วิศวกรรมสาร มข. ปีที่ 32 ฉบับที่ 4 (539 - 550) กรกฎาคม - สิงหาคม 2548
KKU Engineering Journal Vol. 32 No. 4 (539 - 550) July – August 2005

Modified Discrete Sliding mode Model Following Control (DSMFC) for an Induction Motor Drivers *

Phongsak Phakamach [1)]

[1)] Lecturer, Department of Electronics Engineering, Faculty of Engineering, North Eastern University, Khon Kaen 4000

E-mail : p_phakamach@hotmail.com

Abstract

A Discrete Sliding mode Model Following Control or DSMFC strategy for an induction motor drivers is presented. The DSMFC algorithm uses the combination of model following control and sliding mode control to improve the dynamics response for command tracking. A procedure is proposed for choosing the control function so that it guarantee the existence of a sliding mode. The DSMFC approach has been implemented on a microcontroller and applied to a position control of an induction motor. Experimental results illustrate that DSMFC gives a significant improvement on the tracking performances and robust to plant parameter variations and disturbances.

Keywords: Sliding Mode Control, Discrete Time System, Induction Motor Drivers.

* Original manucript submitted: January 12, 2005 and Final manucript received: April 7, 2005

Introduction

Recently, industry application of the high performance vector-controlled induction motor drivers have greatly increased, including machine tools, robotics and paper machines [P.C.Krause *et al.* 1995]. The ultimate object of vector control is to enable decoupling control of torque and flux similar to the control of a separately excited DC motor. However, the dynamic position vector control is sensitive to machine parameter variations. Moreover, the machine parameters and load characteristics are not exactly known, which way very during motor operation. Thus the dynamic of such system are complex and nonlinear, where the linear controller design may not assure satisfactory performances.

To satisfy these requirement, a variable structure control (VSC) or Sliding Mode Control (SMC) is invariant to system parameter variations and disturbances when the sliding mode occurs [U.Itkis, 1976 and V.I.Utkin *et al.* 1999], but it may result in a steady state error when there is load disturbance in it. In order to improve the problem, the Integral Variable Structure Model Following Control (IVSMFC) has been proposed [T.L.Chern *et at.* 1997 and T.L.Chern *et al.* 1998] for achieving a zero steady state error for step command input. The IVSMFC approach combines an integral controller with VSC and applied to the design of a Model Following Control (MFC). However, when command input is changing,e.g., ramp command input, the IVSMFC gives a steady state error. The Modified Integral Variable Structure Control or MIVSC approach, proposed in [S.Nungam and P.Daungkua. 1998], uses a double integral action to solve this problem. Although, the MIVSC method can give a better tracking performance than the IVSMFC method does at steady state, its performance during transient period needs to be improved.

In this paper, the Discrete Sliding mode Model Following Control or DSMFC approach is presented. This approach, which is the extension of FIVSC approach [P.Phakamach and S.Nungam. 1999], incorporates a feedforward path to improve the dynamics response for command tracking. The advantage of the DSMFC approach is that the error trajectory in the sliding motion can be prescribed by the design. Also, it can achieve a rather accurate servo tracking and is fairly robust to plant parameter variations and external load disturbances. An experimental prototype system consisting of a MCS-196MC microcontroller is constructed. As a results, the tracking performance can be remarkably improved. The DSMFC method is applied to an induction motor for a position control system.

Design of DSMFC System

The structure of DSMFC system is shown in Figure 1. It combines the conventional VSC with a double-integral compensator, a feedforward path from the input command, a reference model and a comparator.

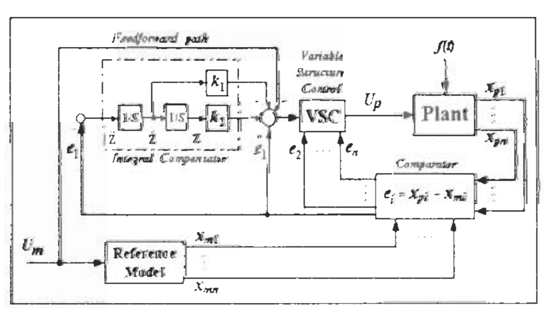

Figure 1 *The structure of DSMFC system*

Let the plant be described by the following equation :

$$\dot{x}_{pi} = x_{p(i+1)} \quad ;i=1,\ldots,n\text{-}1, \qquad \dot{x}_{pn} = -\sum_{i=1}^{n} a_{pi}x_{pi} + b_p U_p - f(t) \tag{1}$$

where a_{pi} and b_p are the plant parameters; $f(t)$ are disturbances and U_p is the control input of the plant.

The reference model is represented by

$$\dot{x}_{mi} = x_{m(i+1)} \quad ;i=1,\ldots,n\text{-}1, \qquad \dot{x}_{mn} = -\sum_{i=1}^{n} a_{mi}x_{mi} + b_m U_m \tag{2}$$

where U_m is the input command of the system.

Defining $e_i = x_{pi} - x_{mi}$;(i=1,...,n) and subtracting (2) from (1), the error differential equation is

$$\dot{e}_i = e_{i+1} \quad ;i=1,\ldots,n\text{-}1, \qquad \dot{e}_n = -\sum_{i=1}^{n} a_{pi}e_i - \sum_{i=1}^{n}(a_{mi} - a_{pi})x_{mi} + b_m U_m - b_p U_p - f(t). \tag{3}$$

Using the SMFC approach [P.Phakamach and S.Nungam, 2000., P.Phakamach and S.Nungam, 2001] to the error dynamics in order to synthesise the control signal, U_p and assuming the asymptotic divergence of the error to zero, the DSMFC system in Fig. 1 can be described as

$$\dot{z} = -e_1, \quad \dot{e}_i = e_{i+1} \quad ;i=1,\ldots,n\text{-}1 \text{ and } \dot{e}_n = -\sum_{i=1}^{n} a_{pi}e_i - \sum_{i=1}^{n}(a_{mi} - a_{pi})x_{mi} + b_m U_m - b_p U_p - f(t) \tag{4}$$

where U_p is the control function.

Consider the discretisation of the system given in (4). If the derivative is approximated by the forward difference as [C.I.Philips and H.T.Nagle, 2000]

$$\dot{e}_i(t) = \frac{e_i(t+T) - e_i(t)}{T}$$

where T is the sampling interval, then the discretised version of the system (4) can be represented as :

$$\dot{z}(k+1) = \dot{z}(k) - Te_1(k), \quad e_i(k+1) = e_i(k) + Te_{i+1}(k) \quad ;i=1,\ldots,n\text{-}1 \tag{5a}$$

$$\dot{e}_n(k+1) = e_n(k) - T\sum_{i=1}^{n} a_{pi}e_i - T\sum_{i=1}^{n}(a_{mi} - a_{pi})x_{mi}(k) + Tb_m U_m(k) - Tb_p U_p(k) - Tf(k) \tag{5b}$$

The switching function, σ is given by

$$\sigma(k) = c_1[e_1(k) - K_1\dot{z}(k) - K_2 z(k) - r(k)] + \sum_{i=2}^{n} c_i e_i(k) \qquad ;C_i > 0 = \text{constant}, C_n = 1. \tag{6}$$

In the discrete variable structure control system, the control input is computed at discrete instants and applied to the system during the sampling interval so that an ideal sliding motion cannot be obtained. The conditions ensuring the existence and reachability of a non-ideal sliding motion are :

$$\sigma(k)\Delta\sigma(k+1) \langle\, 0 \quad \text{and} \quad |\Delta\sigma(k+1)| \,\langle\, \frac{\xi}{2} \tag{7}$$

where $\Delta\sigma(k+1) = \sigma(k+1)$; $\sigma(k)$ and ξ is a small positive number. The control function can be chosen to guarantee that the inequalities (7) are satisfied, so a sliding mode motion control within the range of ξ will appear or $\sigma(k)\langle\xi$.

Design of such a system involves the choice of the control function $U_p(k)$ to guarantee the existence of a sliding mode control, the determination of the switching function $\sigma(k)$ and the integral control gain K_I such that the system has the desired properties and the elimination of chattering phenomena of the control input by using the smoothing function.

Choice of control function

The control signal can be determined as follows. From (5) and (6), we have

$$\Delta\sigma(k+1) = -Tc_1(K_1\ddot{z}(k)+K_2\dot{z}(k))+T\sum_{i=2}^{n}c_{i-1}e_i - \sum_{i=1}^{n}a_{pi}e_i(k)+\sum_{i=1}^{n}(a_{mi}-a_{pi})x_{mi}(k)-Tb_mU_m(k)+Tb_pU_p(k)-Tf(k) \tag{8}$$

Let $a_{pi} = a_{pi}^0 + \Delta a_{pi}$; $i = 1,\ldots,n$ and $b_p = b_p^0 + \Delta b_p$; $b_p^0 > 0$, $\Delta b_p > -b_p^0$,

where a_{pi}^0 and b_p^0 are nominal values; Δa_{pi} and Δb_p are the associated variations.

Let the control function $U_p(k)$ be decomposed into

$$U_p(k) = U_{eq}(k) + U_s(k) \tag{9}$$

where the so called equivalent control $U_{eq}(k)$ is defined as the solution of (9) under the condition where there is no disturbances and no parameter variations, that is $\Delta\sigma(k+1) = 0$, $f(k) = 0$, $a_{pi} = a_{pi}^0$, $b_p = b_p^0$ and $U_p(k) = U_{eq}(k)$. This condition results in

$$U_{eq}(k) = \left\{-c_1(K_1\ddot{z}(k)+K_2\dot{z}(k))-\sum_{i=2}^{n-1}c_{i-1}e_i(k)+\sum_{i=1}^{n-1}a_{pi}^0e_i(k)-\sum_{i=1}^{n}(a_{mi}-a_{pi})x_{mi}(k)+b_mU_m(k)\right\}/b_p^0 . \tag{10}$$

In the sliding motion, $\sigma(k) = 0$, one can obtain

$$e_n(k) = \left[-c_1[e_1(k)-K_1\dot{z}(k)-K_2z(k)-r(k)]-\sum_{i=2}^{n}c_ie_i(k)\right]. \tag{11}$$

Substitution of (11) into (10) yields

$$\begin{aligned} U_{eq}(k) = \Big\{ & -c_1(K_1\ddot{z}(k)+K_2\dot{z}(k))-T\sum_{i=2}^{n-1}c_{i-1}e_i(k)+T\sum_{i=1}^{n-1}a_{pi}^0e_i(k)-T\sum_{i=1}^{n}(a_{mi}-a_{pi})x_{mi}(k)+b_mU_m(k) \\ & +(c_{i-1}-a_{pn}^0)[c_1(e_1(k)-K_1\dot{z}(k)+K_2z(k)-U_m(k))+\sum_{i=2}^{n-1}c_ie_i(k)]\Big\}/b_p^0. \end{aligned} \tag{12}$$

The function $U_s(k)$, is employed to eliminate the influence due to Δa_{pi}, Δb_p and $f(k)$ so as to guarantee the existence of a sliding mode control, this function is constructed as

$$U_s(k)=\varphi_1(e_1(k)-K_1\ddot{z}(k)-K_2 z(k)-U_m(k))+T\sum_{i=2}^{n}\varphi_i e_i(k)+\varphi_{n+1} \quad (13)$$

Where :

$$\varphi_1=\begin{cases}\alpha_1 & \text{if } [e_1(k)-K_1\dot{z}(k)-K_2 z(k)-U_m(k)]\sigma(k)\rangle 0\\ \beta_1 & \text{if } [e_1(k)-K_1\dot{z}(k)-K_2 z(k)-U_m(k)]\sigma(k)\langle 0\end{cases},\quad \varphi_i=\begin{cases}\alpha_i & \text{if } e_i\sigma(k)\rangle 0\\ \beta_i & \text{if } e_i\sigma(k)\langle 0\end{cases};i=2,\dots,n \text{ and}$$

$$\varphi_{n+1}=\begin{cases}\alpha_{n+1} & \text{if } \sigma(k)\rangle 0\\ \beta_{n+1} & \text{if } \sigma(k)\langle 0\end{cases}.$$

Substitute (7) and (9) into (6), to obtain

$$\begin{aligned}\Delta\sigma(k+1)\sigma(k)=T\{&[-\Delta a_{p1}+a_{p1}^0\Delta b_p/b_p^0+c_1(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0)+b_p\varphi_1](e_1(k)-K_1\dot{z}(k)-K_2 z(k)-U_m(k))\sigma(k)\\&+\sum_{i=2}^{n-1}\{[-\Delta a_{pi}+a_{pi}^0\Delta b_p/b_p^0-c_{i-1}\Delta b_p/b_p^0+c_i(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0)+b_p\Psi_i]e_i(k)\sigma(k)\}\\&+[-\Delta a_{pn}+(c_{n-1}-a_{pn}^0)+b_p\Psi_n]e_n\sigma(k)\ +[N(k)+b_p\Psi_{n+1}]\sigma(k)\end{aligned}\quad (14)$$

where

$$N=-(K_1\dot{z}(k)+K_2 z(k))(\Delta a_{p1}-a_{p1}^0\Delta b_p/b_p^0)+\Delta b_p/b_p^0[c_1(K_1\ddot{z}(k)+K_2\dot{z}(k))]+[-\sum_{i=1}^{n}(a_{mi}-a_{pi}^0)x_{mi}(k)+b_m U_m]\Delta b_p/b_p^0-f(k).$$

In order for (7) to be satisfied, the following conditions must be met,

$$\varphi_i=\begin{cases}\alpha_i\ \langle\ \varphi L_i=\mathrm{Inf}[\Delta a_{pi}-a_{pi}^0\Delta b_p/b_p^0+c_{i-1}\Delta b_p/b_p^0-c_i(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0]/b_p\\ \beta_i\ \rangle\ \varphi U_i=\mathrm{Sup}[\Delta a_{pi}-a_{pi}^0\Delta b_p/b_p^0+c_{i-1}\Delta b_p/b_p^0-c_i(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0]/b_p\end{cases}\quad \text{where } i=1,\dots,n-1, c_0=0,$$

$$\varphi_n=\begin{cases}\alpha_n\ \langle\ \varphi L_i=\mathrm{Inf}[\Delta a_{pn}+a_{pn}^0-c_{n-1}]/b_p\\ \beta_n\ \rangle\ \varphi U_i=\mathrm{Sup}[\Delta a_{pn}+a_{pn}^0-c_{n-1}]/b_p\end{cases}\ \text{and}\ \varphi_{n+1}=\begin{cases}\alpha_{n+1}\ \langle\ \varphi L_{(n+1)}=\mathrm{Inf}[-N(k)]/b_p\\ \beta_{n+1}\ \rangle\ \varphi U_{(n+1)}=\mathrm{Sup}[-N(k)]/b_p\end{cases}.\quad (15)$$

For satisfying (7), if the sampling interval T is enough small, one can be obtain :

$$L_1\langle\varphi_1\langle M_1,\quad L_i\langle\varphi_i\langle M_i\ ;i=2,\dots,n\text{-}1,\quad L_n\langle\varphi_n\langle M_n\quad\text{and}\quad L_{n+1}\langle\varphi_{n+1}\langle M_{n+1}\quad (16)$$

where:

$$M_1=\inf\left|[\Delta a_{p1}-a_{p1}^0\Delta b_p/b_p^0+c_{i-1}\Delta b_p/b_p^0-c_1(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0)+\gamma_1/(T|e_1(k)-K_1\dot{z}(k)-K_2 z(k)-U_m(k)|)]/b_p\right|$$

$$L_1=\sup\left|[\Delta a_{p1}-a_{p1}^0\Delta b_p/b_p^0+c_{i-1}\Delta b_p/b_p^0-c_1(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0)-\gamma_1/(T|e_1(k)-K_1\dot{z}(k)-K_2 z(k)-U_m(k)|)]/b_p\right|$$

$$M_i=\inf\left|[\Delta a_{pi}-a_{pi}^0\Delta b_p/b_p^0+c_{i-1}\Delta b_p/b_p^0-c_i(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0)+\gamma_1/(T|x_i(k)|)]/b_p\right|$$

$$L_i=\sup\left|[\Delta a_{pi}-a_{pi}^0\Delta b_p/b_p^0+c_{i-1}\Delta b_p/b_p^0-c_i(c_{n-1}-a_{pn}^0)(1+\Delta b_p/b_p^0)-\gamma_1/(T|x_i(k)|)]/b_p\right|$$

$$M_n=\inf\left|[\Delta a_{pn}-a_{pn}^0-c_{n-1}+\gamma_n/(T|e_n(k)|)]/b_p\right.,\ L_n=\sup\left|[\Delta a_{pn}-a_{pn}^0-c_{n-1}-\gamma_n/(T|e_n(k)|)]/b_p\right.$$

$$M_{n+1}=\inf\left|N(k)+\gamma_{n+1}/T]/b_p\right.,\ L_{n+1}=\sup\left|N(k)-\gamma_{n+1}/T]/b_p\right.$$

in which γ_i ;i=1,…,n+1, are positive constants and $\gamma_1+\cdots+\gamma_{n+1}<\xi/2$.

From (15) and (16), if the T is enough small, one can obtain the bound of α_i and β_i as :

$$L_i < \alpha_i < \varphi L_i \quad \varphi U_i < \beta_i < M_i \quad ;i = 1,\ldots,n+1. \tag{17}$$

If φ_i ;i=1,...,n+1, are chosen as $\varphi_i < \alpha_i < -\beta_i$, finally, the control can be represented as

$$U_p = \Big\{-c_1(K_1\ddot{z}(k)+K_2\dot{z}(k)) - \sum_{i=2}^{n-1} c_{i-1}e_i(k) + \sum_{i=1}^{n-1} d_{pi}^0 e_i(k) - \sum_{i=1}^{n}(a_{mi}-a_{pi}^0)x_{mi}(k) + b_m U_m(k) + (c_{n-1}-a_{pn}^0)\big[c_1(e_1(k)-K_1\dot{z}(k)-K_2 z(k)-U_m(k)) + \sum_{i=2}^{n-1} c_i e_i(k)\big]\Big\}/b_p^0 + \Big(\varphi_1\left|e_1(k)-K_1\dot{z}(k)-K_2 z(k)-U_m(k)\right| + \sum_{i=2}^{n}\varphi_i\left|e_i(k)\right| + \varphi_{n+1}\Big)sign(\sigma(k)) \tag{18}$$

From (17), the upper and low bounds of the φ_i, can be obtain

$$\hat{L}_i < \hat{\varphi}_i < \hat{M}_i \quad ;i=1,\ldots,n+1, \text{ where } \hat{M}_i = -\max(|\varphi L_i|,|\varphi U_i|) \text{ and } \hat{L}_i = -\max(|L_i|,|M_i|) \tag{19}$$

Determination of switching plane and integral control gain

In the above subsection it has been proved that if the solution of the ideal sliding motion is asymptotically stable, it will close to the solution of the non-ideal sliding within the range of ξ. Thus one can choose the switching plane and integral control gain of the basis of the ideal sliding motion. While in the ideal sliding motion, the system can described by (4) can be reduced to :

$$\dot{z}(k+1) = \dot{z}(k) - Te_1(k),\ e_i(k+1) = e_i(k) + Te_{i+1}(k) \quad ;i=1,\ldots,n\text{-}2 \tag{20a}$$

$$\dot{e}_n(k+1) = e_{n-1}(k) - T[C_1K_1\dot{z}(k) - C_2K_2 z(k)] - \sum_{i=1}^{n} a_{pi}e_i(k) \tag{20b}$$

The characteristic equation when the system is on the sliding surface can be shown as

$$H(s) = \frac{E_1(z)}{U_m(z)} = \frac{\left(\frac{z-1}{T}\right)^2 c_1}{\left(\frac{z-1}{T}\right)^n + c_{n-1}\left(\frac{z-1}{T}\right)^{n-1} + \ldots + c_1K_1\left(\frac{z-1}{T}\right) + c_1K_2}. \tag{21}$$

The characteristic equation of the system (21) is

$$\left(\frac{z-1}{T}\right)^n + c_{n-1}\left(\frac{z-1}{T}\right)^{n-1} + \ldots + c_1K_1\left(\frac{z-1}{T}\right) + c_1K_2 = 0\cdot \tag{22}$$

Since this characteristic equation is independent of the plant parameter, the DSMFC approach is robust to plant parameter variations. Further, one can choose the coefficients of the switching function and the integral control gain by the pole assignment technique such that this sliding motion has desirable properties.

Let z-1/T = η. Then (22) can be rewritten as

$$\eta^n + C_{n-1}\eta^{n-1} + \ldots + C_1K_1\eta + C_2K_2 = 0. \quad (23)$$

Using the final value theorem, it can be shown from (21), that the steady-state tracking error due to a ramp command input is zero. The transient response of the system can be determined by suitably selecting the poles of the transfer function (21).

Let
$$\eta^n + \alpha_1\eta^{n-1} + \ldots + \alpha_{n-1}\eta + \alpha_n = 0 \quad (24)$$

be the desired characteristic equation(closed-loop poles), the coefficient C_1, C_2 and K_1, K_2 can be obtained by

$$C_{n-1} = \alpha_1,\ C_1 = \alpha_{n-2},\ K_1 = \alpha_{n-1}/C_1 \text{ and } K_2 = \alpha_n/C_1.$$

Chattering Considerations

Normally, the sign function sign (σ) given by (18), will give rise to chattering in the control signal. To reduce the chattering, the sign function can be replaced by the continuous function, given by

$$M_\delta(\sigma) = \frac{\sigma(k)}{|\sigma(k)| + \delta_0 + \delta_1|\dot{z}(k)|} \quad \text{where } \delta = \delta_0 + \delta_1|\dot{z}(k)| \text{ ;} \delta_0 \text{ and } \delta_1 \text{ are positive constants.} \quad (25)$$

Dynamic Modeling of an Induction Motor

The mathematical modeling of a 3-phase, Y-connected squirrel-cage induction motor in the d–q synchronous rotating reference frame can be described by the following state equation :

$$\begin{bmatrix} v^e_{qs} \\ v^e_{ds} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + pL_{ss} & \omega_e L_{ss} & pM & \omega_e M \\ -\omega_e L_{ss} & r_s + pL_{ss} & -\omega_e M & pM \\ pM & (\omega_e - \omega_r)M & r'_r + pL'_{rr} & (\omega_e - \omega_r)L'_{rr} \\ -(\omega_e - \omega_r) & pM & -(\omega_e - \omega_r)L'_{rr} & r'_r + pL'_{rr} \end{bmatrix} \begin{bmatrix} i^e_{qs} \\ i^e_{ds} \\ i^e_{qr} \\ i^e_{dr} \end{bmatrix} \quad (26a)$$

$$T_e = \frac{3}{4} pM(i^e_{qs} i^e_{dr} - i^e_{ds} i^e_{qr}) \quad (26b)$$

where

r_s, r'_r is the stator resistance and rotor resistance per phase referred to stator; L_{ss}, L'_{rr} is the stator inductance and rotor inductance per phase referred to stator; P is the number of poles; M is the mutual magnetizing induction; P is the differential operator; $v^e_{qs}, (v^e_{ds})$ is the q-axis (d-axis) stator voltage; $i^e_{qs}, (i^e_{ds})$ is the q-axis (d-axis) stator current; $i^e_{qr}, (i^e_{dr})$ is the referred q-axis (d-axis) stator current; ω_r is the rotor electrical angular velocity and ω_e is the synchronous angular velocity. The generated torque, rotor mechanical angular velocity ω_m and load can be express as

$$T_e = J_m p\,\omega_{rm} + B_m \omega_{rm} + T_L \quad (27)$$

where J_m is the inertia of the rotor, B_m is viscous damping coefficient and T_L is the load disturbance torque.

The q-axis stator voltage equation of motor can be represented as

$$v_{qs}^e = R_\sigma i_{qs}^e + L_\sigma \frac{di_{qs}^e}{dt} + K_E \omega_{rm} \tag{28}$$

where $R_\sigma = r_s + L_{ss} / L'_{rr} r'_r, L_\sigma = L_{ss}(1 - M^2 / L_{ss} L'_{rr})$ and $K_E = (P/2) L_{ss} i_{ds}^e$.

The mode of the PWM VSI circuit can be simplified as a constant gain $K_A = V_{DC}/(2E_d)$, where V_{DC} is the DC supply voltage and E_d is the triangular peak value. The current loop compensator gain is g_I and the current feedback gain is K_C. Thus, the dynamic model of the vector-controlled induction motor drive with current control PWM-VSI inverter can be shown in Figure 2.

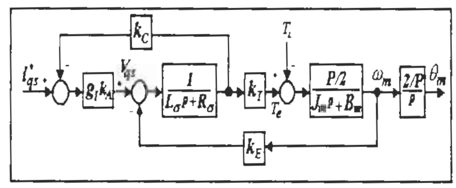

Figure 2 *Dynamic model of vector-controlled induction motor drive with current control loop*

The DSMFC for Vector-Controlled Induction Motor Drives

The objective of the control is to keep the mechanical angular position of the rotor to follow the desired trajectory as closely as possible. The block diagram of DSMFC system is shown in Figure 3 and its implementation is shown in Figure 4. The system contains the induction motor, a power circuit driver and the DSMFC system. The nominal values of the machine parameters and the DSMFC controller are listed in Table 1 and Table 2, respectively.

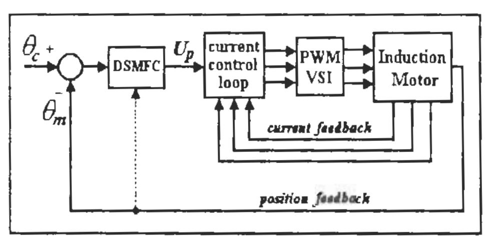

Figure 3 *Block diagram of the DSMFC for vector-controlled of an induction motor control system*

The simplified dynamic model of the vector-controlled induction motor position control can be described as

$$\dot{x}_{p1} = x_{p2}, \ \dot{x}_{p2} = x_{p3}, \ \dot{x}_{p3} = -a_{p1}x_{p1} - a_{p2}x_{p2} - a_{p3}x_{p3} + b_p U_p - f(t) \tag{29}$$

where $a_{p1} = 0$, $a_{p2} = \frac{(g_I K_A K_C + R_\sigma) B_m + K_T K_E}{J_m L_\sigma}$, $a_{p3} = \frac{(g_I K_A K_C + R_\sigma)}{L_\sigma} + \frac{B_m}{J_m}$,

$b_p = \frac{g_I K_A K_C}{J_m L_\sigma}$ and $f(t) = \frac{(g_I K_A K_C + R_\sigma)}{J_m L_\sigma} T_L + \frac{1}{J_m} \dot{T}_L$

and where $x_{p1} = \theta_m$ is mechanical angular angle of the rotor; x_{p2} is mechanical angular velocity of the rotor; x_{p3} is mechanical angular acceleration of the rotor; U_p is control input and $U_m = \theta_c$ is desired position.

The reference model is chosen as

$$\dot{x}_{m1} = x_{m2},\ \dot{x}_{m2} = x_{m3} \text{ and } \dot{x}_{m3} = -a_{m1}x_{m1} - a_{m2}x_{m2} - a_{m3}x_{m3} + b_m U_m . \tag{30}$$

Defining $e_i = x_{pi} - x_{mi}$;(i= 1,2,3), the DSMFC system can be represented as

$$\dot{z}(k+1) = \dot{z}(k) - Te_1(k),\ e_2(k+1) = e_2(k) + Te_3(k)\ ;i=1,\ldots,n-1 \tag{31a}$$

$$e_3(k+1) = e_3(k) - T\sum_{i=1}^{n} a_{pi}e_i(k) - T\sum_{i=1}^{n}(a_{mi} - a_{pi})x_{mi}(k) + Tb_m U_m(k) - Tb_p U_p(k) - Tf(k) \tag{31b}$$

Following the design procedure we have the control law to implement as

$$\begin{aligned} U_p(k) = \{ & c_1(K_1\ddot{z}(k) + K_2\dot{z}(k)) + a^0_{p1}e_1(k) + a^0_{p2}e_2(k) - [(a_{m1} - a^0_{p1})x_{m1}(k) + (a_{m2} - a^0_{p2})x_{m2}(k) + (a_{m3} - a^0_{p3})x_{m3}(k) + b_m U_m)] \\ & + (c_2 - a^0_3)\{c_1(e_1(k) - K_1\dot{z}(k) - K_2 z(k) - r(k)) + c_2 e_2(k)\}\}/b^0 + (\Psi_1|e_1(k) - K_1\dot{z}(k) - K_2 z(k) - r(k)| + \Psi_2|e_2(k)| \\ & + \Psi_3|e_3(k)| + \Psi_4)M_\delta(\sigma) \end{aligned} \tag{32}$$

The switching function, $\sigma(k)$ from (6), is given by

$$\sigma(k) = c_1(e_1(k) - K_1\dot{z}(k) - K_2 z(k) - r(k)) + c_2 e_2(k) + e_3(k). \tag{33}$$

Parameter	Value	Dimension
P	2	*poles*
r_s	1.5	Ω
r_r'	1.8	Ω
L_{ss}	0.175	H
L'_{rr}	0.175	H
M	0.186	H
B_m	0.000127	*N-m/s*
J_m	0.00034	*Kg-m*^{2}
K_C	0.5	*Volt/Amp*
E_d	0.5	*Volt*
V_{DC}	156	*Volt*

Table 1 *Parameters of an induction motor*

Parameter	Value
λ_1	-7.495+32.672i
λ_2	-7.495-32.672i
λ_3	-23.946
λ_4	-5.628
C_1	500.5
C_2	10.65
K_1	7.26
K_2	25.32
φ_1	-0.5
φ_2	-0.0001
φ_3	-0.005
φ_4	-0.001
a_{m1}	15,000
a_{m2}	1,320
a_{m3}	75
b_m	35,000
a_{p2}^0	29,764
a_{p3}^0	13,626
b_p^0	3,662,836
δ_0	5
δ_1	50

Table 2 *Parameters of DSMFC controller*

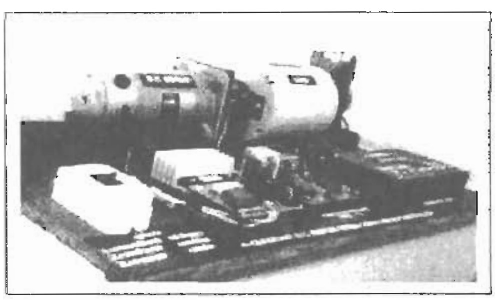

Figure 4 *The DSMFC for an induction motor*

Experimental Results and Discussions

The experimental results of the dynamic response are shown in Figure 5, where a ramp command is introduced and the motor is applied with a variable load torque and parameters variation. The results are compared with obtained from the MIVSC and IVSMFC approaches, Figure 6, compares the position tracking errors. It is clear from the curves that DSMFC can track the command input extremely well during steady state as well as transient periods. Among others, the DSMFC approach gives the minimum tracking error and fast accurate tracking.

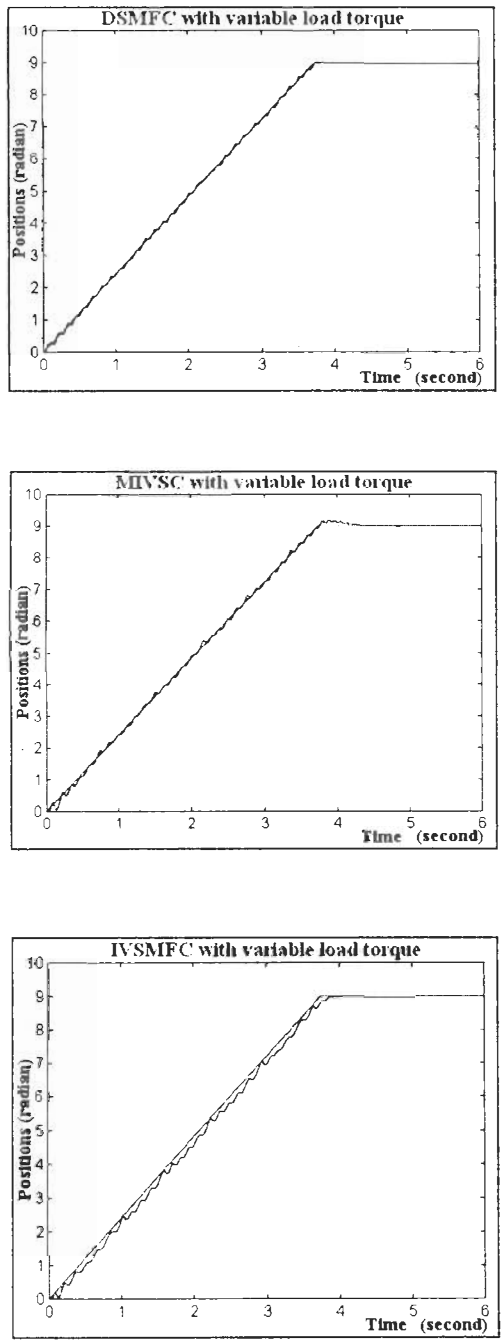

Figure 5 *Comparison of ramp position tracking*

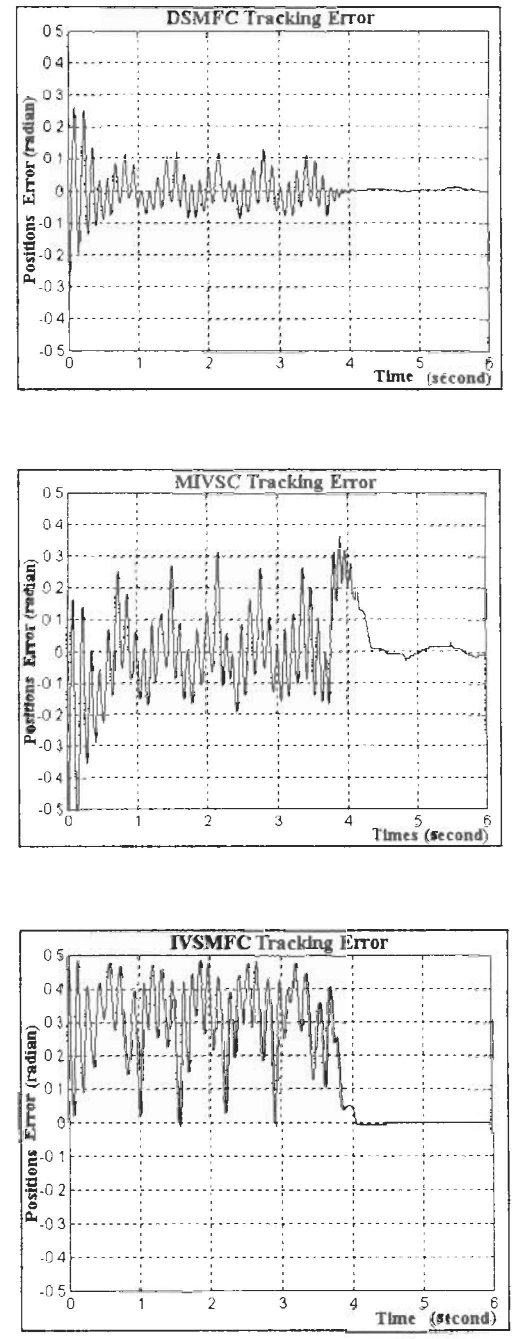

Figure 6 *Comparison of position tracking errors*

Conclusions

An induction motor position control driver using DSMFC approach is presented. It has been developed a procedure for determining the control function and switching plane by using model following control. Also, by using a continuous function, the chattering can be effectively suppressed. The application of SMFC to the induction motor position control system has illustrated that the DSMFC approach can improve the tracking performance by 70% and 80% when compared to the MIVSC and IVSMFC approaches, respectively. Experimental results demonstrate that the proposed approach can achieve accurate position tracking in face of wide plant parameter variations and external load disturbance. Furthermore, The DSMFC approach is robust and applicable to electrical machine control systems. It is therefore expected that the proposed control scheme can be applied to the high performance applications of induction motor such as the high precision control of machine tools and industrials.

Acknowledgement

Author of the paper would like to acknowledge the supported of North-Eastern University, Khon Kaen, Thailand.

References

Chern T.L., J.Chang and G.K.Chang. 1997. DSP-Based Integral Variable Structure Model Following Control for Brushless DC Motor Drivers. **IEEE Transaction on Power Electronic.** 12, 1 (January) : 53-63.

Chern T.L and J.Chang. 1998. DSP-Based Induction Motor Drives using Integral Variable Structure Model Following Control approach. **IEEE International Electric Machines and Drives:** 9.1-9.3

Itkis U. 1976. **Control Systems of Variable Structure.** New York: Wiley.

Krause P.C., O.Wasynezuk and S.D.Sudhoff. 1995. **Analysis of Electric machinery.** IEEE press. New York.

Phakamach P.and S.Nungam. 1999. Design of Feedforward Integral Variable Structure Control System and Application to a Brushless DC Motor Control. **IEEE International Symposium on Intelligent Signal Processing and Communication Systems.** (November): 390-393.

Phakamach P.and S.Nungam, 2000. Design of a Sliding mode Model Following Control for a Brushless DC Servomotor (Best Paper Award). **23rd Electrical Engineering Conference.**(November): 565-568.

Phakamach P. and S.Nungam. 2001. Design of a Sliding mode Model Following Control for Induction Motor Drivers. **The second International Conference on Intelligent Technology.**

Philips C.L and H.T. Nagle. 2000. **Digital Control System Analysis and Design.** Prentice-Hall, International Edition.

Nungam S. and P. Daungkua. 1998. Modified Integral Variable Structure Control for Brushless DC Servomotor. **21st Electrical Engineering Conference.** (November): 138-141.

Utkin V.I., J.Guldner and J.Shi. 1999. **Sliding Mode Controll in Electromechanical Systems.** Taylor & Francis.