Journal of IEEE Korea Council Vol. 1, No. 1

논문 97-01-08

Performance Improvement of an Induction Motor in Low Speed Region

金成奐[*], 朴太植[*], 金南正[**], 柳志潤[***], 朴貴泰[***]

(Seong-Hwan Kim, Tae-Sik Park, Nam-Jeung Kim,
Ji-Yoon Yoo and Gwi-Tae Park)

요 약

일반적으로 유도 전동기의 속도는 엔코더를 사용하여 측정되며, 측정된 평균 속도는 필연적인 시간 지연과 시스템 노이즈 등을 포함하고, 저속 운전시에는 운전 성능을 감소시킬 뿐 아니라 시스템 안정성에도 문제를 일으킨다. 또한 인버터의 데드 타임 효과, 스위칭 소자의 순전압 강하등의 영향으로 발생하는 부정확한 인버터 출력 전압은 토크 리플을 발생시키고 이는 저속 영역에서 더욱 크게 나타난다. 따라서 유도 전동기의 저속 영역에서의 운전 성능을 향상시키기 위하여는 위의 두가지 문제점을 해결하여야 한다. 본 논문에서는 칼만 필터를 이용한 유도 전동기의 정확한 순시 속도 추정과, 데드 타임 및 스위칭 소자의 순전압 강하 보상을 통한 인버터 출력 특성의 개선 방법을 제안하고, 유도 전동기의 극저속 운전 성능을 개선하였다.

Abstract

Since the average speed calculated with encoder pulses inevitably has time delay, the control performance as well as the system stability is deteriorated, especially at the low speed region. Additionally, the distorted inverter output voltage due to the dead time effects and the forward voltage drops of the VSI (Voltage Source Inverter) causes torque ripples and their effects are more severe at the low speed operation of an induction motor. In this paper, an accurate speed estimation method using Kalman Filter Algorithm is presented to improve the performance of an induction motor speed control with a low precision encoder at low speed region. The dead time effects and the forward voltage drops of the VSI are feedforwardly compensated to produce an exact inverter output voltage. Keywords : Speed Estimation, Kalman Filter, Low Speed, Dead Time Effect, Forward Voltage Drop.

Ⅰ. Introduction

Recently, with the help of the improvement of the high performance μ -processors which can process many complicate calculation in real time, induction motor is widely used in the variable speed servo drive system which needs highly delicate torque and speed control because its' hardness of the mechanical structures and easiness of checking and maintenance. In variable speed driving the induction motor, it has good performance in the base speed area and also in the high speed area.

---

[*] 高麗大學校 電氣工學科 博士課程
(Dept. of Electrical Engineering, Korea Univ.)
[**] 大韓民國 特許廳 審査 4局 電氣科
(Electrical Department of Exam. Bereau 4,
Korea Industrial Property Office)
[***] 高麗大學校 電氣工學科 敎授
(Dept. of Electrical Engineering, Korea Univ.)

接受日:1997年7月10日, 修正完了日:1997年10月16日

However, in driving an induction motor in the low speed region, it is difficult to obtain good control performance due to the system noises, processing delay, limit of the speed sensor resolution and the inverter losses.

In this paper, we investigate and analyze the reasons which deteriorate the control performance of an induction motor in low speed region and propose some solutions to enhance the control performance.

In general, the rotary encoder is widely used as a position detector in the servo motor drive system by virtue of its' simplicity of the digital implement. But it is impossible to obtain an accurate instantaneous speed because of the limit of the encoder resolution, environmental noises, measuring error and operating time of processors. Since the speed calculated with the number of pulses from encoder is the average speed, it inevitably has time delay. At the low speed operation, in particular, the time delay increases because the pulse duration of the encoder is longer than the sampling period of the speed controller. The effects of the inevitable time delay deteriorate the control performance as well as the system stability, especially at the low speed operation of an induction motor.[1-3]

Additionally, there are inherent sources for the inverter output voltage waveform distortion, which is caused by the dead time effects and the forward voltage drops of the switching devices. These distorted voltage waveforms cause torque ripple of an induction motor and the torque ripple increases logarithmically as the speed decreases.[5,6] Therefore, the above two problems must be solved to improve the speed control performance at the low speed region.

Recently, to estimate an accurate speed of an induction motor, many estimation methods using adaptive schemes such as MRAS(Model Reference Adaptive Systems), RLS(Recursive Least Squares Estimation) are studied. However, it is difficult to obtain a good result using these estimation methods because system noises increase in the low speed region.[2,4] Kalman Filter Algorithm is proper to estimate the states of system including random noises and robust to the parameter variation.[7-9]

In this paper, Kalman Filter Algorithm which is proper to the system including random noises is implemented to estimate an accurate instantaneous speed, position and load torque of an induction motor. The vector controller of an induction motor consists of using these estimated values to improve the drive performance even with low precision rotary encoder at low speed region. The dead time effects and the forward voltage drops of the VSI are feedforwardly compensated to produce an exact inverter output voltage. Simulations and experimental results show the validity of the proposed method at low speed region.

Ⅱ. Mechanical System Modeling

Mechanical system model of an Induction Motor is shown in Fig. 1 and expressed as follows.

$$J\frac{d\omega_r}{dt} + B\omega_r + \tau_L = \tau_e \tag{1}$$

where J : inertia moment
B : viscous coefficient
ω_r : mechanical rotor angular speed
τ_L : load torque
τ_e : torque reference

The rotor angular speed is calculated from the difference of rotor angular position.

$$\frac{d\theta}{dt} = \omega_r \tag{2}$$

where θ : rotor angular position

During one sampling period, the load torque is nearly constant and we assume that its' derivative is zero.

$$\frac{d\tau_L}{dt} = 0 \tag{3}$$

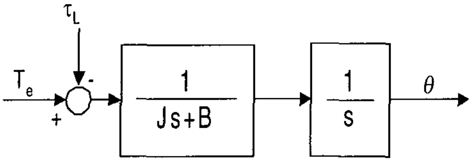

Fig. 1. Mechanical system model of an induction motor.

Ⅲ Kalman Filter Algorithm

1. Discrete System Model with Random Noises

From (1), (2), (3), discrete model of the system can be expressed as follows

$$\begin{aligned} x_{k+1} &= A_k x_k + B_k u_k \\ y_k &= C_k x_k \end{aligned} \qquad (4)$$

where

$$A_k = \begin{bmatrix} a_{11} & 0 & a_{13} \\ a_{21} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad B_k = \begin{bmatrix} b_1 \\ 0 \\ 0 \end{bmatrix}$$

$$a_{11} = 1 - \frac{J}{B} \cdot T_s, \quad a_{13} = -\frac{T_s}{J},$$

$$a_{21} = T_s, \quad b_1 = \frac{T_s}{J}$$

$$C_k = [0 \quad 1 \quad 0]$$

$$x_k = [\ \omega_r \quad \theta \quad \tau_L]^T$$

T_s : speed control period

In (4), the input variable is torque reference and the state variables are mechanical angular speed, mechanical angular position, load torque and the output variable is mechanical angular position.

A real motor drive system has many unexpected noises generated by the current ripples, current measurement error, modelling error, uncertainty of the motor parameters and so on.

A system model which includes random noises is expressed as follows.

$$\begin{aligned} x_{k+1} &= A_k x_k + B_k u_k + G\omega_k \\ y_k &= C_k x_k + v_k \end{aligned} \qquad (5)$$

where ω_k : process noise

v_k : measurement noise

G : System noise matrix

Both ω_k and v_k are assumed to be zero-mean white Gaussian noise inputs and Q and R are their variance matrices respectively.

$$\omega_k = [\, u_{noise} \quad \tau_{noise}]^T, \quad v_k = \theta_{noise}$$

$$G = \begin{bmatrix} b_1 & a_{13} \\ 0 & 0 \\ 0 & 1 \end{bmatrix}$$

where u_{noise} : process noise of torque reference

τ_{noise} : process noise of load torque

θ_{noise} : measurement noise of rotor position

Because the influences between the torque reference noise and the load torque noise are negligible, it is possible to set the off-diagonal elements of Q matrix to zero.

$$Q = \begin{bmatrix} q_0 & 0 \\ 0 & q_1 \end{bmatrix}, \quad R = [r_0]$$

where q_0 : covariance of torque reference

q_1 : covariance of load torque

r_0 : covariance of position measurement

2. Discrete Kalman Filter Algorithm

Kalman filter algorithm is appropriate to the dynamic system which has random noises because it treats the biased system noises, modeling error and other unexpected noises as disturbances and has robustness to the parameter variation.

The recursive algorithm of the discrete Kalman filter to estimate the accurate speed, position and the load torque of an induction motor drive with the inaccurate angular position information is as follows.

i) initialize

$$\begin{cases} P_0 = Var(x_0) \\ \hat{x}_0 = E(x_0) \end{cases}$$

ii) time update

$$\begin{cases} P_k^- = A_k P_{k-1} A_k^T + GQG^T \\ \hat{x}_{k^-} = A_k \hat{x}_{k-1} + B_k u_{k-1} \end{cases}$$

iii) measurement update

$$\begin{cases} K_k = P_k^- C_k^T (C_k P_k^- C_k^T + R)^{-1} \\ P_k = (I - K_k C_k) P_k^- \\ \hat{x}_k = \hat{x}_{k^-} + K_k (y_k - C_k \hat{x}_{k^-}) \end{cases} \tag{6}$$

where $Var(x)$: variance of x

$E(x)$: mean value of x

P_k : error covariance matrix

K_k : Kalman gain matrix

Discrete Kalman filter has two steps at each time k. One is the time update, and the other is the measurement update. To estimate states optimally, Kalman gain is adjusted by P_0, R, Q matrices. With larger Q and smaller R, the measured value has intensity and with smaller Q and larger R, the estimation model has intensity in the estimation. In (6), GQG^T means the uncertainty from the process noise ω_k and with this, P_k^- is larger than P_k. But using the measured value y_k at the estimation, the error covariance can be decreased and it is possible to estimate states accurately.

In Fig. 2, the vector controller using Kalman Filter Algorithm is shown. The PI control with anti-windup and Space Vector Modulation(SVM) are used as a current regulator. The estimated speed is used as a feedback value of the speed controller and the estimated load torque compensates the disturbance feedforwardly.

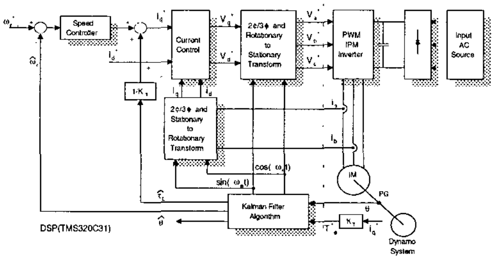

Fig. 2. Vector controller using Kalman Filter Algorithm.

Ⅳ. Compensation of Dead Time Effects and Forward Voltage Drop

VSI(Voltage Source Inverter) is frequently used in driving the small and medium power 3-phase induction machine. The torque and the speed of the machine are controlled by the inverter output voltages. So, it is very important to produce an inverter output voltage which is exactly same as the desired one to increase the control performance.

It is possible to produce an exact reference voltage if the switching devices of the inverter operate ideally. However, Inverter output voltage and current waveform are distorted by the following reasons and cause torque ripples.

i) Dead time which inserted in PWM patterns to prevent short circuit.
ii) Forward voltage drops of the switching devices of the inverter.

1. Dead Time Effects and Compensation

Dead time should be inserted in PWM patterns to prevent that two switching devices of the inverter arm conduct simultaneously, which cause DC link voltage to be short circuit. Dead time cause inverter output voltage waveform distortion and torque ripples. Torque ripples due to dead time are inversely proportional to the inverter output frequency and the applied load.

There are several methods in modulating the inverter voltage such as optimal PWM, sinusoidal PWM, SVM(Space Vector Modulation). Among them, SVM method is the most appropriate when using the high-speed digital processor because it has the advantages that the utilization rate is higher than the other methods and easy to realize by digital processor.

Fig. 3 shows the inverter output voltage and gate pulses with SVM.

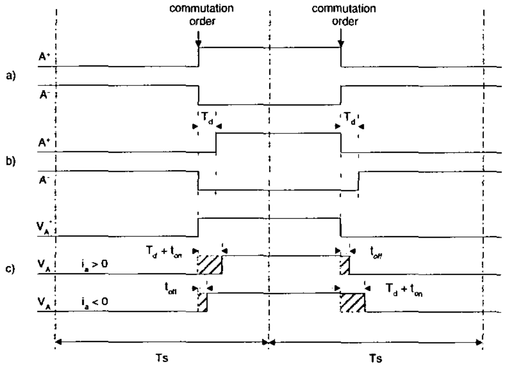

Fig. 3. Inverter voltage and gate pulses.
(a) gate pulse
(b) gate pulse with dead time inserted
(c) inverter voltage

From Fig. 3, two commutations occur in the two switching period and the mean error of the output voltage is as follows.

$$\delta v_{dt} = \begin{cases} -\dfrac{\delta T}{2T_s} V_{dc} \ , & \text{if} \ \ i_A > 0 \\ +\dfrac{\delta T}{2T_s} V_{dc} \ , & \text{if} \ \ i_A < 0 \end{cases} \qquad (7)$$

where $\delta T = T_d + t_{on} - t_{off}$, T_d : dead time
t_{on} : on time, t_{off} : off time

Eq. (7) means that inverter output voltages are differ from the reference voltages with the magnitude of δv_{dt} only related to the current polarity not to the magnitude nor the phase of the currents.

So, we apply the new reference voltage by summing the above error voltage to the inverter voltage reference according to the detected current polarity. As a result, the real inverter output voltage is same as the desired one and the dead time effects are compensated.

2. Forward Voltage Drops and Compensation

In driving the inverter, there's an error between inverter output voltage and the reference voltage because of the Collector-Emitter voltage drop of the IGBT(V_{ce}) and voltage drop of the diode(V_d). Distorted inverter output voltage waveform produces torque ripples such as dead time effects.

There are two forward voltage drops according to the switching condition. Fig. 4 shows the form of the occurred forward voltage drops with respect to the switching states and the error voltage due to the forward voltage drops is shown in Fig. 5.

When phase current is positive and the upper switch is ON, current flows through Ar+ and V_{ce} drop occurs. If lower switch is ON, current flows through D- and V_d drop occurs. Same manner, when phase current is negative and the upper switch is ON, V_d drop occurs. If lower switch is ON, V_{ce} drop occurs.

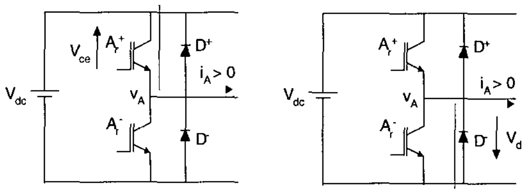

Fig. 4. Forward voltage drops with respect to the switching state.

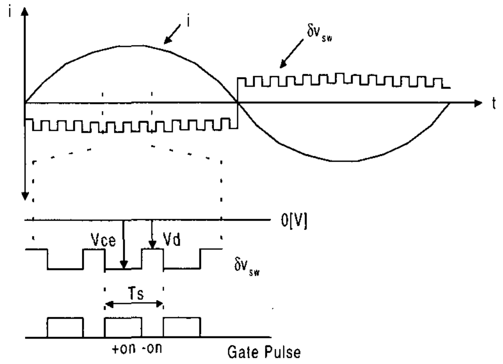

Fig. 5. Voltage drop of the inverter due to the forward voltage drops.

Inverter output voltage errors due to forward voltage drops δv_{sw} can be expressed as follows.

$$\delta v_{sw} = \frac{V_{ce}+V_d}{2} \tag{8}$$

The nominal values of the V_{ce}, V_d and their average are shown in Fig. 6.

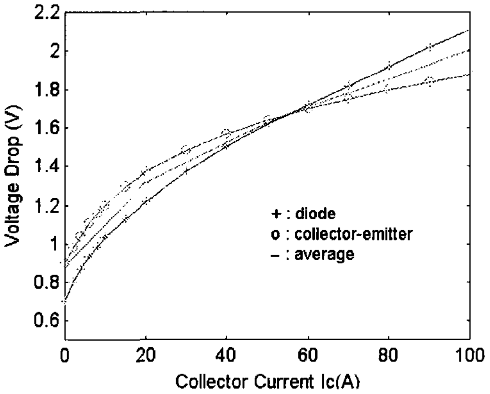

Fig. 6. Forward voltage drops versus collector current.

From Eq. (8) and Fig. 6, the real inverter voltages differ from the reference voltages with the magnitudes of the above voltage drops according to the phase current magnitude. So, we record the above error voltages according to the current magnitude to the ROM table, and apply new inverter reference voltages by summing the error voltages to the reference voltages according to the detected phase current magnitude. As a result, the forward voltage drop effects can be eliminated.

V. Simulation Results

A 2.2kW, 3 phase squirrel-cage induction motor is used in the simulation and experiment. The ratings and the nominal parameters' values of the induction motor are shown in Table 1. The estimation and control variables of the vector controller and the estimator are shown in Table 2.

Table 1. Ratings and parameters of induction motor.

Voltage	150 [V]	Rs 0.385 [Ω] Rr 0.342 [Ω]
Frequency	50 [Hz]	Ls 0.03257 [H] Lr 0.03245 [H]
Current	14 [A]	Lm 0.03132 [H]
Rated Torque	14 [Nm]	J 0.0088 [Kg · m2] B 0.007781[Kg · m2/s]

Table 2. Estimation & control variables.

speed control period	1.25[ms]
current control period	125[μ s]
estimation period	250[μ s]
flux reference	0.2[wb]
q0	10
q1	5000
r0	0.001

Fig. 7 and Fig. 8 show the simulation results of the proposed speed control system when the speed references are 5rpm, 10rpm respectively. The instantaneous speed and load torque are estimated accurately. The proposed control system has good dynamic performance when the load is applied.

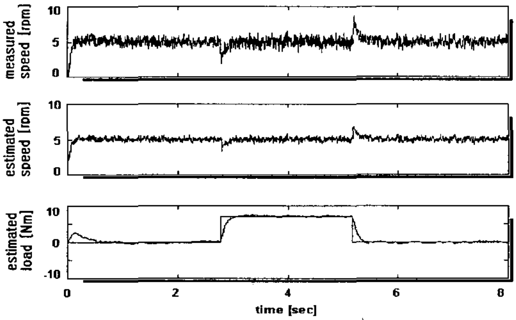

Fig. 7. Characteristics of speed control with estimated speed and load after disturbance compensation (5[rpm]).

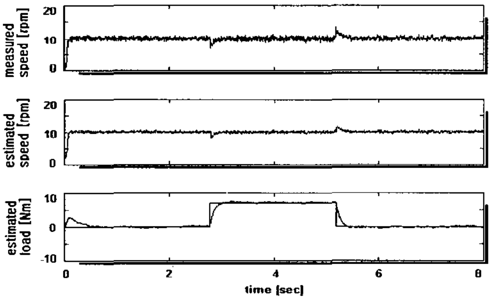

Fig. 8. Characteristics of speed control with estimated speed and load after disturbance compensation (10[rpm]).

VI. Experiments

Experimental system consists of 2.2kW induction motor, voltage-fed inverter with a 600V, 50A intelligent power IGBT module, dynamo system for the load test and digital signal processor(DSP) control board. The encoder has the resolution 2048 (p/r) which is used for the position feedback.

The vector control and the Kalman filter algorithm are realized by using DSP (TMS320C31) and 12-bit AD converter is used in the current sampling. The gate pulse generator for SVM and M/T[3] counter circuits for the speed measurement are simplified by using the erasable programmable logic devices(EPLD). Dead time inserted in PWM patterns is 5μ s. Turn on time and turn off time of the IPM are 0.3μ s and 0.5 μ s respectively.

Fig. 9 shows the speed and phase current without dead time and forward voltage drop compensations. Phase current is not purely sinusoidal and speed control performance is deteriorated. due to the torque ripple. Fig. 10 shows the speed and phase current with dead time and forward voltage drop compensations. Phase current is purely sinusoidal and there's no torque ripple.

Fig. 11 shows the variable speed control characteristic at the low-speed region. Fig. 12 and Fig. 13 show the speed control characteristic at 10 rpm with no load and with load applied.

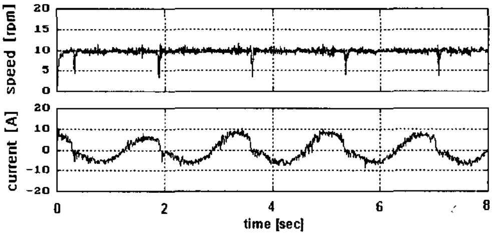

Fig. 9. Speed and phase current without dead time and forward voltage drop compensation.

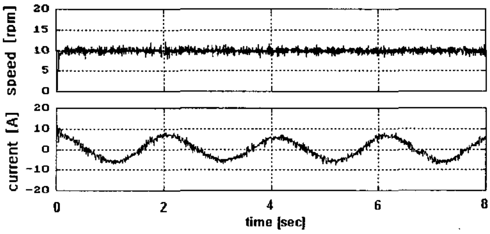

Fig. 10. Speed and phase current with dead time and forward voltage drop compensation.

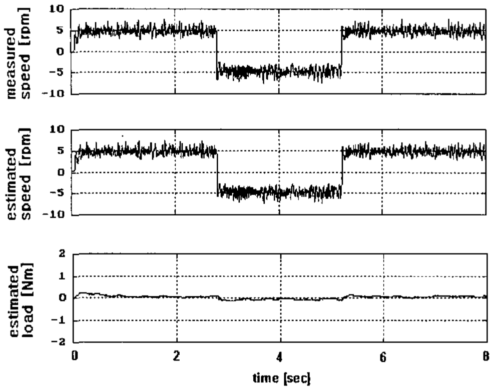

Fig. 11. Characteristics of speed control with estimated speed and load(no load, ±5[rpm]).

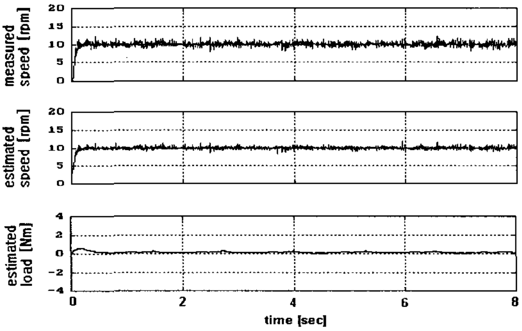

Fig. 12. Characteristics of speed control with estimated speed and load after load torque compensation (no load, 10[rpm]).

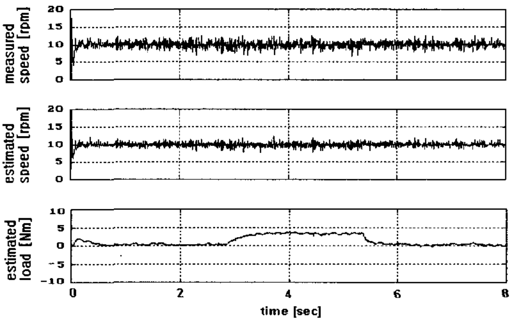

Fig. 13. Characteristics of speed control with estimated speed and load after load torque compensation (load applied, 10[rpm]).

From the results, the proposed system had good control performance with good stability in low speed region.

VI. Conclusion

In this paper, speed and load torque estimation method of an induction motor using Kalman filter algorithm was proposed. With the proposed method, the instantaneous speed and load torque are estimated accurately with the low precision encoder at the low speed region. Vector controller of an induction motor is consisted using these estimated values. The dead time effects and the forward voltage drops of the VSI are feedforwardly compensated to produce an exact inverter output voltage.

The simulation and experimental results show that the proposed method has good control performance and stability at the low speed region even with the low precision encoder.

References

[1] Kenji Kubo, Masahiko Watanabe, Fusaaki Kozawa, Kyouichi Kawasaki, "Disturbance Torque Compensated Speed Observer for Digital Servo Drives", Conf. Rec., IEEE/IAS Ann. Mtg., pp.1182-1187, 1990

[2] Yoichi Hori, "Robust and Adaptive Control of a Servomotor using Low Precision Shaft Encoder", IEEE IECON'93 Nov.15-19, 1993,

[3] T.Ohmae et al., "A Microprocessor-Controlled High Accuracy Wide-Range Speed Regulator for Motor Drives", IEEE Trans. Ind. Electron., vol. IE-29, no. 3, pp.207-211, 1982

[4] C. Schauder, "Adaptive Speed Identification for Vector Control of Induction Motor without Rotational Transducers", IEEE, IAS, pp 493-499 Implementation of an Extended Kalman Filter Synchronous Motor", IEEE

trans. on Power for the State Estimationof a Permanent Magnet Electronics, Vol. 6, No.3, pp. 491 - 497, 1991

[5] Takashi Sukegawa, Katsuhiro Mizuno, Takayuki Matsui, Toshiaki Okuyama, "Fully Digital, Vector Controlled PWM VSI-Fed ac Drives with an Inverter Dead-Time Compensation Strategy", IEEE Trans. on Industrial Applications, Vol. 27, No. 3, pp.552-559, 1991

[6] Johann W.K, Jans Ertl, "Influence of the Modulation Method on the Conduction and Switching losses of PWM Converter System", IEEE, PESC, pp.372-381, 1991

[7] Mohibder S. Grewal, Angus P. Andre WS, *KALMAN FILTERING Theory and Practice*, PRENTICE HALL, 1993

[8] Frank L. Lewis, *APPLIED OPTIMAL CONTROL AND ESTIMATION*, Prentice-Hall, pp.457-525, 1992

[9] R. Dhaoua, N. Mohan, L. Norum, "Design and Implementation of an Extended Kalman Filter for the State Estimationof a Permanent Magnet Synchronous Motor", IEEE trans. on Power Electronics, Vol. 6, No.3, pp. 491 - 497, 1991

저자소개

金成奐(學生會員)
第1卷 第1號 논문 97-01-07 참조.
현재 고려대 전기공학과 박사과정.

朴太植(學生會員)
第1卷 第1號 논문 97-01-07 참조.
현재 고려대 전기공학과 박사과정.

金南正(準會員)
第1卷 第1號 논문 97-01-07 참조.
현재 대한민국 특허청 심사관.

柳志潤(正會員)
第1卷 第1號 논문 97-01-07 참조.
현재 고려대 공대 전기공학과 교수.

朴貴泰(正會員)
第1卷 第1號 논문 97-01-07 참조.
현재 고려대 공대 전기공학과 교수.