RLS 기법을 이용한 유도전동기의 속도센서없는 벡터제어

論 文
48B-3-7

Speed-Sensorless Vector Control of an Induction Motor Using Recursive Least Square Algorithm

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Abstract - This paper is on realization of the speed-sensorless vector control of an induction motor using the RLS(Recursive Least Square) algorithm. The speed estimator is including the RLS algorithm and a rotor flux observer. The RLS algorithm has speed and rotor time constant as parameter vectors and rotor flux observer is designed to have robustness to stator resistance variation and through the IP(Integral and Proportional) speed controller stable performance is obtained for estimating rotor speed. Finally the total algorithm are realized in induction motor drive system and its effectiveness is verified.

Key Words : Speed-Sensorless, Recursive Least Square, Integral and Proportional control

1. INTRODUCTION

Obtaining the exact rotor speed is required for accurate speed control and a resolver or encoder etc. is used in its measuring. But using these sensors has its limits in the its application and improvement of performance because of the environmental noises and the operating time of processors. To solve these problems, speed sensorless vector control has been studied and reported since 1980. In the early studies, the induction motor speed was calculated by using the instantaneous orientation of the flux vector. The difficulty in this case lies in determining the instantaneous orientation of the relevant vector. In recent years, modern control theories have been applied to speed estimation; Schauder[1]'s Model Reference Adaptive System, Hori[2]'s a new sensitivity function, Kubota[3]'s a full order observer and adaptive control theory, Lipo[4]'s Extended Kalman Filter and so on. But it is difficult for these schemes to obtain a satisfactory stable performance and variable speed responses especially in low speed region.

In this paper, to realize a stable speed-sensorless vector control system, a new speed-sensorless vector control scheme consisting of RLS(Recursive Least Square) algorithm, robust rotor flux observer and IP(Integral and Proportional) speed controller is proposed and the total algorithm are realized in induction motor drive system and its effectiveness is verified.

2. STATE EQUATIONS FOR INDUCTION MOTOR

State equations for an induction motor can be expressed in the synchronous frame in terms of stator current(i_s) and rotor flux(λ_r) as (1) where v_s is input stator voltage.

$$\begin{bmatrix} \dot{i}_s \\ \dot{\lambda}_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} i_s \\ \lambda_r \end{bmatrix} + \begin{bmatrix} B_1 \\ 0 \end{bmatrix} v_s \tag{1}$$

and the output equation is as the following.

$$i_s = [I \quad 0] \begin{bmatrix} i_s \\ \lambda_r \end{bmatrix} \tag{2}$$

where

$$i_s = \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix},\ \lambda_r = \begin{bmatrix} \lambda_{dr} \\ \lambda_{qr} \end{bmatrix},\ v_s = \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}$$

$$A_{11} = -[R_s/\sigma L_s + R_r(1-\sigma)/\sigma L_r]I - \omega_e J$$

$$A_{12} = [(1-\sigma)R_r/\sigma L_m L_r]I - [(1-\sigma)\omega_r/\sigma L_m]$$

$$A_{21} = [L_m R_r/L_r]I,\ A_{22} = -[R_r/L_r]I - [\omega_e - \omega_r]J$$

$$B_1 = I/\sigma L_s\ ,\ I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\ ,\ J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

σ, ω_e and ω_r represent total leakage factor, synchronous speed and rotor speed respectively.

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接受日字 : 1997年 4月 4日
最終完了 : 1999年 2月 11日

3. DESIGN OF ROTOR FLUX OBSERVER

Two points must be considered in the design of a rotor flux observer used in the speed estimator. First, it must be robust to parameter variation. Second, the rotor flux observer must be designed to minimize the lag which can be caused in estimating rotor flux. The d-q vector model of rotor flux observer which satisfies the above considerations in the stationary reference frame is shown in Fig. 1 and the rotor flux observer consists of two lag circuits.

The rotor flux observer in Fig. 1 can be expressed in frequency domain as follows.

$$\vec{\lambda}^{s}_{dqr}=\frac{T_c\ \vec{E}^{s}_{c}}{1+j\omega_e T_c}+\frac{\vec{\lambda}^{s*}_{dqr}}{1+j\omega_e T_c} \tag{3}$$

where $*$ means reference value and the arrow represents a vector and

$$\vec{\lambda}^{s*}_{dqr}=\begin{bmatrix}\lambda^{s*}_{dr}\\ \lambda^{s*}_{qr}\end{bmatrix},\ \vec{E}_c=\begin{bmatrix}E^{s}_{dr}\\ E^{s}_{qr}\end{bmatrix},\ \vec{\lambda}^{s}_{dqr}=\begin{bmatrix}\lambda^{s}_{dr}\\ \lambda^{s}_{qr}\end{bmatrix}$$

Calculated back EMF($\vec{E}^{s}_{c}$) with variation of leakage inductance and real back EMF($\vec{E}_{dqr}$) can be represented as follows.

$$\begin{aligned}\vec{E}^{s}_{c} &= \vec{V}^{s}_{dqs}-(R^{n}_{s}+j\omega_e L^{n}_{\sigma})\ \vec{I}^{s}_{dqs}\\ \vec{E}^{s}_{dqr} &= \vec{V}^{s}_{dqs}-(R_{s}+j\omega_e L_{\sigma})\ \vec{I}^{s}_{dqs}\end{aligned} \tag{4}$$

where R^{n}_{s} and L^{n}_{σ} are nominal values. Therefore estimated rotor flux vector is expressed as (5).

$$\vec{\lambda}^{s}_{dqr} = \vec{\mu} T_c \vec{E}^{s}_{c}+\vec{\mu}\ \vec{\lambda}^{s*}_{dqr} \tag{5}$$

where T$_c$ is a time constant of lag circuit and P means a differential operator and

$$\vec{\mu} = \frac{1}{1+j\omega_e T_c} = |\vec{\mu}|\angle\phi$$

$$|\vec{\mu}| = \frac{1}{\sqrt{1+(\omega_e T_c)^2}}\ ,\ \angle\phi = -\tan^{-1}(\omega_e T_c)$$

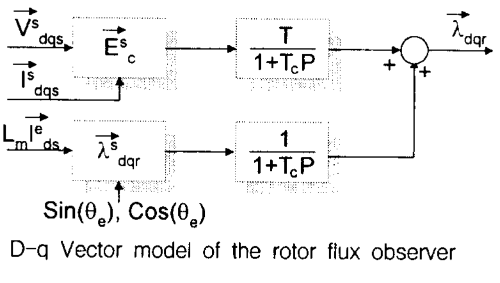


Fig. 1. D-q Vector model of the rotor flux observer

Also rotor flux vector in (5) can be divided to three components of $\vec{\lambda}_1$, $\vec{\lambda}_2$ and $\vec{\lambda}_3$ as (6). In (6), $\vec{\lambda}_2$ is related to parameter variations and can be ignored as T$_c$'s setting to T$_r$ and the rotor flux can be estimated without the lag by the compensating effect of $\vec{\lambda}_3$ through overall speed region[5].

$$\begin{aligned}\vec{\lambda}^{s}_{dqr} &= \vec{\mu} T_c\ (\vec{E}^{s}_{dqr}+(\varDelta R_s+j\omega_e\varDelta L_\sigma))\ \vec{I}^{s}_{dqs}+\vec{\mu}\ \ \vec{\lambda}^{s*}_{dqr}\\ &= \ \vec{\mu} T_c\ \vec{E}^{s}_{dqr} && (=\vec{\lambda}_1)\\ &+\ \vec{\mu} T_c(\varDelta R_s+\ j\omega_e\varDelta L_\sigma\ )\vec{I}^{s}_{dqs} && (=\vec{\lambda}_2)\\ &+\ \vec{\mu}\ \ \vec{\lambda}^{s}_{dqr} && (=\vec{\lambda}_3)\end{aligned} \tag{6}$$

where $\varDelta$ means the difference between actual value and nominal value. In this paper, T$_c$ is set to T$_r$ and rotor flux observer becomes robust to parameter variations and this rotor flux observer will be used as the plant model in speed estimator.

4. SPEED ESTIMATION USING RLS ALGORITHM

4.1 Structure of speed estimator

The proposed speed estimator is shown in Fig. 2. To apply RLS algorithm to induction motor speed estimation, the voltage model (7) without rotor speed (ω_r) is selected as the plant model and the current model (8) with rotor speed (ω_r) is selected as the adjustable model, where the outputs of plant model and adjustable model are defined as $y(k)\triangleq\lambda_{dqr}$. $\hat{y}(k)\triangleq\hat{\lambda}_{dqr}$ respectively.

$$p\begin{bmatrix}\lambda^{s}_{dr}\\ \lambda^{s}_{qr}\end{bmatrix}=\frac{L_r}{L_m}\left[\begin{bmatrix}v^{s}_{ds}\\ v^{s}_{qs}\end{bmatrix}-\begin{bmatrix}R_s+\sigma L_s p & 0\\ 0 & R_s+\sigma L_s p\end{bmatrix}\begin{bmatrix}i^{s}_{ds}\\ i^{s}_{qs}\end{bmatrix}\right] \tag{7}$$

$$p\begin{bmatrix}\lambda^{s}_{dr}\\ \lambda^{s}_{qr}\end{bmatrix}=\begin{bmatrix}-1/T_r & -w_r\\ w_r & -1/T_r\end{bmatrix}\begin{bmatrix}\lambda^{s}_{dr}\\ \lambda^{s}_{qr}\end{bmatrix}+\frac{L_m}{T_r}\begin{bmatrix}i^{s}_{ds}\\ i^{s}_{qs}\end{bmatrix} \tag{8}$$

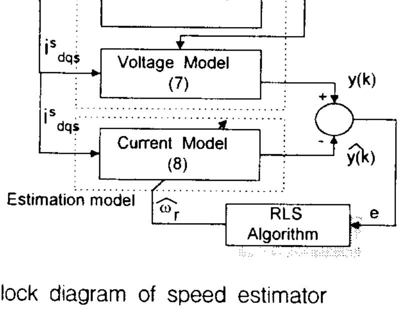


Fig. 2. Block diagram of speed estimator

4.2 The Design of Speed Estimator

To define regressor vector and parameter vector in RLS algorithm, the adjustable model in (8) must be discrete to (9).

$$\begin{bmatrix} \lambda^{s}_{qr}(k+1) \\ \lambda^{s}_{dr}(k+1) \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} \lambda_{qr}(k) \\ \lambda_{dr}(k) \end{bmatrix} + \begin{bmatrix} b_{11} & 0 \\ 0 & b_{22} \end{bmatrix} \begin{bmatrix} i^{s}_{qs} \\ i^{s}_{ds} \end{bmatrix} \tag{9}$$

where $a_{11} = 1 - 1/T_r h$, $a_{12} = \omega_r h$, $a_{21} = -a_{12}$, $a_{22} = a_{11}$, $b_{11} = b_{22} = L_m / T_r h$, h = sampling time

Estimated speed and rotor open time constant can be derived as follows.

$$\hat{\omega}_r = \hat{a}_{12}/h, \qquad \hat{T}_r = h/(1 - \hat{a}_{11}) \tag{10}$$

where ^ means estimated value and the regressor vector and the parameter vector can be defined as (11).

$$\begin{aligned} \Phi^T(k) &= [\ \lambda^{s}_{qr}(k),\ \lambda^{s}_{dr}(k),\ i^{s}_{qs}(k)\ ] \\ \theta^T(k) &= [\ \hat{a}_{11}\ \hat{a}_{12}\ \hat{b}_{11}\ ]^T \end{aligned} \tag{11}$$

To minimize cost function in (12), (13) must be repeated and parameters can be estimated by RLS algorithm.

$$V(\theta, k) = \frac{1}{2} \sum_{i=1}^{k} \mu^{k-i} (y(i) - \Phi^T \theta)^2 \tag{12}$$

where $0 < \lambda \le 1$

$$\hat{y}(k) = \Phi^T(k)\ \hat{\theta}(k) \tag{13}$$

where

$$\begin{aligned} \hat{\theta}(k) &= \hat{\theta}(k-1) + K(k)(y(k) - \Phi^T(k)\hat{\theta}(k-1)) \\ K(k) &= P(k)\Phi(k) \\ &= P(k-1)\Phi(k)(\mu I + \Phi^T(k)P(k-1)\Phi(k))^{-1} \\ P(k) &= (I - K(k)\Phi^T(k))P(k-1)/\mu \end{aligned}$$

and T and μ represent the transpose matrix and forgetting factor respectively. To improve transient characteristics the forgetting factor is used as follows

$$\mu(k) = \mu_0 \mu(k-1) + (1 - \mu_0) \tag{14}$$

μ_0 and $\mu(0)$ are μ_0=0.98 and $\mu(0)$=0.95 and the initial value of covariance matrix P was set to 500I experimentally. But if a constant estimation period is used and two parameters are estimated simultaneously, the performance of speed estimation is deteriorated because any variation period of speed and rotor time constant is not same and in the transient the speed estimation is effected directly by rotor time constant which is being estimated but not exact. So in this paper, only the rotor speed is estimated in realtime and the rotor time constant is repeatedly replaced by pre-estimated value.

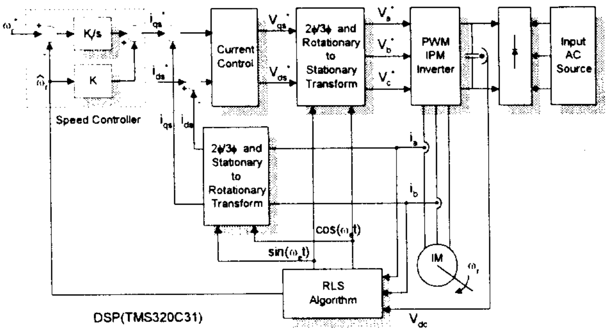


Fig. 3. Total speed sensorless vector controller

5. VECTOR CONTROLLER

In Fig. 3 total speed sensorless vector controller is shown and rotor flux oriented vector control is adopted as vector controller. The PI(Proportional and Integral) control with anti-windup and Space Vector Modulation is used as current controller and voltage modulator.

Estimated speed using RLS algorithm is feedback to a IP speed controller and used in calculating of the torque current reference and rotor flux position. To estimate rotor speed stably in transient state, an IP speed controller is used and shown in Fig. 3. The IP speed controller makes the variation in torque current, which is used in RLS speed estimator, smooth under transient state. So the characteristic of speed estimation under transient state is more stable but it has disadvantage that speed rising time is more long.

6. EXPERIMENTS

A 2.2kW servo induction motor and a voltage-fed inverter with a 600V, 50A intelligent power module are used in experiments and the vector control algorithm and estimation algorithm are realized by using digital signal processor (TMS320C31) and 12 bit AD converter is used in current sampling and its sampling frequency is 8kHz and a deadtime compensation scheme is used to improve low speed response and actual speed is measured by M/T method. The ratings and the parameter's nominal values of induction motor are shown in Table 1.

To remove the effect of estimation lag and parameter variations, rotor flux observer in (3) which is based on (7) is used as plant model of speed estimator in experiments.

Fig. 4(A) is the estimated rotor flux in steady state and Fig. 4(B) shows its characteristics in transient state when rotor speed is changed from positive speed to negative speed and the nominal value of the stator resistance has the variation of 100%, 50% and 150% with flux reference of 0.2 [wb]. In steady state the rissajous of estimated rotor flux is circle and the estimated rotor flux is maintained exactly to 0.2 [wb] without lag. Also in Fig. 4(B), when the speed is changed to a negative speed, the rotor flux is reversed.

Fig. 5, 6 and Fig. 7 show the speed estimation and speed control characteristics, where rotor speed is estimated in realtime and rotor time constant is pre-estimated using actual speed. At various speed the value of estimated rotor time constant is almost same as nominal values in regular environment and its deviation from nominal value is only ±3%, so in experiment the nominal value is used.

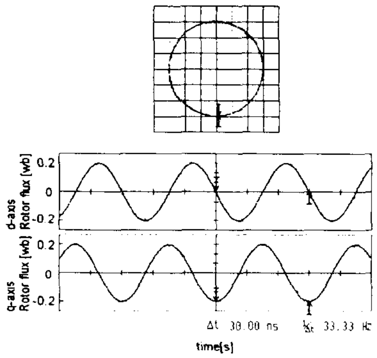
In Fig. 5(±1500[rpm]), 6(±500[rpm]) and Fig. 7(30[rpm]) the estimated speed converges well to actual speed and the stable speed characteristics are shown in acceleration and deceleration. Also we can see the typical characteristics of the IP speed controller and slow but very stable estimation characteristics[6] in the transient and the steady state especially in low speed region.

Table 1 Ratings and parameters of an induction motor

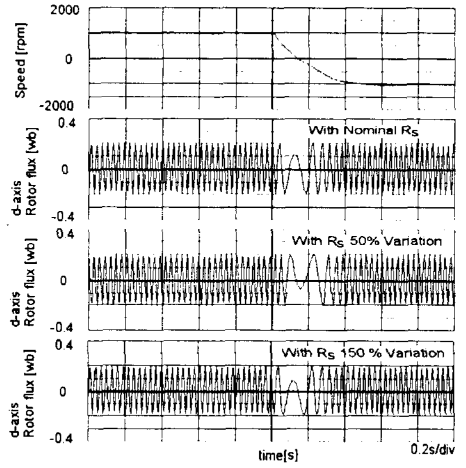
Power	2.2 [kW]	R_s	0.385	[Ω]
Voltage	150 [V]	R_r	0.342	[Ω]
Current	14 [A]	L_s	0.03257	[H]
		L_r	0.03245	[H]
Base Speed	50 [Hz]	L_m	0.03132	[H]

7. CONCLUSION

New speed-sensorless vector control scheme consisting of RLS(Recursive Least Square) algorithm, robust rotor flux observer and IP(Integral and Proportional) speed controller has been proposed. The total algorithm have been realized in induction motor drive system and stable estimation performance and variable speed characteristics have been obtained and its effectiveness has been verified.



(A) Flux estimation in steady state(1000rpm, 0.2[wb])



(B) Robust flux estimation against R_s variations

Fig. 4 Robust flux estimation

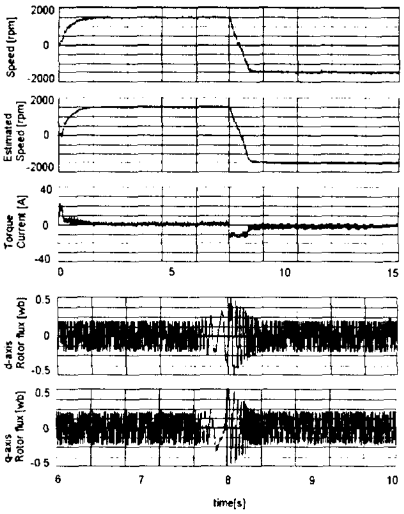


Fig. 5 Variable speed responses in speed sensorless control (±1500rpm)

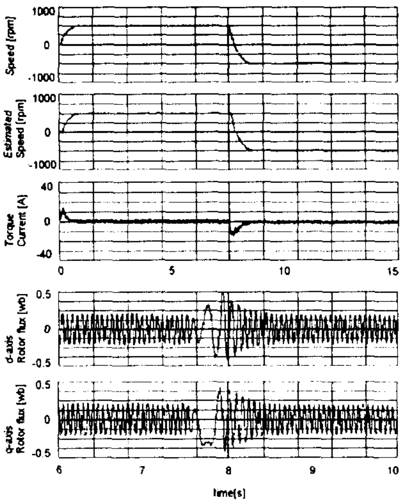


Fig. 6 Variable speed responses in speed sensorless control (±500rpm)

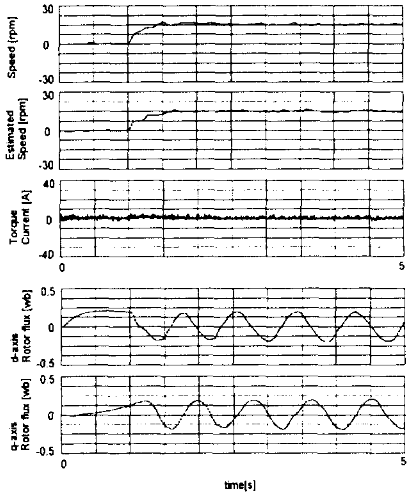


Fig. 7 Low speed responses in speed sensorless control (30rpm)

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