論 文
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# 電流形 인버터에 의해 驅動되는 誘導電動機의 時間最適 위치제어에 관한 硏究

## A Study on Time Optimal Position Control of A CSI Fed Induction Motor

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요 약

전류형 인버터에 의해 구동되는 유도전동기 서어보시스템에 폰트리아진 최소원리를 적용한 시간최적 위치제어 방식을 제안하였다. 유도전동기를 자속 기준제어하여 d축과 q축 성분전류를 독립적으로 제어함으로서 우수한 과도특성을 낼 수 있으며 이때 유도전동기는 선형화된 2차시스템으로 모델링 할 수 있다. 이 시스템에 대하여 상태 공간상에서의 스위칭커브는 헤밀토니안 방정식으로부터 얻을 수 있다. 시간최적제어 해의 타당성은 16비트 미이크로프로세서로 의한 5마력 유도전동기 서어보시스템에 적용하여 입증하였다. 실험결과는 같은 조건하에서 디지탈 시뮬레이션 결과와 잘 일치하였다.

ABSTRACT

The time optimal position control scheme based on the Pontryagin's minimum principle is proposed in the current source inverter(CSI) fed induction motor system. The field oriented induction motor system is modelled with a second order plant and a switching curve is obtained by solving Hamiltonian equation. The validity of time optimal control solution has been verified by experimental tests carried out with a prototype MC68000 based microcomputer system, and 5Hp induction motor. Experimental results are in a close agreement with those the digital simulation ones.

### 1. Introduction

In the position control the better transient characteristics are required, as the transient occurs frequently, than in the speed control. Since the DC motors have the capability of high performance torque control by means of the independent control of the field and armature current, DC motors have been widely used in servo applications where the fast response is required.

In the case of induction motors, it is very difficult to get the good transient characteristics, compared with DC motors, for coupling effect between the flux and torque current. Introducing the field oriented control by which the flux and torque current are decoupled, ad controlled independently, this difficulty can be overcome.[1] The induction motors with

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field oriented control are able to have the transient performance nearly equal or even superior to that of the DC motors in the position control.

The time optimal control, the control that it takes the minimum time to reach the desired position, has been successfully applied to the DC motor position control.[2,3] Up to now, the time optimal problems with DC motor servo systems have been discussed in many papers. To solve the optimal control problem including both the linear and nonlinear system, Pontryagin's minimum principle, dynamic programming, or the calculus of variation can be used.[4,5]

In the induction motor drives, however, the optimal control scheme is rarely used because of the high order and nonlinear dynamics of induction motor.[6] But with field oriented control algorithm, dynamics of induction motor can be supposed and reduced to the simplified linear model.

In this paper the current source inverter fed induction motor with the field oriented control loop is applied to the position control, and a new control strategy, the time optimal control based on the minimum principle, is studied. The induction motor and time optimal controller is added to the second order as if DC motor and time optimal controller is added to the field oriented control loop as a outer loop. Then a simple set of switching curve is given by solving a second order state equation. The cost function depends only on the time in time optimal control problem regulating from the arbitrary initial state to the orgin. The control input u(t) to minimize this cost function should be determined by solving Hamiltonian equation, which generates switching pattern, positive or negative maximum value, called time optimal controller. This is a type of the bang bang controller. The proposed control scheme was implemented on a microprocessor system and was applied to control strategy derived analytically and its validity is verified with both the digital computer simulations and experiments.

## 2. Dynamic Model of a CSI fed Induction Motor

The phasor relation which appears in the field oriented control is given in Fig.1. Eq.1 shows the relations betwen the stator current based on d-q axis and stator current based on rotor flux-axis.

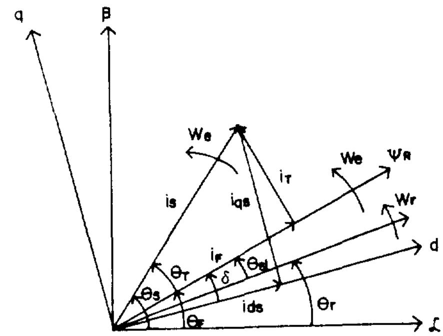


**Fig. 1.**Diagram of stator current vector.

$$\begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} = \begin{bmatrix} -\cos\delta & \sin\delta \\ \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} i_T \\ i_F \end{bmatrix} \qquad (1-a)$$

In Fig.1, if d-axis is oriented to rotor flux-axis, then $\delta = 0$

$$i_{qs} = i_T \text{ and } i_{ds} = i_F \qquad (1-b)$$

If the stator current vector which is synchronously rotating at constant magnitude is decoupled into the two orthogonal components of d-and q-axis is oriented to the rotor flux axis, then components of d-axis become the magnetizing current and the torque current, respectively.

$$I_s^* = \sqrt{i_F^2 + i_T^2} \qquad (2-a)$$

$$\theta_T = \tan^{-1}(i_T / i_F) \qquad (2-b)$$

Where $\theta_T$ is torque angle.

$$\theta_r = \int \omega_r dt$$

$$\theta_{s1} = \int (\omega_e - \omega_r) dt = \int \omega_{sl} \, dt$$

$$\theta_F = \theta_r + \theta_{s1}$$

$$\theta_s = \theta_F + \theta_T$$

Where $\theta_F$ is field angle.

$$I_s = \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} = \mathrm{Im} \begin{bmatrix} 1 \\ e^{-j\frac{2}{3}\pi} \\ e^{-j\frac{4}{3}\pi} \end{bmatrix} (i_F + j i_T) e^{j\theta_F}$$

$$= \mathrm{Im} \begin{bmatrix} 1 \\ e^{-j\frac{2}{3}\pi} \\ e^{-j\frac{4}{3}\pi} \end{bmatrix} I_s^* e^{j(\theta_T + \theta_F)} \qquad (3)$$

Since the stator current vector is referred to the stationary stator frame, it can be expressed as follows: From eq.(3), it is evident that the magnitude of the stator current $I_S$ and its torque angle $\theta_T$ can be controlled simultaneously.

The basic equations of induction motor in the d–q axis which synchronously rotates with an angular velocity $\omega e$ are expressed as follows.[7]

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_s+L_sP & \omega_e L_s & MP & \omega_e M \\ -\omega_e L_s & R_s+L_sP & -\omega_e M & MP \\ MP & \omega_{s1} M & R_r+L_rP & \omega_{s1} L_r \\ -\omega_{s1} M & MP & -\omega_{s1} L_r & R_r+L_rP \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (4)$$

Where P is the derivative operator, $\frac{d}{dt}$ . And the developed electrical torque is given by

$$T=(3P/4)M(i_{qs}i_{dr}-i_{ds}i_{qr}) \quad (5)$$

The equivalent circuit of the induction motor on the d–q axis. One is the stator winding and the other the rotor winding as shown is Fig.2.[8]

From Fig.2, the equation of rotor linkage flux are expressed as following.

$$\begin{aligned} \psi_{dr} &= M(i_{ds}+i_{dr})+L_{1r}i_{dr} \\ &= Mi_{ds}+L_r i_{dr} \\ \psi_{qr} &= M(i_{qs}+i_{qs})+L_{1r}i_{qr} \\ &= Mi_{qs}+L_r i_{qr} \end{aligned} \quad (6)$$

The rotor voltage equations are as follows.

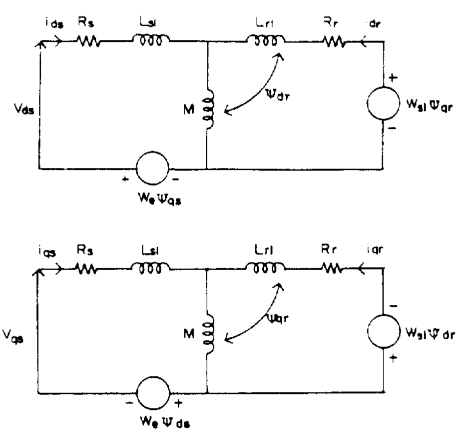


**Fig. 2.** d and q axis equivalent circuits in field coordinate.

$$\begin{aligned} R_r i_{qr} + P\psi_{qr} + \omega_{s1}\psi_{qr} &= 0 \\ R_r i_{dr} + P\psi_{dr} - \omega_{s1}\psi_{dr} &= 0 \end{aligned} \quad (7)$$

If d–axis is oriented to the rotor flux vector, the q–axis component of rotor flux vanishes.

$$\begin{aligned} \psi_{dr} &= \psi_r \\ \psi_{qr} &= P\psi_{qr} = 0 \end{aligned} \quad (8)$$

Substituting eq.(8) into eq.(7)

$$\begin{aligned} R_r i_{qr} + \omega_{s1}\psi_r &= 0 \\ R_r i_{dr} + P\psi_r &= 0 \end{aligned} \quad (9)$$

Substituting eq.(8) into eq.(6)

$$\begin{aligned} i_{qr} &= -\frac{M}{L_r} i_{qs} \\ i_{dr} &= \frac{\psi_r}{L_r} - \frac{M}{L_r} i_{ds} \end{aligned} \quad (10)$$

From eq.(9) and eq.(10) $\omega_{sl}$, $\psi_r$are given by

$$\omega_{s1} = \frac{M}{T_r} - \frac{i_{qs}}{\psi_r} \quad (11)$$

$$P\psi_r = \frac{1}{T_r}(-\psi_r + Mi_{ds}) \quad (12)$$

Where $T_r$is $L_r/R_r$, rotor time constant.
Torque equation is obtained from eq.(5), (10)

$$\begin{aligned} T &= \frac{3}{2}\left(\frac{P}{2}\right)\frac{M}{L_r} i_{qs}\psi_{dr} \\ &= K_t \psi_r i_{qs} \end{aligned} \quad (13)$$

Where $K_t = \frac{3}{2}\left(\frac{P}{2}\right)\frac{M}{L_r}$

Since the flux is constant in steady state $P\psi_r = 0$.
So, from eq.(12)

$$\psi_r = Mi_{ds} \quad (14)$$

Substituting eq.(14) into eq.(11), slip angular velocity is expressed in terms of $i_{ds}$and $i_{qs}$.

$$\omega_{s1} = \frac{1}{T_r}\frac{i_{qs}}{i_{ds}} \quad (15)$$

Also, the torque can be expressed with $i_{qs}$and $i_{ds}$by substituting eq.(14) into eq.(13)

$$T = K_T i_{ds} i_{qs} \quad (16)$$

Where $K_T$ is $K_t M$

Using eq.(1-b), stator current may be expressed as $i_{qs} = i_T$ and $i_{ds} = i_F$.
The developed torque is given as follows.

$$T = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + T_L \tag{17}$$

Substituting eq.(16) into(17), then the transfer function can be given by

$$\frac{Ⓗ(s)}{I_{qs}(s)} = \frac{K_T i_{ds}}{JS\left(S + \frac{B}{J}\right)} \tag{18}$$

From(18), it can be concluded that the induction motor can be simplified as a second order system.[9),10)] This relationship is shown in Fig.3.
Consider the simplified open loop position control system in Fig.3 whose dynamics are given by

$$d\theta/dt = \omega_r \tag{19}$$

$$d\theta^2/dt^2 = -\frac{B}{J}\frac{d\theta}{dt} + \frac{K_T i_T}{J} \tag{20}$$

$u(t) = i_T$ is used as control input in position system, assuming $x_1(t) = \theta(t) - \theta_{ref}$, $x_2(t) = \dot{x}_1(t) = +\omega_r$.

The differential equation system is obtained as follows:

$$\begin{bmatrix} \dot{x}_1(t) \\ \dot{x}_2(t) \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -a \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{K_T}{J} \end{bmatrix} u(t) \tag{21}$$

Where a is $\frac{B}{J}$.

$$[x_1(0)\ \ x_2(0)] = [\theta(0) - \theta_{ref}\ \ 0]^T,$$

$$[x_1(T)\ \ x_2(T)] = [0\ \ 0]^T \tag{22}$$

$$\text{or}\ \ \dot{x}(t) = Ax(t) + Bu(t) \tag{23}$$

The admissible control input is constrained by

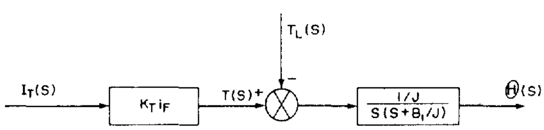


**Fig. 3.** Simplified second order system of induction motor.

$$u(t) \le i_T \tag{24}$$

The cost function is

$$J_1 = \int_0^{T^*} dt = T^* \to \min \tag{25}$$

Now the problem can be described as follows: Consider admissible control input inequality constraint determines a time optimal control u(t) which minimizes the $T^*$any initial state to the origin of the second order system.

## 3. Solution of the Time Optimal Control Problem

$$H = 1 + p_1(t)x_2(t) - ap_2(t)x_2(t) + \frac{K_T}{J}p_2(t)\,u(t) \tag{26}$$

The admissible controls are constrained by

$$u(t) \le i_T \tag{27}$$

and a is positive real number. The eigenvalues of this system equation (21) are 0 and -a ; thus, since both eigenvalues are real and nonnegative, it can be proved that there must exist for the system on unique optimal control taking the system from any initial state to the origin and has at most (n-1) switchings.[11] From the minimum principle, we obtain.

$$u(t) = -i_T\,\mathrm{sgn}(p_2(t)) \tag{28}$$

It is obvious that the control u(t) can switch at most 1 times and take piecewise constant sequence $(-i_T, +i_T)$, $(+i_T, -i_T)$. We first determine the set of points from which the origin can be reached with $u(t) = i_T$(call this set $V_1+$), and the set of points from which the origin can be reached with $u(t) = i_T$(call this set $V_1-$). Define $V_1$ to be the set of all states from which the origin can be reached in positive time by applying the single constant control $u(t) = i_T$or $u(t) = -i_T$
The solution are

$$x_2(t) = \pm\frac{1}{a}[1 - e^{-at}] \tag{29}$$

$$x_1(t) = \pm\frac{1}{a}t \pm \frac{1}{a^2}e^{-at} \pm \frac{1}{a^2} \tag{30}$$

To determine $V^+_1$, use the upper sign(which corresponds to $u(t) = i_T$), solve (29) for t, and substitute in (30) to obtain the relationship

$$x_1(t) = -\frac{1}{a^2}\ln\left(-a\left[x_2(t) - \frac{1}{a}\right]\right) - \frac{1}{a}x_2(t) \quad (31)$$

The set of points in the $x_1$- $x_2$ plane for which this equation is satisfied is $V^+_1$.
Similar reasoning yields as expression for $V^-_1$

$$V_1 = \left\{x_1(t),\ x_2(t) : x_1(t) = \frac{1}{a^2}\ln\left(a\left[x_2(t) + \frac{1}{a}\right]\right) - \frac{1}{a}x_2(t)\right\} \quad (32)$$

Since (31) applies for $x_2(t)<0$ and (32) applies for $x_2(t)>0$, the expression for $V_1$(the set of all points that are in either $V^+_1$ or $V^-_1$) is given by

$$V_1 = \left\{x_1(t),\ x_2(t) : x_1(t) = \frac{x_2(t)}{|x_2(t)|}\frac{1}{a^2}\ln\left(a|x_2(t)| + \frac{1}{a}\right) - \frac{1}{a}x_2(t)\right\} \quad (33)$$

The switching function is then

$$S(x(t)) = x_1(t) - \frac{x_2(t)}{|x_2(t)|}\frac{1}{a^2}\ln\left(a\left[x_2(t) + \frac{1}{a}\right]\right) + \frac{1}{a}x_2(t) \quad (34)$$

Fig.4 illustrates the projections of some time optimal trajectories. Here AOB is called the switching curve.

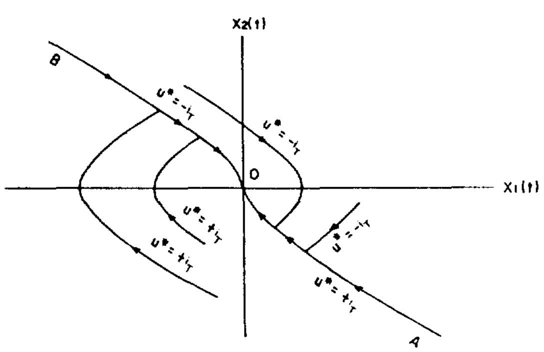


**Fig. 4.** Projection of time-optimal trajectories on the $x_1$- $x_2$ plane.

For initial points below AOB,we take $u = +i_T$ until the switching curve is reached, followed by $u = -i_T$ until the origin is reached. Similary for points above AOB, $u = -i_T$ until the switching curve is reached, followed by $u = +i_T$ until the origin is reached.
Of course, for points on the switching curve, there is no switch at all; on AO, we take $u = +i_T$ and or BO, $u = -i_T$. So we have solved our problem which was to find the optimal trajectory from an arbitrary starting point. And control law is expressed as follows:

$$u(t) = \begin{cases} -i_T, & \text{for } x(t) \text{ such that } S(x(t)) > 0 \\ +i_T, & \text{for } x(t) \text{ such that } S(x(t)) < 0 \\ -i_T, & \text{for } x(t) \text{ such that } S(x(t)) = 0 \text{ and } x_2(t) > 0 \\ +i_T, & \text{for } x(t) \text{ such that } S(x(t)) = 0 \text{ and } x_2(t) < 0 \\ 0, & \text{for } (x(t)) = 0 \end{cases} \quad (35)$$

The ideal relay performs the signum operation on the signal $-S(x(t))$, and the output of ideal relay is time optimal control $u(t)$ which is used to drive the induction servo motor system. And the complete time optimal system is illustrated in block diagram form in Fig.6.

## 4. System Hardware

MC68000 16bit microprocesssor is used to implement the position control scheme. From the feedback informations such as position, speed, and DC link current, the feedback loop are executed to determine the inverter gating angle and converter delay angle. Considering the mechanical and electrical time constant, the position and speed control loop is executed every 10 msec and current control loop every 2msec respectively. Hardware blockdiagram including peripherals is shown in Fig.5. The position is measured with pulse generator and DC link current the hall CT. D/A converters are used to display the internal variables executed in the processor.

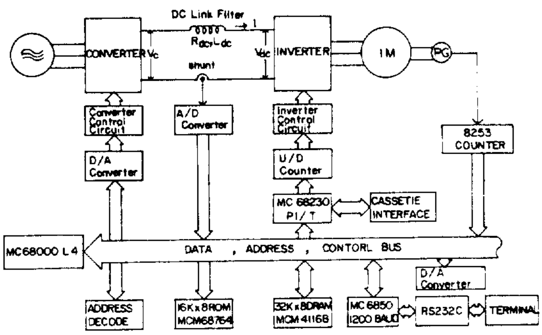


**Fig. 5.**Block diagram of microcomputer hardware.

## 5. Software Configuration for the Time Optimal Position Control

Fig.6 shows the overall block diagram of the time optimal control. As shown in Fig.6, time optimal controller is added to the typical field oriented control loop of the CSI fed induction motor. The field current $i_F$ is maintained constant for the constant air gap flux of the motor and the torque current $i_T$ is determined by the time optimal controller. In the time optimal controller switching function $S(x(t))$ is calculated by the position error, rotor speed and function generator and control input is applied through the ideal relay to transform the value of the sign changed switching pattern into the positive or negative maximum of torque current. By the time optimal controller, it takes the minimum time to reach the wanted position limiting the acceleration and deceleration rates and rotor speed within the tolerable range. Therefore the speed pattern consists of the acceleration period, the constant speed period, and the deceleration period.

Fig.7 shows the software flow-chart. Software is composed of speed interrupt servece routine, current interrupt service routine, main program including the time optimal operation and key display program.

Speed interrupt routine calculates the motor speed and current interrupt one regulates DC link current given in eq. (2-a). Operation of main

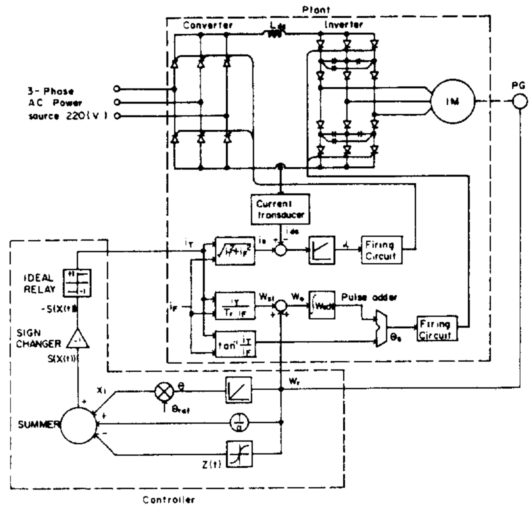


**Fig. 6.** Block diagram of time optimal control.

program is executed as following steps.

1) $\omega_r$ is calculated with encoder pulses read from speed interrupt service routine.
2) Actual position is calculated from intergral of real speed $\omega_r$. Switching function is also obtained in terms of speed, position error, and function generator. A look up table is used to calculate the logarithm. Through switching function after sign changer, and the ideal relay, and torque current command is given to have positive or negative maximum value when the speed reaches the limited value, torque current is maintained constant according to load.
3) Slip angular velocity is evaluated as follows.

$$\omega_{sl} = \frac{1}{T_r} \frac{i_T}{i_F}$$

4) $W_T$ is calculated in terms of $\omega_{sl}$

$$\theta_T = \tan^{-1}(i_T/i_F) = \tan^{-1}(T_r \omega_{sl})$$

Taking the derivative

$$\omega_T = \frac{d\theta_T}{dt} = \frac{T_r}{1+T_r^2\,\omega_{sl}^2} \frac{d\omega_{sl}}{dt}$$

For a infinitesimal period

$$\frac{\Delta\theta_T}{\Delta t}=\frac{T_r}{1+T_r^2\ \omega_{sl}^2}\ \frac{\Delta\omega_{sl}}{\Delta t}$$

$\omega_T$ is a factor that produces quick response and vanishes in steady state.

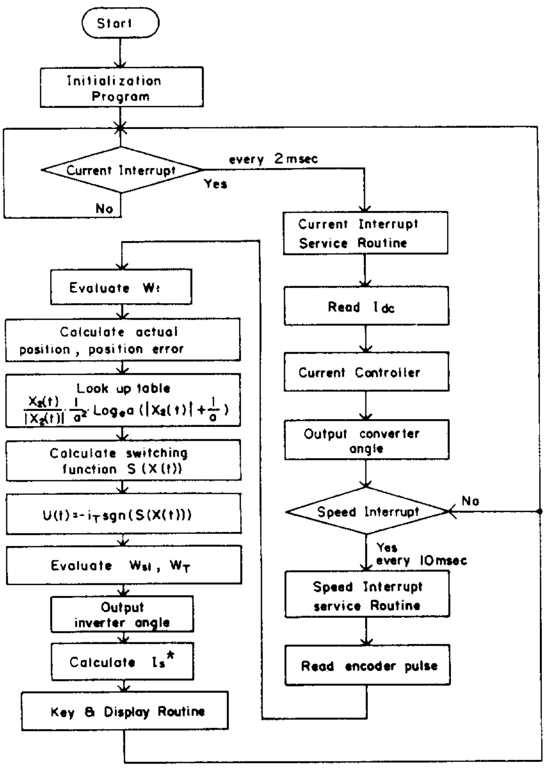


**Fig.** 7.Flow chart of software.

5) Synchronous speed $\omega_e$ is summed as follows

$$\omega_e=\omega_r+\omega_{sl}+\omega_T$$

Thereafter the inverter switching point are obtained with $\omega_e$.

## 6. Simulation and Experimental Results

The microprocessor-based control system based on a single 16bit microprocessor(Motorola 68000) was employed to control a 5Hp induction motor.[12] The motor parameters are listed in appendix. The digital computer simulations are shown in Fig.8, Fig. 9.

Torque current $i_T$ is limited to the positive maximum value in the acceleration and the negative maximum one in the deceleration periods, ad maintained constant value according to the load in the constant speed range. Experimental results are shown in Fig.10, Fig. 11. It is seen that the experimental results, at the same operation condition matches well the simulation ones.

## 7. Conclusions

A microprocessor based time optimal position control scheme for induction motor drive is discussed, and the following concluding remarks are confirmed.

1) The induction motor system with the field oriented control is regarded as the model equivalent

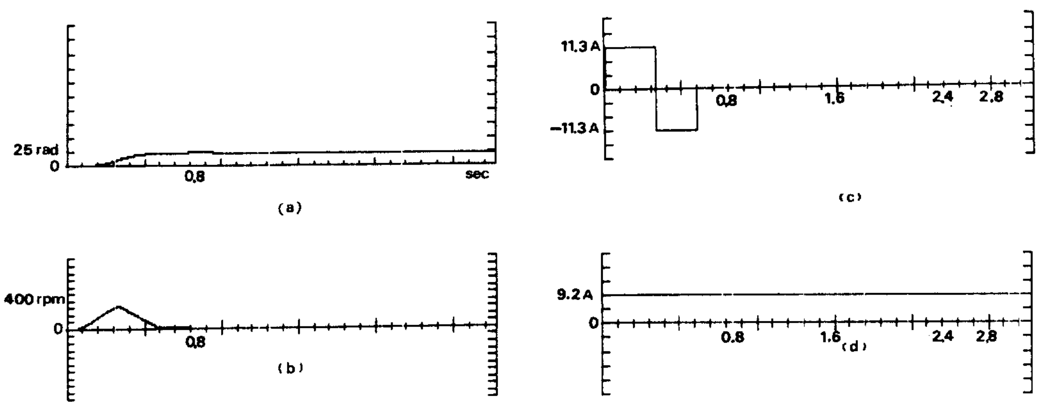


**Fig. 8.** The waveforms of (a)position (b)speed (c)torque current (d)exciting current at $\theta_{ref}=25$ [rad]

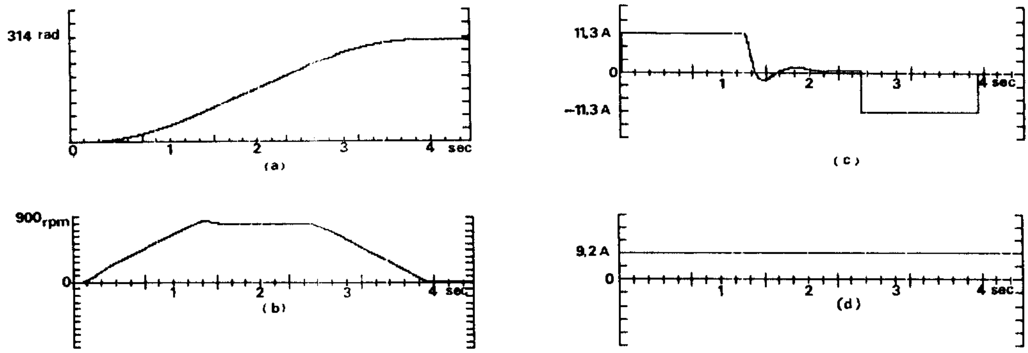


**Fig. 9.** The waveforms of (a)position (b)speed (c)torque current (d)exciting current at $\theta_{ref}=314$ [rad].

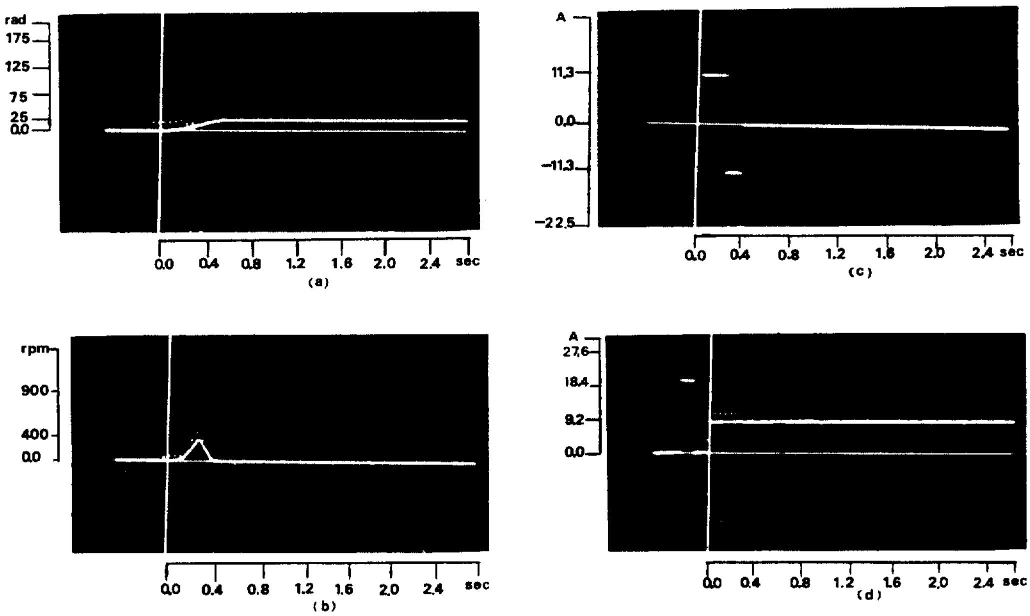


**Fig. 10.** The waveforms of (a)position (b)speed (c)torque current (d)exciting current at $\theta_{ref}=25$[rad].

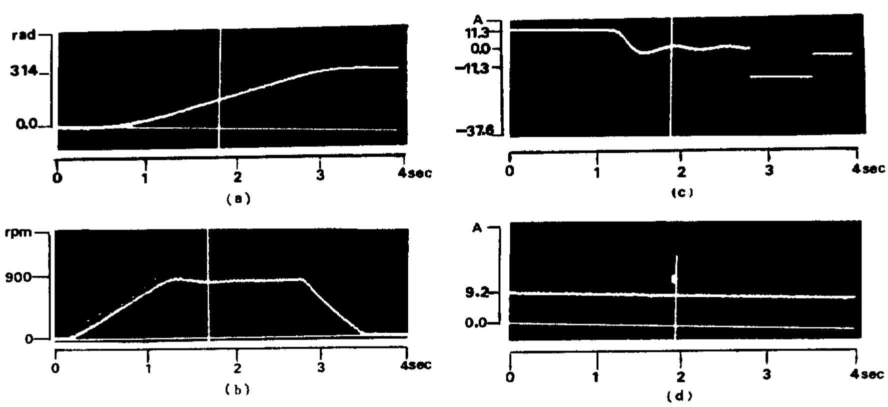


**Fig. 11.** The waveforms of (a)position (b)speed (c)torque current (d)exciting current at $\theta_{ref}=314$[rad].

to the DC motors, and then the Pontryagin's principle is applied to the system for the time optimal position control.

2) The field oriented induction motor is modelled with the second order plant, and time optimal controller is constructed to derive control input from the Hamiltonian equation.
3) The experimental results concide nearly with the simulation ones, and it is expected that the scheme of the time optimal control are useful to the high performance servo applications.
4) For the precise position control, it is required that the time optimal controller is switched over PI controller when the position reaches the vicinity of the origin.[13),14)]

## Nomenclature

| | |
|---|---|
| d, q | : Equivalent two-phase transformed variable as in $i_{qs}$ and $i_{ds}$ |
| $i_{ds}$, $i_{qs}$ | : Two-phase d, q axis motor stator current variables |
| $i_F$ | : Current of flux component |
| $i_T$ | : Current of torque component or output of ideal relay |
| $i_{dr}$, $i_{qr}$ | : Two-phase d, q axis motor rotor current variables |
| $V_{ds}$, $V_{qs}$ | : Two-phase d, q axis motor stator voltage variables |
| $V_{dr}$, $V_{qr}$ | : Two-phase d, q axis motor rotor voltage variables |
| $\psi_{ds}$, $\psi_{qs}$ | : d-, q-component of stator flux |
| $\psi_{dr}$, $\psi_{qr}$ | : d-, q-component of rotor flux |
| $\psi_r$ | : Rotor flux |
| $I_s$ | : Stator current vector |
| $I_{dc}$ | : D.C link current |
| $I_s^*$ | : Reference current |
| $\omega_e$ | : synchronous angular velocity |
| $\omega_r$ | : Rotor angular velocity |
| $\omega_{sl}$ | : Slip angular velocity |
| $\omega_T$ | : Torque angular velocity |
| $\theta_S$ | : Synchronous angle |
| $\theta_F$ | : Field angle |
| $\theta_T$ | : Torque angle |
| $\theta_{sl}$ | : Slip angle |
| $\theta_r$ | : rotor angle |
| $\delta$ | : Arbitrary fixed angle |
| **P** | : Number of pole pair |
| P | : Differential operator |
| M | : Mutual inductance |
| $K_t$, $K_T$ | : Torque constant |
| B | : Friction coefficient |
| J | : Moment of intertia of motor |
| T | : Output torque |
| $\theta_{ref}$ | : Reference position |
| $\theta$ | : Actual position |
| u(t) | : Control input |
| $J_1$ | : Cost function |
| S | : Laplace operator |
| H | : Hamiltonian |
| $p_1(t)$ and $p_2(t)$ | : Adjoint variables associated with $x_1(t)$ and $x_2(t)$ |
| sgn | : Signum function |
| $V_1^+$ | : The set of points which the origin can be reached with $u(t) = -i_T$ |
| $V_1^-$ | : The set of points which the origin can be reached with $u(t) = -i_T$ |
| $V_1$ | : The union of $V_1^+$ and $V_1^-$ |
| S(x(t)) | : Switching function |
| Z(t) | : Function generator |

## Appendix

Motor Rating

| | |
|---|---|
| Rated Voltage | 220V |
| Rated current | 15A |
| Power | 5hP |
| Speed | 1735r/min |
| Frequency | 60Hz |

Motor is three-phase delta connected with four ploes.

Motor Parameter

$R_s = 0.434\Omega$

$R_r = 0.356\Omega$

$L_s = 0.0463H$

$L_r$ = 0.0557H
M = 0.0546H
J = 0.21kg.m²
B = 0.019kg.m²/sec

DC Link Parameter
$R_{dc}$ = 0.3Ω
$L_{dc}$ = 80mH

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