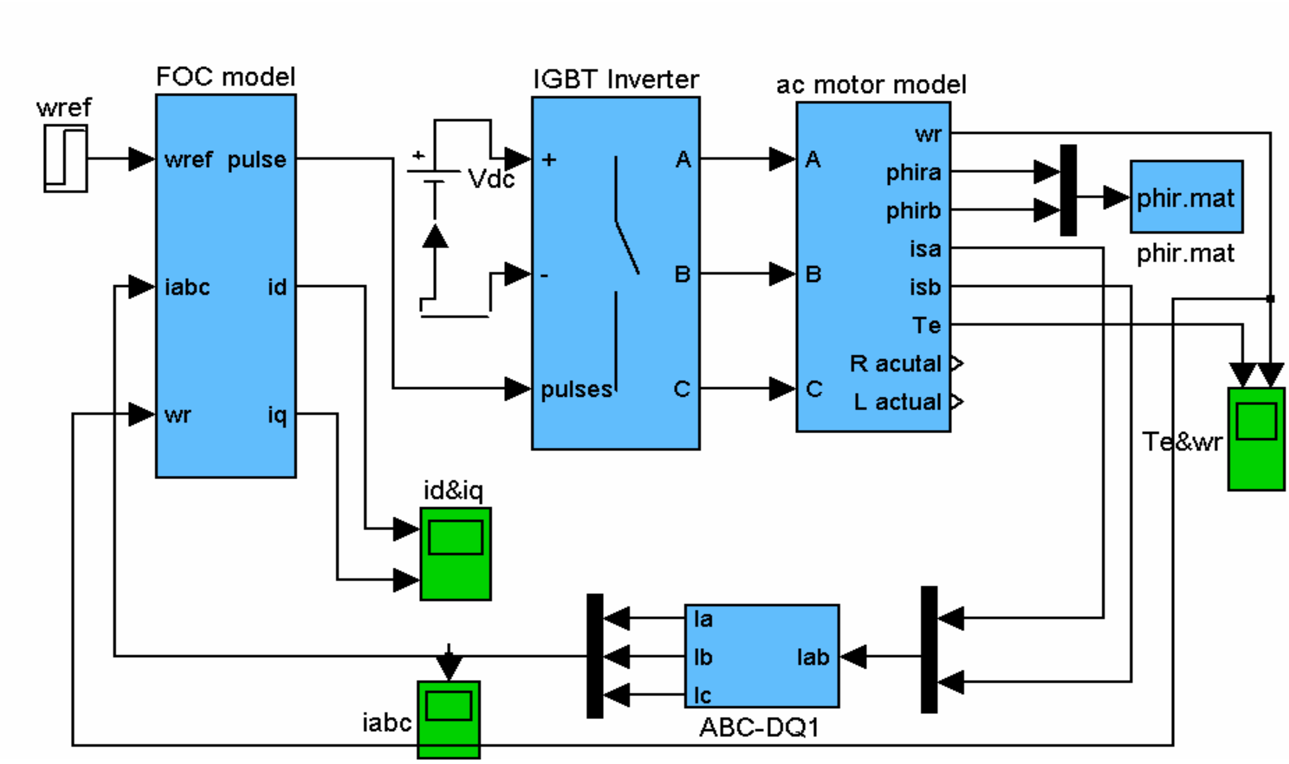

Fig.3 Vector-controlled system of AC motor

3.1 Vector control system model

The block diagram of the whole asynchronous induction motor vector control system is build using MATLAB/SIMULINK and S function as shown in Fig.3. The whole system composes speed loop (outer loop) and current loop (inner loop). The output of speed loop is the input of current loop. Current loop mainly realizes the decoupled control of rotor field-orientation torque control (FOC) based on the internal model control, which are all included in the FOC model module in Fig.3. The IGBT inverter comes from the SIMULINK / Simpowersystems module directly. ABC-DQ module performs the transformation of the current from the two phase stator reference frame to three phase stator reference. The ac-motor model in the diagram is composed by the writer by using the S function in MATLAB, considering the alternating asynchronous machine dynamic model of magnetic saturation effect caused under different load condition.

3.2 Design of internal current controller

From formula (12), we can get the structural block diagram of alternating inductive machine internal current model decoupled control realization using MATLAB/Simulink. Please refer to Fig. 4.

The input of the current internal model controller as shown in Fig.4 is the output of the speed controller *wr*, the current id, iq, which are obtain from the Park transformation, the output is the vd and vq, which are the input of the FOC functional module, which is not discussed in detail in this paper.

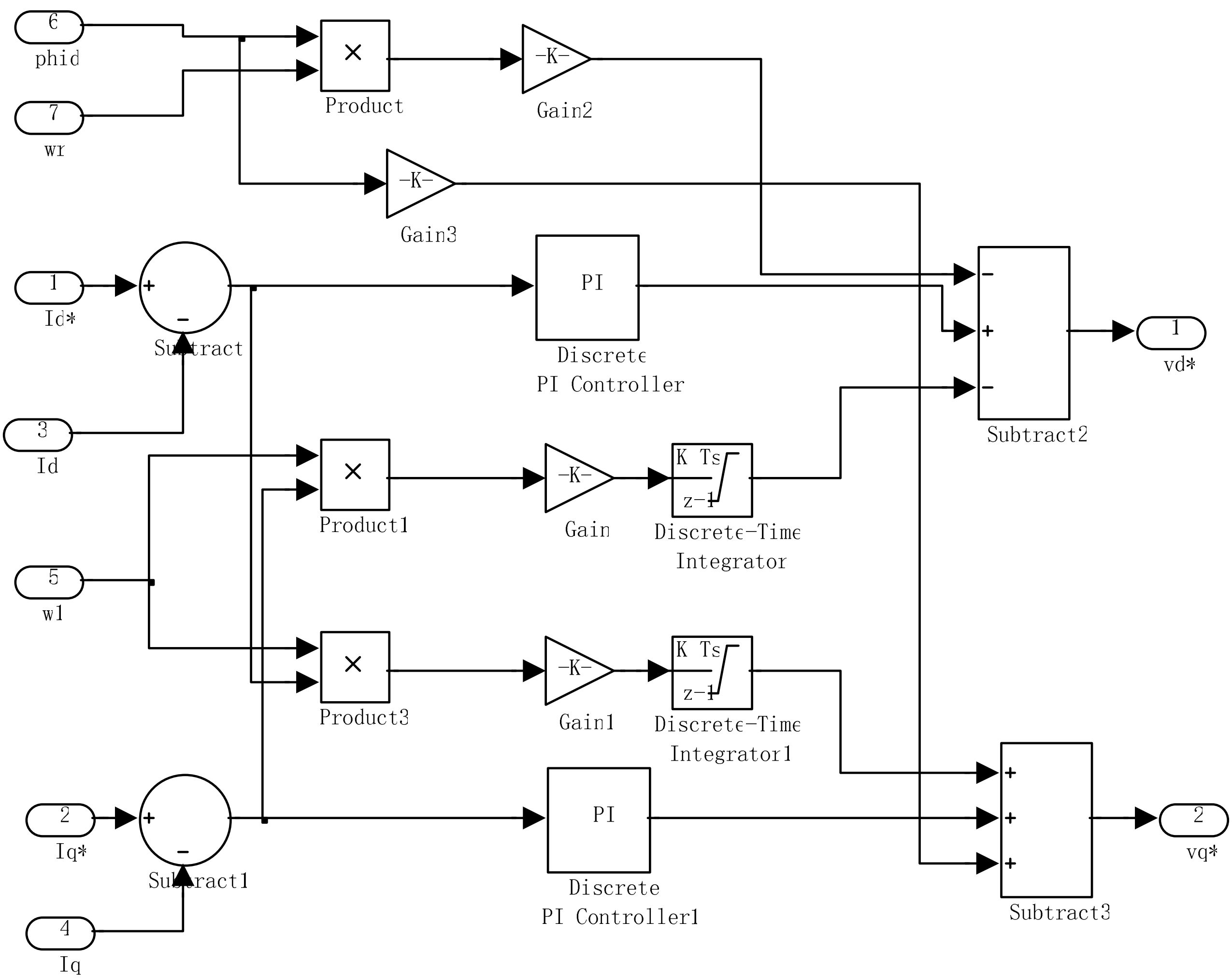

Fig.4 Current Internal-Model Controller

4 Simulation results

Based on the MATLAB model in section 3, the simulation studies have been conducted on conditions of both ignoring and considering the magnetic saturation, and effect under different load. we simulate and research the magnetic test-type asynchronous machine vector control based on rotor field-orientation and internal current model control, the parameters of the induction motor are shown in the appendix. Diagram 5~7 and 8~10 are the simulation results of magnetic saturation effect ignoring and considering different load, respectively.

4.1 Effect of ignoring machine magnetic saturation

Under the condition of ignoring the magnetic saturation, we can get the simulation results as shown in diagram 5~7. The operation condition is that the induction motor is started without any load when t=0s, and the load is changed to 200Nm abruptly when t=1s, then change to 150Nm when t=2s, and back to 0Nm when t=3s. Fig.5 shows the Simulated Response of electromagnetic torque, Fig.6 shows the Simulated Response of d- and q-axis current, and Fig.7 is the Rotor speed response. It can be seen from these waveforms that both the dynamic and static performance of the torque, current and the rotor speed are good, which prove the decoupled performance of the vector control based on rotor vector-orientation and internal current model control on condition of ignoring magnetic saturation effect.

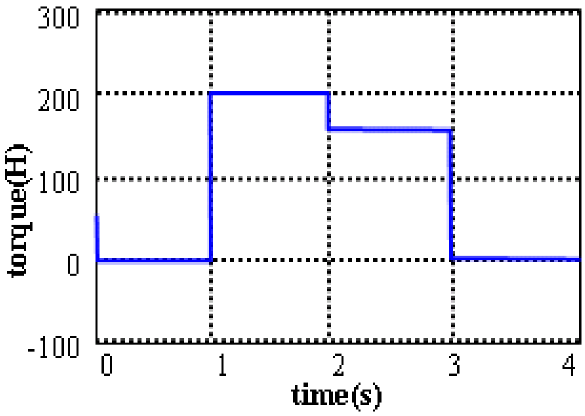

Fig.5 Simulated Response of electromagnetic torque

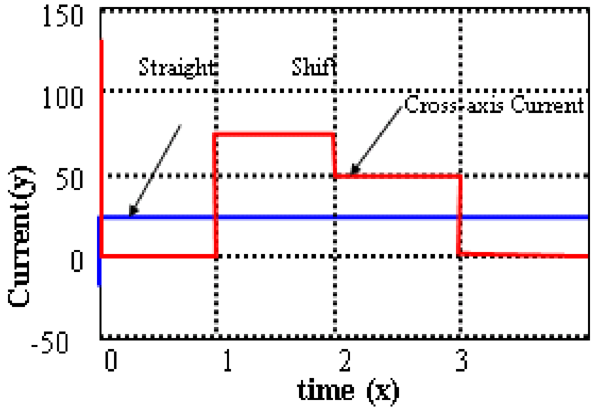

Fig.6 Simulated Response of d- and q-axis current

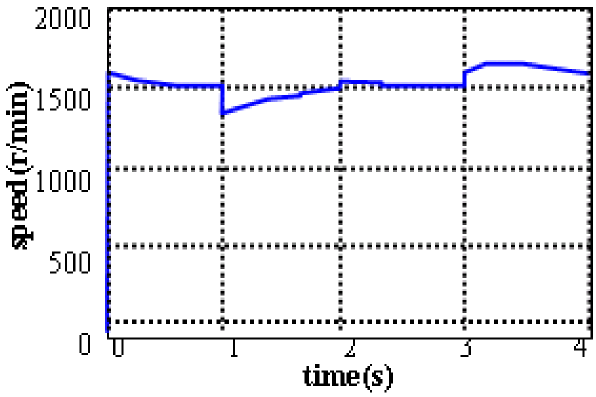

Fig.7 Rotor speed response

4.2 Effect of considering machine magnetic saturation

While, the machine magnetic saturation effect can not be totally ignored in practical cases. Therefore, we also simulate the air field saturation caused by load change on condition of synchronous machine's actual circulation while considering the nonlinear parameters caused by machine magnetic saturation effect. The simulation results are shown in Figs.8~10.

In Figs.8~10, the operation conditions are exactly the same as for the Figs.5~7. However, we can see from the waveforms that the current adjustment dynamic performance based on internal current model control is correspondingly worse than the simulation result when ignoring the magnetic saturation effect of the induction motor (the quadrature axis current dynamic course in Fig.9). But, it can been seen from these figures that the internal model controller can still supply good steady torque decoupled effect, which can also be analyzed from feedback control theory.

Taking the axis current decouple in Fig.4 as an example, the decoupled signal is from current i_{sq} single closed-loop route way. Considering the lower part structure of diagram 4, take

$$C(s) = \alpha \frac{\hat{R}_s' + \hat{L}_\sigma}{s},$$

$$P(s) = \frac{1}{\hat{R}_s' + \hat{L}_\sigma s},$$

$$W_1(s) = \frac{\alpha \omega_1 \hat{L}_\sigma}{s},$$

and $W_2(s) = \omega_1 \hat{L}_\sigma$

It can be obtained from the above four equations that the decoupled voltage of d axis.

$$\Delta V_{qd}(s) = W_2(s) I_{sq}(s) - [I^*_{sq}(s) - I_{sq}(s)] W_1(s),$$

then we can get

$$\frac{\Delta V_{qd}(s)}{I^*_{sq}(s)} = \frac{C(s)P(s)W_2(s) - W_1(s)}{1 + C(s)P(s)} = \frac{\alpha \omega_1 (L_\sigma - \hat{L}_\sigma)}{s[1 + C(s)P(s)]},$$

Shown from the above formula, the decoupled pressure, caused by parameters estimation error because of magnetic saturation, with the denominator of $1 + C(s)P(s)$, is controlled by minus feedback and then achieve good decoupled effect.

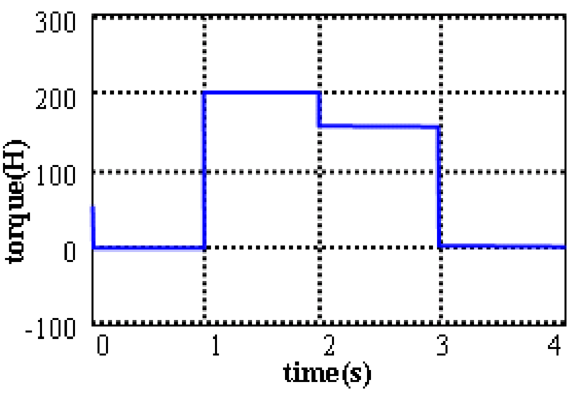

Fig.8 Simulated Response of electromagnetic torque

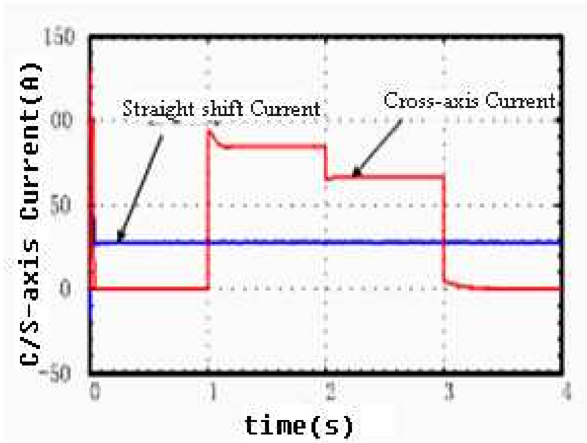

Fig.9 Simulated Response of d- and q-axis current

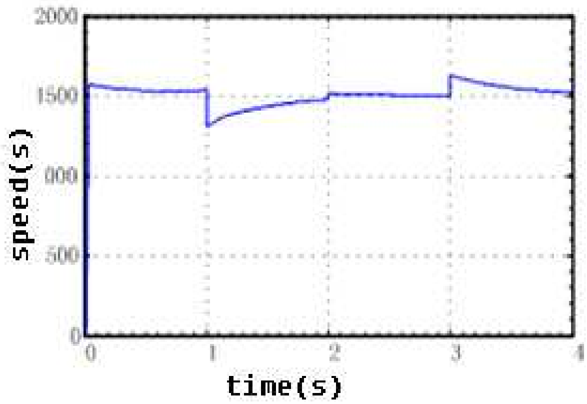

Fig.10 Simulated Rotor speed response

5 experimental results

In order to verify the effectiveness of the proposed control strategy, an experimental implementation of the control scheme is carried out according to Fig. 3. The experimental setup incorporates a DSP board DS1102 , which is based on the 32-bit floating point DSP TI TMS320C31. The board is also equipped with a fixed-point 16-bit TMS320P14 DSP, which is used as a slave processor. In this work, the slave processor is configured to work as digital input/output subsystem as shown in Fig. 11, A three-phase insulated gate bipolar transistor (IGBT) intelligent power-module is used for an inverter, which is supplied by a dc link voltage supply.

In this work, two phase currents ia and ib are sensed by the Hall-effect current sensors. These currents are fed to the DSP through the signal conditioning circuit. Furthermore, the position of the rotor is sensed by an incremental encoder and fed to the encoder interface on the DSP board. The control algorithm is written in C language and is compiled by the TI C compiler to generate the object code. The outputs of the board are six logic signals, which

are fed to the IGBT inverter to drive the induction motor.
The sampling time for experimental implementation is determined to be 100 μ s. The design data of the experimental motor is given in the Appendix as well.

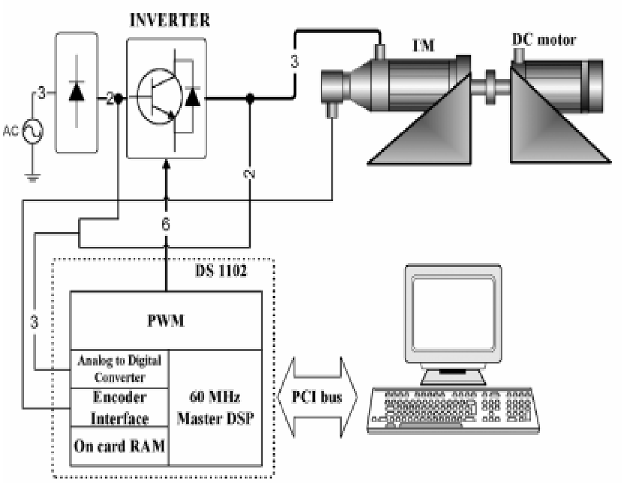

Fig. 11. Experimental setup for the asynchronous motor drive

It should be noted that the machine magnetic saturation effect can not be ignored in experimental case. Under exact the same operation conditions as in the simulation studies for Figs.8-10, the corresponding experimental results are shown in Figs.12-14.

Figs12-14 show the dynamic and static decoupling torque performance under the rotor flux linkage orientation and current internal model control based vector control. From these torque, current and rotor speed response waveforms it can be seen that using the internal model current controller, the experimental result match the simulation results very well. It proved the effectiveness of the proposed internal model controller based vector control for the synchronous induction motor.

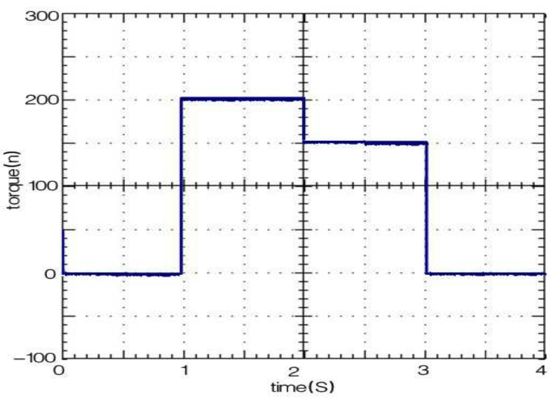

Fig.12 experimental Response of electromagnetic torque

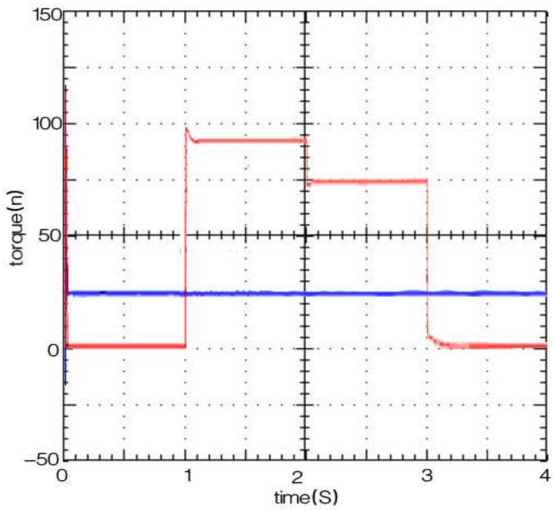

Fig.13 experimental Response of d- and q-axis current

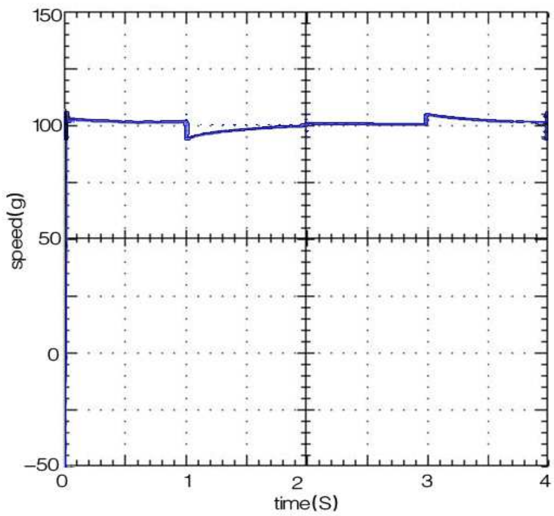

Fig.14 experimental Rotor speed response

6 Conclusions

Considering that the machine parameters in real system will bring magnetic saturation to cause nonlinear change because of load change, while the asynchronous machine model in MATLAB/SIMULINK didn't consider magnetic saturation effect, the writer composed the asynchronous inductive machine dynamic model which considers machine magnetic saturation. The magnetic test-type asynchronous inductive machine vector control simulation system based on the internal current model control adjustor and rotor magnetism-orientation brought by itself can supply good torque dynamic and static characteristics and decoupled effect on condition of the model mismatch caused by machine model match and field saturation effect. Moreover, the internal current model adjustor can only confirm the control parameters of quadrature and direct axis according to the needed current band width and estimated model parameters. The experimental prototype based on the TI DSP has also been setup, and the proposed control method for asynchronous induction motor has also been verified by experiment results. Table1 show the Asynchronous machine parameters

Appendix:

P_N	37300W
p	2
n_N	1420 r/min
U_N	460V (line-line)
R_1	0.087 Ω
R_2	0.226Ω
L_m	34.7 mH
L_1	35.5 mH
L_2	35.5 mH
J	0.0067 kgm^2

Table 1 Asynchronous machine parameters

References:

[1] Blaschke. Felix, Principle of field orientation as used in the new Transvektor control system for induction machines, *Siemens Review[J]*, v 39, n 5, May, 1972, pp 217-220.

[2] Su Weifeng, Liu Congwei, Sun Xudong, et al. Speed controller for induction motors based on Kalman filtering) [J]. *J Tsinghua Univ*, 2003, 43(9): 1202-1205

[3] Longya Xu, Wei Cheng, Torque and Reactive Power Control of a Doubly Fed Induction Machine by Position Sensorless Scheme, *IEEE TRANSACTIONON INDUSTRY APPLICATIONS [J], Vol. 31, No.3, MAY/JUNE* 1995, pp636-642.

[4] Zhang Xu, Qu Wenlong. A novel compensation method of stator flux estimating in low speed region [J]. *Adv. Tech. of Elec. Eng. & Energ*y, 2002, 22(3): 50-54

[5] R.Datta and V.T. Ranganathan, Decoupled control of active and reactive power for a grid-connected doubly-fed wound rotor induction machine without position sensors. *In Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Fourth IAS Annual Meeting*, pp. 2623-2628.

[6] Lennart Harnefors, Hans-Peter Nee, Robust Current Control of AC Machines Using the Internal Model Control Method, *IEEE Industry Application Society Annual Meeting [C],* pp 303-309.

[7] Lennart Harnefors, Hans-Peter Nee, Model-Based Current Control of AC Machines a Using the Internal Model Control Method, *IEEE Transactions on Industry Applications [J], Vol.34, No.1, January/February*, 1998, pp.133-141.

[8] Liu Guohai,Dai XianZhong, Induction Motor decoupling control system, IEC Journal[J], 2001, 16（5）, 30－34.

[9] Kadjoudj M, Benbouzid M E H. A robust hybrid current control for permanent magent synchronous motor drive\[A\]. IECON’01\[C\]. Piscataway: IEEE, 2001, 2 068-2 073.

[10] DEPENBROCK M.Direct Self_Control(DSC) of inverter_fed induction machine[J].IEEE Trans Power Electronics,1988,PE-3(4),420-429.

[11] GIUSEPPE S.BUJA, MARIAN P. KAZMIERKOWSKI. Direct Torque Control of PWM Inverter_Fed AC Motors_A Survey[J].IEEE trans Industrial Electronics, 2004, 51(4): 744-757.

[12] Cheng Boshi, Electric Traction Control System [M],BeiJing: Machinery Industry Press, 1997.4,PP.55-81.

[13] Vasudevan, *Different viable torque control schemes of induction motor for electric propulsion systems*, Industry Applications Conference, 2004.

[14] Ouadi.H, *Modeling saturated induction motors*, Control Applications, 2004. Proceedings of the 2004 IEEE International Conference.

[15] Agamy. M.S,*Adaptive fuzzy variable structure control of induction motors*,Electrical and Computer Engineering, 2004.

[16] Kuo, Ying-Piao; Lee, Chun-Yao; Shiu, Jin-Wei; Chang, Hong-Chan , Development of top-down experimental procedure for partial discharge recognition of current transformers, *WSEAS Transactions on Systems*, August 2005, p 1233-1241

[17] Jikuya, Ichiro; Hodaka, Ichijo , A geometric characterization of stabilizability by double periodic state feedback for linear periodic continuous-timesystems,*WSEAS Transactions on Systems*, January 2007, p 1-8
[18] Breaz, Radu Eugen; Bologa, Octavian; Racz, Gabriel Sever; Oleksik, Valentin,Motion control with fuzzy controllers - A study by means of simulation,*WSEAS Transactions on Systems*, January 2007, p 96-101
[19] Gang.Youl.Jeong,*Speed-sensorless induction motor control system using a rotor speed compensation with the rotor flux error*,Power Electronics Specialists Conference, 2004.
[20] Soshin. K etc,*Utilization development of speed sensor-less vector controlled inverter with the novel automatic tuning scheme of the induction motor parameters*,Power Electronics, Machines and Drives, 2004 .
[21] Grantham.C etc, *Rapid parameter determination for induction motor analysis and control*, Industry Applications,2003 .
[22] Vasic. V etc,*A stator resistance estimation scheme for speed sensorless rotor flux oriented induction motor drives ,*Energy Conversion,2003 .
[23] Soshin. K etc,*Sensorless induction motor drive incorporating vector controlled scheme PWM inverter-fed with autotuning machine parameter estimation strategy*, Power Electronics Specialist Conference, 2003.