Design of Improved Discrete Variable Structure Controller for Induction motor Position control

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ABSTRACT – In this paper, the discrete variable structure controller (DVSC) is proposed for vector controlled induction motor position control. The variable structure control (VSC) which guarantees accuracy and robustness in nonlinear control system is developed in discrete time domain for applying to real servo system. Furthermore, the load torque observer is introduced to reduce chattering problem. The computer simulation results are presented to verify the proposed control scheme.

1. INTRODUCTION

The VSC is a very superior modern control theory and used widely because of its robustness, invariance and order reduction effect against perturbance of plant and external disturbances[1]. However, because of a discontinuous control input with finite sampling time, a chattering is a unique problem in VSC. This problem results in system output error like current harmonics, speed oscillation. So it is considered the sliding mode load torque observer (SMLTO) which estimates imposed load and it makes chattering bound in quasi- sliding mode (QSM). Recently, the most control systems tend to be implemented with digital processor that has relatively a fast sampling period, it is necessary that a conventional VSC be designed to discrete version.

In this paper, After improving the definitions about QSM that was mentioned in [4], we design the proposed DVSC and it is applied to position controller for vector controlled induction motor. The proposed DVSC position controller guarantees fast dynamic response without overshoot in transient state, accuracy and robustness against parameter variation and external disturbance in steady state. Finally, the computer simulation results validate that the proposed position control scheme has good performance.

2. DESIGN of IMPROVED DVSC

It is difficult to control induction motor because it has multi-variable and nonlinear properties. However the torque characteristics of vector controlled induction motor are similar to dc motor.

The mechanical dynamic equation of induction motor can be described as

$$J\frac{d}{dt}\omega_m + B\omega_m = K_t i_{qs}^1 \tag{1}$$

where J, B, ω_m, i_{qs}^1 and K_t are the moment of inertia, viscous friction, rotor mechanical speed, q-axis stator current and torque constant respectively. Let the difference between the position reference and real position value defines state x_1 and the derivative of x_1 defines state x_2 as follow

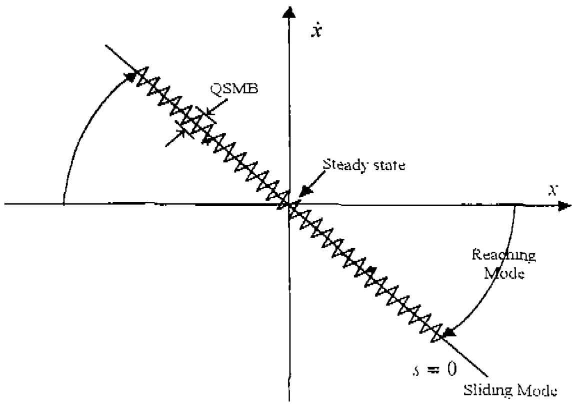


Fig. 1 Quasi-sliding mode

$$\begin{aligned} x_1 &= \theta - \theta^* \\ x_2 &= \dot{x}_1 \end{aligned} \tag{2}$$

Considering real applications implemented with digital system, which has frequency limitation, it is desirable to develop the conventional VSC in discrete time domain. In the DVSC theory of [4], the attributes are too strict to implement with real systems. Therefore, considering chattering problem for application, the attribute A2 in [4] must be improved as follow A^*.

- ▶ A^* : When the disturbance exists within a specified band, the state trajectory should cross the switching plane in every sampling period.

By substituting (1) into (2), we can obtain (3)

$$\dot{\mathbf{x}} = \mathbf{A}_c\mathbf{x} + \Delta\mathbf{A}_c\mathbf{x} + \mathbf{b}_c i_{qs}^1 + \mathbf{f}_c \tag{3}$$

where

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \qquad \mathbf{A}_c = \begin{bmatrix} 0 & 1 \\ 0 & -B/J \end{bmatrix}$$

$$\mathbf{b}_c = \begin{bmatrix} 0 \\ K_t/J \end{bmatrix}, \qquad K_t = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} i_{ds}^*$$

$\Delta\mathbf{A}_c\mathbf{x}$ and $\mathbf{f}_c$ are the parameter variation and external disturbance including some noises respectively.

The (3) can be described in discrete system as

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \Delta\mathbf{A}\mathbf{x}(k) + \mathbf{b}i_{qs}^1(k) + \mathbf{f}(k) \tag{4}$$

where

$$\mathbf{A} = e^{\mathbf{A}_c T_s}$$

$$\mathbf{b} = \left\{\int_0^{T_s} e^{\mathbf{A}_c\tau} d\tau\right\}\mathbf{b}_c$$

T_s = sampling period of DVSC

If the matching conditions are satisfied

$$\Delta\mathbf{A}\mathbf{x}(k) = \mathbf{b}\overline{\mathbf{A}}$$
$$\mathbf{f}(k) = \mathbf{b}\bar{f}$$

we can rewrite (4) as

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{b}[i_{qs}^1 + \bar{d}(k)] \tag{5}$$

where $\bar{d}(k) = \Delta\mathbf{A}\mathbf{x}(k) + \bar{f}(k)$. Let $d(k) = \mathbf{cb}\bar{d}(k)$ to reduce calculations and the upper band of disturbance is limited as follow

$$-D \le d(i) \le D, \qquad i = 0,1,2,\ldots \tag{6}$$

where D denotes the tolerative band of disturbance mentioned in A^*.

We can define the switching function as

$$s(k) = \mathbf{cx}(k) = cx_1(k) + x_2(k) \tag{7}$$

There were many control schemes that have been proposed to obtain the control law in the past, we adopt a reaching law approach[4] which satisfies the reaching condition naturally. The (8) is an incremental term of the switching function and it makes the sliding mode exist.

$$s(k+1) - s(k) = -qT_s(k) - \varepsilon T_s\,\mathrm{sgn}[s(k)] \tag{8}$$

where $\varepsilon > 0, q > 0$ and $1 - qT_s > 0$.

By substituting (8) into (7)

$$
\begin{aligned}
&s(k+1)-s(k)\\
&=\mathbf{cAx}(k)+\mathbf{cb}[i_{qs}^{1}(k)+\bar{d}(k)]-\mathbf{cx}(k)\\
&=-qT_s s(k)-\varepsilon T_s\,\mathrm{sgn}[s(k)]
\end{aligned}
\tag{9}
$$

To obtain the control input, we can rearrange (9)

$$
\begin{aligned}
i_{qs}^{1}(k)=-(\mathbf{cb})^{-1}\{&\mathbf{cAx}(k)-(1-qT_s)s(k)\\
&+\varepsilon T_s\,\mathrm{sgn}[s(k)]\}
\end{aligned}
\tag{10}
$$

Thus, the increment of switching function is obtained by substituting (10) into (9)

$$
\begin{aligned}
&s(k+1)-s(k)\\
&=-qT_s(k)-\varepsilon T_s\,\mathrm{sgn}[s(k)]+\mathbf{cb}\bar{d}(k)
\end{aligned}
\tag{11}
$$

To satisfy the attribute A^{*}, the sign of $s(k)$ must be changed in every sampling period

$$
\mathrm{sgn}[s(k+2)]=-\mathrm{sgn}[s(k+1)]=\mathrm{sgn}[s(k)]
\tag{12}
$$

By substituting (10) and (11) into (12)

$$
\begin{aligned}
s(k+2)=\mathrm{sgn}[s(k)]\{&(1-qT_s)^2\,|s(k)|+qT_s\varepsilon T_s\}\\
&+(1-qT_s)d(k)+d(k+1)
\end{aligned}
\tag{13}
$$

Then, we can solve (13) for D using (6) as follow

$$
D<\frac{qT_s\varepsilon T_s}{2-qT_s}
\tag{14}
$$

When (14) is satisfied, the sigh of $s(k)$ is changed in every sampling. If the disturbance exists within tolerative band, the size of $s(k)$ can be restricted as

$$
|s(k)|<\Delta=\frac{\varepsilon T_s}{1-qT_s}
\tag{15}
$$

and Quasi-Sliding Mode Band(QSMB) is 2Δ. The size of the switching function of nominal system in steady state can be obtained as follow

$$
\Delta s=\frac{\varepsilon T_s}{2-qT_s}
\tag{16}
$$

3. SMLTO DESIGN

The load torque is compensated feed-forwardly using a sliding mode load torque observer. The disturbance by reason of parameter variation should be limited within tolerate band, but the observation error can be existed out of the band. To observe the imposed load, the sliding mode load observer is designed as

$$
\begin{aligned}
\dot{\hat{\omega}}_m&=-\frac{B}{J}\hat{\omega}_m-\frac{1}{J}\hat{T}_L+\frac{K_t}{J}i_{qs}+K_1\,\mathrm{sgn}(s_t)\\
\dot{\hat{T}}_L&=K_2\,\mathrm{sgn}(s_t)
\end{aligned}
\tag{17}
$$

The sliding line is chosen as follow

$$
s_t=\omega_m-\hat{\omega}_m
\tag{18}
$$

The sufficient condition for existing the sliding mode is described as follow

$$
\dot{s}_t s_t<0
\tag{19}
$$

and the constant K_1 must be

$$
K_1>\left|-\frac{1}{J}(T_L-\hat{T}_L)+w\right|
\tag{20}
$$

The stator current reference that estimated by load torque observer is described as follow

$$
i_{qs}^{*2}=\hat{T}_L/K_t
\tag{21}
$$

Therefore, the total control input is sum of i_{qs}^{*1} and i_{qs}^{*2} as

$$
i_{qs}^{*}=i_{qs}^{*1}+i_{qs}^{*2}
\tag{22}
$$

Expansion of sliding line

So far, it has been explained DVSC system, which make the state trajectory reach to the sliding line. However it is defined as $x_2 = \omega_m$ in (2) and if the state vector reaches to sliding line for desired position, the motor speed cannot be infinite and a speed limitation ($\omega_{\max}$) should be designed to restrict the motor speed. For Example, when the initial condition of θ and ω_m is zero, position error $x_1 = \theta^*$ and the state vector has two different trajectories depend on the position reference as shown in Fig. 2. In case A, the state trajectory meets the sliding line under the speed limitation and the state trajectory is over the speed limitation in case B. In this case, we regard the speed limitation as expanded sliding line and make the state trajectory follow expanded sliding line like case C. Thus, the proposed DVSC can be applied to all position reference.

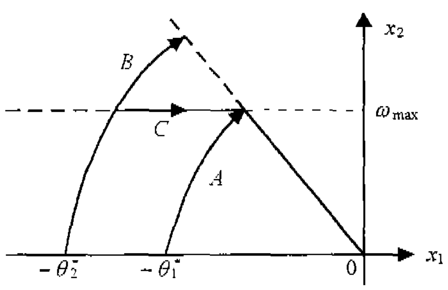


Fig. 2 Expansion of sliding line

The block diagram of the proposed DVSC for vector controlled induction motor is shown in Fig. 3.

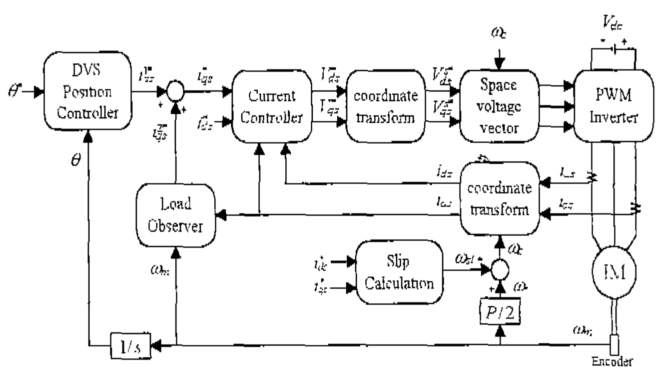


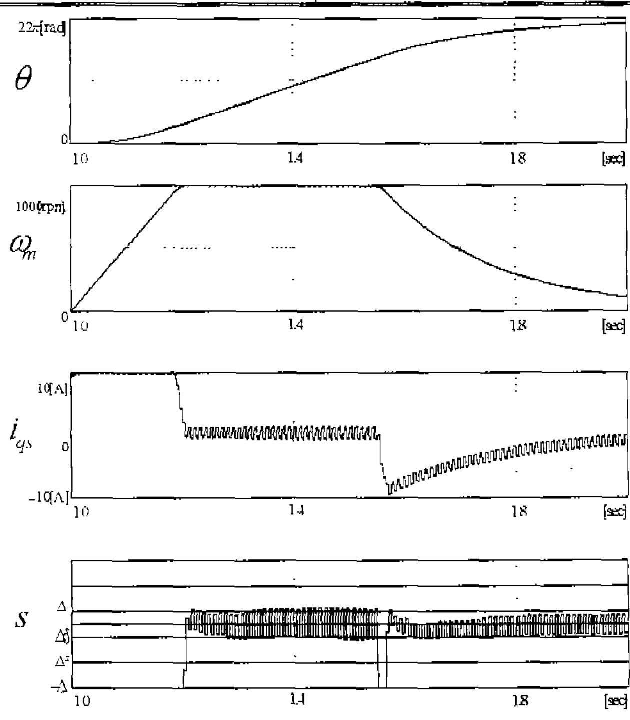
Fig. 3 The block diagram of overall system

4. SIMULATION

To verify the proposed controller, the computer simulation is carried out. The sampling period of inner vector control loop, DVSC position controller, and SMLTO are 100[μs], 5[ms] and 100[μs] respectively. Additionally, a voltage source inverter and space voltage vector PWM (pulse-width modulation) method are applied for considering real systems. Let qT_s and εT_s of position controller are 0.5 and 0.1 respectively and K_1 of the observer are 200. The parameters and ratings of three-phase squirrel-cage induction motor used in simulation are shown in Table 1.

Table 1. The parameters and ratings of IM

Rated voltage 250[V]	Rated current 8.4[A]
Rated speed 1420[rpm]	Poles 4
Rated output 2.2[kW]	Rated load 14[Nm]
$R_s = 1.45\ [\Omega]$	$R_r = 0.925[\Omega]$
$L_s = 100.8$ [mH]	$L_r = 100.2$ [mH]
$L_m = 96.7$ [mH]	$J = 0.0245[Nms^2/rad]$
$B = 0.0035[Nms^2/rad]$	



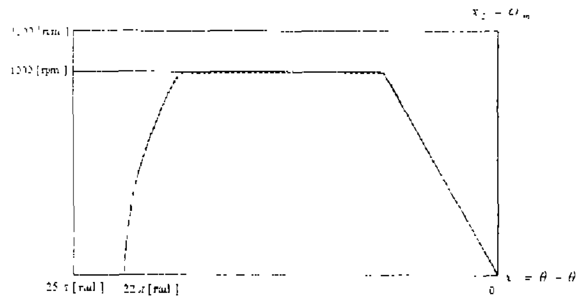


Fig. 4 The response waveforms and state trajectory with $\theta^* = 22\pi$ [rad]

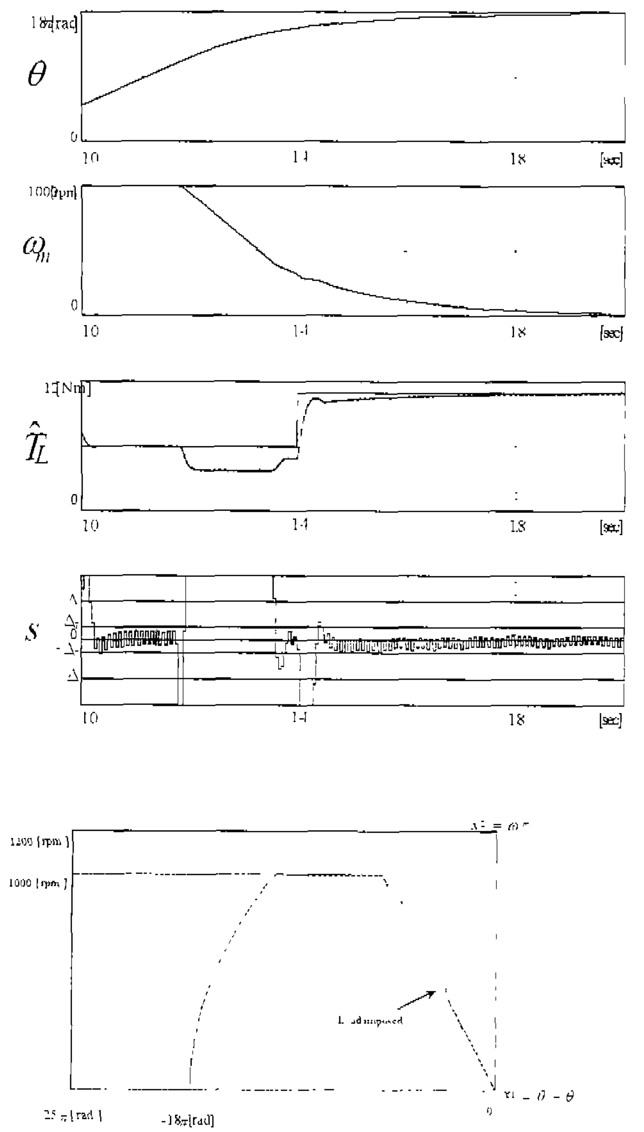


Fig. 5 The response waveforms and state trajectory with parameter variation ($J = J_0 * 1.5$)

When J and B have the nominal value, the response waveforms with position reference 22π [rad] are shown in Fig. 4. Although K_t becomes a constant by the vector control loop, it is not ideal constant practically. Thus, the variation of K_t occurs in the disturbance. The position response curve tracks reference value with maximum torque output and the sign of $s(k)$ is changed in every sampling time. Particularly, the position error in steady state is not exceeding the QSMB.

Firstly, when practical J is changed to 150% of nominal value at about $t = 1.18$ [sec], the response waveforms are shown in Fig. 5. An observation error is occurred in transient state and the switching function $s(k)$ goes outside from the QSMB for a while, but the observer returns quickly in steady state and shows good switching operation. Secondly, when load (10[Nm]) is imposed at $t = 1.4$ [sec], the $s(k)$ goes away from QSMB, but it is shown that the position response recovers the reference value with estimating load torque and $s(k)$ also comes back quickly within the QSMB. Therefore, it is verified that the proposed controller has robustness against parameter variation and external load.

5. CONCLUSIONS

In this study, the VSC is improved in discrete version for applying to servo digital system in the direction of reducing chattering problem. The SMLTO is used to observe the external load and the sliding line is expanded to guarantee the proposed DVSC. As this control scheme is applied to position controller for vector controlled induction motor, there are good performances which are fast dynamic response without overshoot, robustness and invariance against external disturbance and internal parameter variation. The computer simulation results verify that the proposed DVSC agrees with the theory.

REFERENCE

[1] V. J. Utkin, "Sliding Mode Control Design Principles and Applications to Electric Drives", IEEE Trans. on Ind. Electron. Vol. 40, no. 1, Feb. 1993.

[2] D. Milosavljevic, "General conditions for the existence of a quasi-sliding mode on the switching hyperplane in discrete variable structure systems", Automat. Remote Contr., vol. 46, 1985.

[3] S. Z. Sarpturk, Y. Istefanopuios, and O. Kaynak, "On the stability of discrete-time sliding mode control systems", IEEE Trans. Automat. Contr., vol. 32, no. 10, 1987.

[4] W. B. Gao, Y. Wang, and A. Homaifa, "Discrete-time variable structure control systems", IEEE Trans. on Ind. Electron., vol. 42, no. 2, Apr. 1995.

[5] J. Y. Hung, W. Gao, and J. C. Hung, "Variable Structure Control : A Survey," IEEE Trans. Ind. Electron. Vol. 40, No. 1, Feb., 1993.