⊙ 速報研究論文

Sensorless Speed Control of Induction Motor Using Observation Technique

H. S. Kim* · C. H. Lee** · H. U. Ahn** · S. B. Kim***

관측기관을 이용한 유도전동기의 센서리스 속도제어

김환성 · 이충환 · 안휘웅 · 김상봉

Abstract

Sensorless speed estimation in induction motor systems is one of the most fundamental research subjects to the motor control engineers. Based on the estimated speed, the vector control has been applied to the high precision torque control. However, most speed estimation methods use adaptive scheme, so that it takes long time to estimate the speed. Thus the adaptive estimation scheme is not effective to the induction motor which requires short sampling time.

In this paper, a new linearized equation of induction motor system is proposed and a sensorless speed estimation algorithm based on observation techniques is developed. First, the nonlinear induction motor equation is linearized at an equilibrium point. Second, a proportional integral(PI) observer is applied to estimate the speed state in the induction motor system. Finally, simulation results will assure the effectiveness of the new linearized equation and the sensorless estimation algorithm by using PI observer in the nonlinear induction motor system.

1. Introduction

Induction motor systems have been widely used in industrial field. For controlling the speed or the torque of induction motor, the speed sensor is necessary and it is directly connected to motor shaft. But the connection of the speed sensor reduces motor's sturdiness, increases the cost, and restricts the applications of the vector control[1]~[7].

Recently, sensorless speed estimation in the induction motor system is one of the most fun-

* 한국해양대학교 이공대학 물류시스템공학과(원고접수일 : 98년 10월)
** 부경대학교 대학원 기계공학과
*** 부경대학교 공과대학 기계 · 자동차공학부

damental research subjects. Based on the estimated speed, the vector control has been applied to the high precision torque control.

Some approaches are based on the model reference adaptive system(MRAS)[2] and the observer or the extended Kalman filter[4]. Most of all MRAS schemes require pure integration of measured variables in their reference models and require long calculation time based on a priori suitable initial parameters. The observer and Kalman filtering techniques are based on accurate mathematical model and are effected by parameter variations, unknown initial conditions, and drift.

Conventional sensorless speed control approaches are built by estimation methods of flux or speed using stator terminal voltages and currents, but there exist a large speed estimation error, specially in the very low speed range.

The problems related to speed estimation have been studied by many researchers. Schauder studied the adaptive speed identification with MRAS that was based on the estimated rotor angular speed and based on the parameter identification method[5]. Shin-Naka clarified the impossibility of simultaneous estimation of both the speed and the rotor resistance theoretically[6]. However most approaches use the rotor flux states, and the estimated rotor flux states become unstable in the low speed range.

In this paper, a new linearized equation of induction motor system which does not include the flux states is proposed, and sensorless speed control algorithms based on observation technique are developed. First, the nonlinear motor equation is linearized at an equilibrium point, where the flux states are not included. Second, a PI observer is applied to estimate the speed in the induction motor system with unknown load torque variation. Finally, the simulation results are presented and prove the effectiveness of the new linearized equation and the sensorless speed estimation method by using PI observer.

2. Linearization of Induction Motor System

2.1 Description of the induction motor

For modelling the induction motor, the following voltage and current nonlinear differential equation with $d-q$ axis which fixed on stator frame is well reported[1].

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s+\frac{dL_s}{dt} & 0 & \frac{dM}{dt} & 0 \\ 0 & R_s+\frac{dL_s}{dt} & 0 & \frac{dM}{dt} \\ \frac{dM}{dt} & pw_{re}M & R_r+\frac{dL_r}{dt} & pw_{re}L_r \\ -pw_{re}M & \frac{dM}{dt} & -pw_{re}L_r & Rr+\frac{dL_r}{dt} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \tag{1}$$

where R_s is stator resistance, R_r is rotor resistance, L_s is stator self-inductance, L_r is rotor self-inductance, M is mutual inductance, p is number of pole pairs, v_{ds}, v_{qs} are $d-$ and $q-$ axis stator voltages, i_{ds}, i_{qs} are $d-$ and $q-$ axis stator currents, i_{dr}, i_{qr} are $d-$ and $q-$ axis rotor currents, and ω_{re} is electrical rotor angular velocity.

Let (1) be transformed by $r-\delta$ axis, where δ frame rotates together with rotor current. Then the following equation is obtained.

$$\begin{bmatrix} v_{rs} \\ v_{\delta s} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s+\frac{dL_s}{dt} & -\omega L_s & \frac{dM}{dt} & -\omega L \\ \omega L_s & R_s+\frac{dL_s}{dt} & \omega M & \frac{dM}{dt} \\ \frac{dM}{dt} & -(\omega-p\omega_{re})M & R_r+\frac{dL_r}{dt} & -(\omega-p\omega_{re})L_r \\ (\omega-p\omega_{re})M & \frac{dM}{dt} & (\omega-p\omega_{re}) & R_r+\frac{dL_r}{dt} \end{bmatrix} \begin{bmatrix} i_{rs} \\ i_{\delta s} \\ 0 \\ i_{\delta r} \end{bmatrix} \tag{2}$$

where v_{rs}, $v_{\delta s}$ are $r-$ and $\delta-$ axis stator voltages, i_{rs}, $i_{\delta s}$ are $r-$ and $\delta-$ axis stator currents, $i_{\delta r}$ is $\delta-$ axis rotor current, and ω is electrical angular velocity.

For simplicity the nonlinear terms that are given as (2) in [1] can be rewritten as follows:

$$\frac{di_{rs}}{dt} = -\frac{R_s}{\sigma L_s} i_{rs} + \frac{\omega+p\omega_{re}M^2}{\sigma L_s L_r} i_{\delta s} + \frac{p\omega_{re}M}{\sigma L_s} i_{\delta r} + \frac{1}{\sigma L_s} v_{rs} \tag{3}$$

$$\frac{di_{\delta s}}{dt} = -\frac{\omega+p\omega_{re}M^2}{\sigma L_s L_r} i_{rs} - \frac{R_s}{\sigma L_s} i_{\delta s} + \frac{R_r M}{\sigma L_s L_r} i_{\delta r} + \frac{1}{\sigma L_s} v_{\delta s} \tag{4}$$

$$\frac{di_{\delta s}}{dt} = \frac{p\omega_{re}M}{\sigma L_r} i_{rs} + \frac{R_s M}{\sigma L_s L_r} i_{\delta s} - \frac{R_r}{\sigma L_r} i_{\delta r} + \frac{M}{\sigma L_s L_r} v_{\delta s} \tag{5}$$

where σ is leakage coefficient $(=1-M^2/(L_s L_r))$.

The output equation of induction motor system is represented as

$$T_e = -pMi_{rs}i_{\delta r} \tag{6}$$

where T_e is motor torque.

A mechanical equation of induction motor system with disregarding the spring and the damping factors is obtained as follows :

$$\frac{d\omega_{re}}{dt} = \frac{-R_w\omega_{re}}{J} + \frac{T_e - T_L}{J} \tag{7}$$

where, R_w is break coefficient, J is inertia moment, and T_L is load torque.

2.2 Linearization of the induction motor system

For linearization of the induction motor system at an equilibrium point, first of all we must describe the induction motor by the following function.

$$Z = f(i_{rs}, i_{\delta s}, \delta_r, v_{rs}, v_{\delta s}, \omega, \omega_{re}) \tag{8}$$

Using total derivative, the above equation can be rewritten as

$$\Delta Z = \frac{\partial f}{\partial i_{rs}}\Delta i_{rs} + \frac{\partial f}{\partial i_{\delta s}}\Delta i_{\delta s} + \frac{\partial f}{\partial i_{\delta r}}\Delta i_{\delta r} + \frac{\partial f}{\partial v_{rs}}\Delta v_{rs} + \frac{\partial f}{\partial v_{\delta s}}\Delta v_{\delta s} + \frac{\partial f}{\partial \omega}\Delta\omega + \frac{\partial f}{\partial \omega_{re}}\Delta\omega_{rs} \tag{9}$$

So, (3) to (5) are transformed into total derivative forms respectively as

$$\Delta\frac{di_{rs}}{dt} = -\frac{R_s}{\sigma L_s}\Delta i_{rs} + \frac{\omega^{\cdot}+p\omega^{\cdot}_{re}M^2}{\Delta L_s L_r}\Delta i_{\delta s} + \frac{pw^{\cdot}_{re}M}{\Delta L_s}\Delta i_{\delta r} + \frac{i^{\cdot}_{\delta s}}{\sigma L_s L_r}\Delta\omega + \left(\frac{pM^2 i^{\cdot}_{\delta s}}{\sigma L_s L_r} + \frac{pMi^{\cdot}_{\delta r}}{\sigma L_s}\right)\Delta\omega_{re} + \frac{1}{\sigma L_s}\Delta v_{rs} \tag{10}$$

$$\Delta\frac{di_{\delta s}}{dt} = -\frac{\omega^{\cdot}+p\omega^{\cdot}_{re}M^2}{\Delta L_s L_r}\Delta i_{rs} - \frac{R_s}{\Delta L_s}\Delta i_{\delta s} + \frac{R_r M}{\Delta L_s L_r}\Delta i_{\delta r} - \frac{i^{\cdot}_{rs}}{\sigma L_s L_r}\Delta\omega - \frac{pM^2 i^{\cdot}_{rs}}{\sigma L_s L_r}\Delta\omega_{re} + \frac{1}{\sigma L_s}\Delta v_{\delta s} \tag{11}$$

$$\Delta\frac{di_{\delta r}}{dt} = \frac{p\omega^{\cdot}_{re}M}{\sigma L_r}\Delta i_{rs} + \frac{R_s M}{\sigma L_s L_r}\Delta i_{\delta s} - \frac{R_r}{\sigma L_r}\Delta i_{\delta r} + \frac{pMi^{\cdot}_{rs}}{\sigma L_r}\Delta\omega_{re} - \frac{M}{\sigma L_s L_r}\Delta v_{\delta s} \tag{12}$$

And also, the output equation (6) is rewritten as

$$\Delta T_e = -pMi^{\cdot}_{\delta r}\Delta i_{rs} - pMi^{\cdot}_{rs}\Delta i_{\delta r} \tag{13}$$

where $^{\cdot}$ denotes constant value at the given equilibrium point.

In the above equations (10) to (13), we can abbreviate the symbol Δ for assuming the equilibrium state of the induction motor system.

Substituting (13) into (7), we get

$$\frac{d\omega_{re}}{dt}=\frac{-R_w\omega_{re}}{J}-\frac{pMi^{*}_{\delta r}i_{rs}}{J}-\frac{pMi^{*}_{rs}i_{\delta r}}{J}-\frac{T_L}{J} \tag{14}$$

Using (10) to (12) and (14), the nonlinear induction motor system is given as the following simple linearized form :

$$\begin{bmatrix} \dot{i}_{rs} \\ \dot{i}_{ds} \\ \dot{i}_{dr} \\ \dot{\omega}_{re} \end{bmatrix}=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & 0 & a_{43} & a_{44} \end{bmatrix}\begin{bmatrix} i_{rs} \\ i_{\delta s} \\ i_{\delta r} \\ \omega_{re} \end{bmatrix}+\begin{bmatrix} b_{11} & b_{11} & 0 \\ b_{21} & 0 & b_{23} \\ 0 & 0 & b_{33} \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} \omega \\ v_{rs} \\ v_{\delta s} \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \\ 0 \\ d_{41} \end{bmatrix}T_L \tag{15}$$

where, denotes $\frac{d}{dt}$ and the corresponding coefficients are given as follows :

$$a_{11}=a_{22}=\frac{R_s}{\sigma L_s},\ a=-a_{21}=\frac{\omega^{*}+pM^2\omega^{*}_{re}}{\sigma L_s L_r},\ a_{13}=\frac{pM\omega^{*}_{re}}{\sigma L_s},$$

$$a_{14}=\frac{pM(Mi^{*}_{\delta s}+L_r i^{*}_{\delta r})}{\sigma L_s L_r},\ a_{23}=\frac{R_r M}{\sigma L_s L_r},\ a_{24}=-\frac{pM^2 i^{*}_{rs}}{\sigma L_s L_r},$$

$$a_{31}=\frac{pM\omega^{*}_{re}}{\sigma L_r},\ a_{32}=\frac{R_s M}{\sigma L_s L_r},\ a_{33}=-\frac{R_r}{\sigma L_r},\ a_{34}=\frac{pMi^{*}_{rs}}{\sigma L_r},$$

$$a_{41}=-\frac{pMi^{*}_{\delta r}}{J},\ a_{43}=-\frac{pMi^{*}_{rs}}{J},\ a_{44}=-\frac{R_w}{J}$$

$$b_{11}=\frac{i^{*}_{\delta s}}{\sigma L_s L_r},\ b_{12}=b_{23}=\frac{1}{\sigma L_s}$$

$$b_{21}=-\frac{i^{*}_{rs}}{\sigma L_s L_r},\ b_{33}=-\frac{M}{\sigma L_s L_r},\ d_{41}=-\frac{1}{J}$$

3. Estimate the Speed by Observation Techniques

In the previous section, the induction motor system is linearized and described as the state space form. Thus, the system (15) can be rewritten as the following state space form.

$$\dot{x}(t)=Ax(t)+Bu(t)+Dd(t) \tag{16}$$

$$y(t)=Cx(t) \tag{17}$$

$$x(t)=\begin{bmatrix} i_{rs} \\ i_{\delta s} \\ i_{\delta r} \\ \omega_{re} \end{bmatrix},\ u(t)=\begin{bmatrix} \omega \\ v_{rs} \\ v_{\delta s} \end{bmatrix},\ d(t)=T_L,\ C=\begin{bmatrix} 1\,0\,0\,0 \\ 0\,1\,0\,0 \end{bmatrix}$$

where $x(t)$ denotes the state vector, $u(t)$ input vector, and $d(t)$ external input vector. And also it is assumed that the states of i_{rs} and $i_{\delta s}$ can be measured by sensors.

Thus, we can design an observer to estimate the rotor angular velocity (ω_{re}) from (16) and (17).

The remained problem is to design an observer for estimating the motor speed with unknown load variation. The problem of observing the system with unknown external input is important in the practical system. In order to solve this problem, a PI observer that has been considerable attention recently, is introduced. In application fields of observer techniques, the PI observer is useful for system without considering the external input signal.

3.1 Estimation method by PI observer

Consider a proportional integral (PI) observer which can estimate and cancel the step disturbance as follows : [7]-[8]

$$\dot{\hat{x}}(t)=(A-K_pC)\hat{x}(t)+K_py(t)+Bu(t)+D\zeta(t) \tag{18}$$

$$\dot{\zeta}(t)=K_I(y(t)-C\hat{x}(t)) \tag{19}$$

where $\hat{x}(t)$ denotes the estimated state vector, and K_P and K_I are gains of PI observer.

The necessary condition for existing the PI observer gains K_P and K_I is given in the following lemma.

Lemma 1 [7] : The necessary condition for existing the PI observer gains is that the following condition holds :

$$\text{rank}\begin{bmatrix} A & D \\ C & 0 \end{bmatrix}=n+m \tag{20}$$

where $n+m$ is sum of order of state vector and external input vector.

Using the PI observer the external input $d(t)$ can be estimated as

$$\hat{d}(t)=T_L=\zeta(t) \tag{21}$$

where $\hat{d}(t)$ is an estimated external input.

4. Simulation Results

In the previous section, the PI observer was introduced to estimate the motor speed. In this section, we show the simulation proceeding and estimation method by using PI observer under the load variations. To implement the estimation method by using PI observer, the following transformation equations between 3 phases to 2 phases are given by $r-\delta$ coordinate as

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix}=\begin{bmatrix} \sqrt{2/3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{2} \\ -1/\sqrt{6} & -1/\sqrt{2} \end{bmatrix}\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} v_{rs} \\ v_{\delta s} \end{bmatrix}$$

and

$$\begin{bmatrix} i_{rs} \\ i_{\delta s} \end{bmatrix}=\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} \sqrt{2/3} & -1/\sqrt{6} & -1/\sqrt{6} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix}\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix}$$

where

$$\theta=\int \omega dt+\theta_0$$

and θ_0 is initial phase between r - axis and δ - axis.

The parameters of induction motor system are shown in Table 1 and 2. The PI observer gains are designed by pole placement method with desired poles {-3, -6, -60, -120, -360} as follows :

$$K_P=10^6\times\begin{bmatrix} 0.0004 & -0.0001 \\ 0.0001 & 0.0001 \\ 0.1474 & -0.0359 \\ 2.8012 & -0.6851 \end{bmatrix},$$

$$K_I=10^5\times[-1.4652 \quad 0.3613]$$

Table 1. Motor Parameters

Symbol	Values	
R_s	5.132	[Ω]
R_r	5.132	[Ω]
v_{rs}	1.6	[V]
$v_{\delta r}$	1.5	[V]
R_w	0	[Ω]
L_s	3.864	[H]
L_r	3.864	[H]
M	0.0473	[H]
J	0.05	[kgm²]
p	2	

Table 2. Motor Parameters at equilibrium point

Symbol	Values	
i^*_{rs}	5.03	[A]
$i^*_{\delta s}$	4.52	[A]
$i^*_{\delta r}$	-4.41	[A]
ω^*	188.4	[Red/sec]
ω^*_{re}	89.5	[Rad/sec]

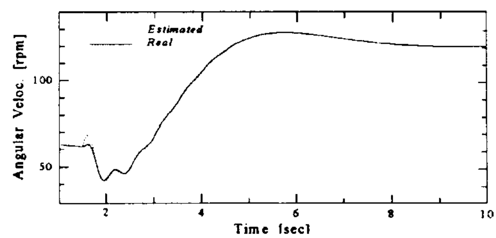

Fig. 1 Speed estimation results with no load variations

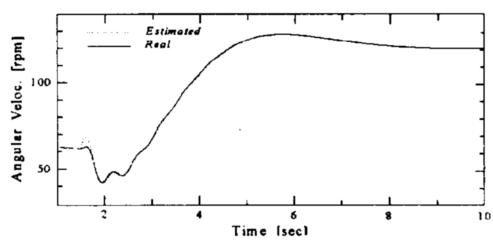

Fig. 2 Speed estimation results with load variations

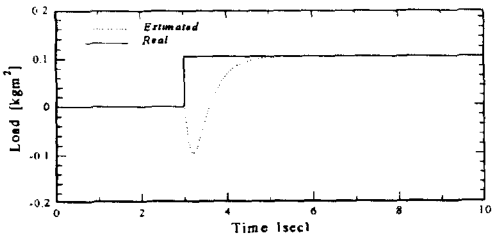

Fig. 3 Load estimation result with load variation

Fig. 1 and 2 show the simulation results of the estimation of the motor speed with and without load variation using the PI observer. As one of merits, the estimated speed always follows the real speed, because of including integrator in the PI observer. Fig. 3 represents the estimated load torque which is changed by step state without previous information.

5. Conclusions

In this paper, a new linearized equation of induction motor system was proposed and a sensorless estimation algorithm was shown. First, the nonlinear motor equation is linearized at an equilibrium point. Second, for the estimation of sensorless speed states, the proportional integral observer is applied in the induction motor system with unknown load torque variation. Finally, the simulation results were presented and showed the effectiveness of the new linearized equation and the sensorless speed estimation method in the induction motor system.

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저 자 소 개

김환성(金煥成)
1965년 6월생. 1991년 부경대학교(구, 부산수대) 기관공학과 졸업(학사). 1993년 동대학원 기계공학과 제어공학전공 졸업(석사). 1996년 일본 구마모토대학 제어공학 졸업(박사), 1998년 9월-현재 한국해양대학교 물류시스템공학과 전임강사. 관심분야는 제어이론 및 물류기기 제어분야. 당학회 회원

이충환(李忠煥)
1967년 12월생. 1991년 부경대학교 기계공학과 졸업(학사). 1993년 2월 동 대학원 졸업(석사), 1993년~현재 (주)쌍용자동차 보전부 근무. 관심분야는 로바스트 제어분야, 전동기제어 및 응용분야 등.

안휘웅(安輝雄)
1961년 9월생. 1988년 부경대학교 기관공학과 졸업(학사). 1990년 동 대학원 기계공학과 졸업(석사). 현재 동대학원 박사과정, 1990년-1992년 현대정공(서보모터설계근무), 1993년-현재 CNC 공작기계 부서 제어부 근무, 관심분야는 서보모터설계 및 공작기계 정밀제어분야 등.

김상봉(金相奉)
1955년 8월생. 1978년 부경대학교 기관공학과 졸업(학사). 1980년 2월 동 대학원 졸업(석사). 1988년 일본 동경공업대학졸업 (박사). 1988년~현재 부경대학교 기계·자동차공학부 교수. 관심분야는 로바스트 제어분야, 생물·기계공학분야, 화상처리응용분야 등.