A New Improved Continuous Variable Structure Tracking Controller For BLDD Servo Motors

브러쉬없는 직접구동 전동기를 위한 새로운 개선된 연속 가변구조 추적제어기

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Abstract

A new improved robust variable structure tracking controller is presented to provide an accurately prescribed tracking performance for brushless direct drive(BLDD) servo motors(SM) under uncertainties and load variations. A special integral sliding surface suggested for removing the reaching phase problems can define its ideal sliding mode and virtual ideal sliding trajectory from an initial position of SM. The tracking error caused by the nonzero value of the sliding surface is derived. A corresponding continuous control input with the disturbance observer is suggested to track a predetermined virtual ideal sliding trajectory within a prescribed value under all the uncertainties and load variations. The usefulness of the proposed algorithm is demonstrated through the comparative simulations for a BLDD SM under load variations.

요 약

본 연구에서는 불확실성과 부하 변동 하에 브러쉬없는 직접구동 전동기의 정확한 사전결정 추적성능을 제공하기 위한 새로운 개선된 강인한 가변구조 추적 제어기를 설계하였다. 리칭 페이즈를 제거하기 위한 특수 적분 슬라이딩 면은 서보 전동기의 초기 위치부터 이상 슬라이딩 모드와 가상 이상 슬라이딩 궤적을 정의한다. 영이 아닌 슬라이딩 면에 의하여 발생되는 추적오차를 유도하였다. 외란 관측기를 갖는 연속 입력을 제안하여 불확실성과 부하 변동 하에 사전 결정 가상 이상 슬라이딩 궤적을 사전 값 내에 추적하도록 한다. 제안된 알고리듬의 유용성을 부하 변동 하에 브러쉬없는 직접구동 전동기에 대한 비교 시뮬레이션으로 입증한다.

Keywords – tracking control, variable structure system, sliding mode control, disturbance observer, direct drive, brushless motor

I. Introduction

In the tracking control, the use of direct drive motors ever increases because of their many advantages over non-direct drive motors. One of them is the very high torque generation at low to moderate speeds. However these are dominant harmful factors in controller design for brushless direct drive servo motor(BLDD SM)s, Since load variations and external disturbances can directly influence on servo systems.

As a robust and precise algorithm, a sliding mode control(SMC) is considered for both brushless servo motors[2],[3] and BLDD SMs[4],[5]. It is well known that the controlled system in the sliding mode is completely robust against load variations and external

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disturbances[1]. On the other hand, there exists an inevitable chattering resulted from the switching of the control structure[6],[7] which can cause the torque ripple and excite the unmodelled dynamics of direct drive servo systems. Therefore, the continuous variable structure systems has been extensively investigated to replace discontinuous parts by the continuous saturation function[6],[8] or the bounded layer method[9],[10]. There are an uniformly ultimately bounded stability analysis of the continuous VSS[11], its implementation with the derivatives of all the states[7],[12], and utilizing the sliding surface as a partial control gain[4], combining with the disturbance observer[13] and continuous sliding mode control[14] for reducing the chattering problems, and [15] for improving the robustness of the individual techniques.

In these previous works, however, it is difficult to obtain the pre-information on a tracking error as an important performance measure in a servomechanism. Therefore, [16] presented a continuous VSS controller to possibly guarantee the prescribed tracking performance. However, its applications are limited only to the tracking problems that the desired trajectory should be planned from the initial position of motors. When the initial position of planned desired trajectories is severely different from that of motors, the tracking problems may be mixed with the regulation problems and then the reaching phase problems can arise.

In this paper, a new improved continuous variable structure controller is designed to provide the accurately prescribed tracking performance in the control of a BLDD SM to follow a planned desired trajectory with an arbitrary initial point. To remove the reaching phase problems, a special integral sliding surface is introduced. Its ideal sliding mode and a unique virtual ideal sliding trajectory is defined in Definition 1. The relationship between the tracking error to the predetermined virtual ideal sliding trajectory and the value of the sliding surface is obtained in Theorem 1. It is possible to control the BLDD SM to track the transient virtual sliding trajectory within a prescribed value. The comparative computer simulation studies are given to show the effectiveness of the proposed algorithm.

II. Modeling of BLDD SM and Backgrounds

A brushless type direct drive servo motor physically has the same structure as a synchronous machine, but is specially designed for the purpose of very high torque generation at low speed[17]. By means of the field-oriented vector control, a BLDD SM for the design of the VSS can be described as follows

$$J\cdot\ddot{\theta}(t)+D\cdot\dot{\theta}(t)+T_L(t,\theta(t))=p/2k_t\cdot i_{qs} \qquad (1)$$

where $k_t=(3/2)(p/2)\lambda_m$. It is assumed that the left-hand side of (1) is smooth enough to ensure a local existence, a uniqueness of the solution for every initial condition and also the continuity of the control, and motors operate within the linear region of input, not in saturation region of input. The system parameters J, D, and k_t in (1) are assumed to be bounded as

$$J\in[J_{\min}\quad J_{\max}]$$
$$D\in[D_{\min}\quad D_{\max}]$$
$$k_t\in[k_{t_{\min}}\quad k_{t_{\max}}] \qquad (2)$$

Let J^0, D^0, and k_t^0 denote the nominal parameter values. There exist unavoidable estimation errors from the real values caused by simplification, linearization, and uncertain terms, etc.

Now define the state vector, $X(t)\in R^2$ in the error coordinate system for the VSS as,

$$X(t)\equiv[e_1(t)\quad e_2(t)] \qquad (3)$$

where $e_1(t)$ and $e_2(t)$ are trajectory error and its derivative, respectively, and are expressed as

$$e_1(t)=\theta_d(t)-\theta(t)$$
$$e_2(t)=\dot{\theta}_d(t)-\dot{\theta}(t) \qquad (4)$$

Then, the error state equation of a BLDD SM is expressed as

$$\dot{X}(t)=\begin{bmatrix}0 & 1\\ 1 & -D/J\end{bmatrix}X(t)+\begin{bmatrix}0\\ 1/J\end{bmatrix}T_{L(t,\theta(t))}+\begin{bmatrix}0\\ 1/J\end{bmatrix}u(t)+\begin{bmatrix}0\\ pk_t/2J\end{bmatrix}\cdot i_{qs}(t) \qquad (5)$$

$$u(t)=\ddot{\theta}_d+D/J\cdot\dot{\theta}(t) \tag{6}$$

A variable structure tracking control for BLDD SMs is considered where the desired trajectory, $\theta_d(t)$ is given as

$$\theta_d(t)=\theta_i+(\theta_f-\theta_i)\cdot t/T \\ -(\theta_f-\theta_i)\cdot\sin(\pi t/T)/\pi \tag{7}$$

where θ_i and θ_f is an arbitrary initial position and final destination position of desired trajectory, respectively. T implies execution time from θ_i to θ_f In the tracking control, an initial position of the desired trajectory may differ from an initial position of motors, i.e., $\theta_i\neq\theta(0)$. Hence, the objective of the controller design for (5) is to derive a BLDD SM to track the predetermined sliding trajectory from $\theta(0)$ to θ_f with a prescribed tracking performance. When the initial position of the desired trajectory is severely different from that of motors, the reaching phase problems may occur in the VSS with the conventional sliding surface. However, the proposed tracking controller is design to handle this as an extended tracking problem without any disadvantages mentioned above.

III. A Continuous Variable Structure Tracking Controller

3.1 Integral-Augmented Sliding Surface and Tracking Error Analysis

To have a desired error dynamics of second order with a zero steady state error for (5)[16] and to predetermine the virtual trajectory without reaching phase, the conventional sliding surface is augmented by an integral state with a special initial condition as follows:

$$s(t)\equiv e_2(t)+C_1\cdot e_1(t)+C_0\cdot e_0 \\ =\sum_{i=0}^{2}C_i\cdot e_i(t),\quad C_2=1 \tag{8}$$

where

$$e_0(t)=\int_0^t e_1(\tau)d\tau+e_0(0), \\ e_0(0)=-\{e_2(0)+C_1e_1(0)/C_0 \tag{9}$$

where C_0 and C_1 are the non zero positive constants as the design parameters which are selected so that (8) becomes the Hurwitz polynomial. This integral sliding surface is basically a linear combination of the three state variables, $e_0(t)$, $e_1(0)$, and $e_2(t)$. If there is no $e_0(0)$ in (8), the reaching phase may occur since $s(t)\neq 0$ at $t=0$ as in the most previous researches on the VSS tracking control. Thus, it is assumed that both of the initial positions are equal. And it is noted that as $t\to\infty$, $e_1(t)\to 0$ with $e_0(t)\to 0$ and $e_2(t)=\dot{e}_1(t)\to 0$. The ideal sliding mode of the integral sliding surface (8) and the virtual ideal sliding trajectory $\theta_s(t)\ \theta_s(t)$ from $\theta(0)$ to θ_f can be described by the following Definition 1.

Definition 1: ***Ideal sliding mode and virtual ideal sliding trajectory***

The ideal sliding mode of (8) with respect to $\theta_d(t)$ *is defined as*

$$\dot{e}_{s2}(t)+C_1\cdot e_{s2}+C_0\cdot e_{s1}(t)=0 \tag{10}$$

which can be driven from $\dot{s}(t)=0$ *and rewritten into a matrix form as*

$$\dot{X}_s(t)=A\cdot X_s(t),\qquad X_s(0) \tag{11}$$

where

$$A=\begin{bmatrix}0 & 1\\ -C_0 & -C_1\end{bmatrix} \tag{12}$$

$$X_s(t)=[\,e_{s1}(t)\ \ e_{s2}(t)\,]^T \\ =[\,\theta_d(t)-\theta_s(t)\ \ \dot{\theta}_d(t)-\dot{\theta}_s(t)\,]^T \\ X_s(0)=[\,\theta_d(0)-\theta_s(0)\qquad \dot{\theta}_d(0)-\dot{\theta}_s(0)\,]^T \\ =[\,\theta_i-\theta(0)\qquad 0-\dot{\theta}_s(0)\,]^T \tag{13}$$

The solutions of (11), $\theta_s(t)$ *and* $\dot{\theta}_s(t)$ *define the virtual ideal sliding trajectory from* $\theta(0)$ *to* θ_f *which can be predetermined by designing the integral sliding surface, (8).*

In Definition 1, the convergence rate of the virtual ideal sliding trajectory depends on the choice of the coefficients C_0 and C_1. These coefficients are chosen such that (10) becomes the Hurwitz polynomial which guarantees the exponential stability of the sliding dynamics. In other words, there exist positive constants K and χ such that

$$\|\exp\{At\}\| \le K \cdot \exp\{-\chi t\} \tag{14}$$

where $\|\exp\{At\}\|$ denotes as the induced Euclidean norm. The minimum value of K/χ is defined as μ.

It is noted that the continuous input under consideration can practically result in a small tracking error to $\theta_s(t)$. The relationship between this maximum error and the bound of the sliding surface will be stated in Theorem 1 to obtain the prescribed tracking performance.

Theorem 1: *For a positive constant* γ *if the sliding surface defined in (8) satisfies* $|s(t)| \le \gamma$ for any $t \ge 0$, and $|\overline{X}| \le \gamma/\chi$ is satisfied at initial time, then

$$|\overline{X}_1| \le \varepsilon_1 \text{ and } |\overline{X}_2| \le \varepsilon_2 \tag{15}$$

is satisfied for all $t \ge 0$, where ε_1 and ε_2 *are the positive constants defined as follows*:

$$\varepsilon_1 = \mu \cdot \gamma, \ \ \varepsilon_2 = \gamma \cdot (1 + \mu \cdot M), \ \ M = \|[C_0 \ \ C_1]\| \tag{16}$$

and $|\overline{X}|$ is the tracking error vector to the virtual ideal sliding trajectory

$$\overline{X}(t) = [\overline{X}_1 \ \ \overline{X}_2]^T = [\theta_s(t) - \theta(t) \ \ \ \dot{\theta}_s(t) - \dot{\theta}(t)]^T$$

Proof: Refer the proof of Theorem 1 in [16] with

$$s(t) = e_2(t) + C_1 \cdot e_1(t) + C_0 \cdot e_0(t) \cdot \\ -\{\dot{e}_{s2}(t) + C_1 \cdot e_{s2}(t) + C_0 \cdot e_{s1}(t)$$

Theorem 1 implies that the tracking error of the real trajectory to $\theta_s(t)$ and its derivative are uniformly bounded, if the sliding surface is bounded by the continuous control input for all uncertainties and load variations.

3.2. Continuous Control Input and Stability Analysis

Assuming an acceleration information is available, a continuous control input for the q-axis current is proposed as follows:

$$i_{qs}(t) = i_{eqm}(t) + i_c(t) + i_s(t) \tag{17}$$

where $i_{eqm}(t)$ is a modified equivalent control which is directly determined according to the choice of the sliding surface (8)

$$i_{eqm}(t) = (J^0 \cdot C_1 - D^0) e_2(t) + J^0 \cdot C_0 e_1(t) + J^0 \cdot u(t) \tag{18}$$

$i_c(t)$ is an effective compensation term based on the disturbance observer[21]

$$i_c(t) = i_{qs}(t-h) - (2/pk_t)(J^0 \cdot \hat{\ddot{\theta}}_e(t) + D^0 \cdot \dot{\theta}(t)) \tag{19}$$

and $i_s(t)$ is a continuous feedback of the integral sliding surface which help the tracking more close to the virtual ideal sliding trajectory

$$i_s(t) = J^0 \cdot (g_1 \cdot s(t) + g_2 \cdot s(t)/(|s(t)| + \delta)) \tag{20}$$

where h is a sufficiently small sampling time, δ is a small positive constant, and $\hat{\ddot{\theta}}_e(t)$ denotes an estimated value of a real acceleration information simply obtained by Euler's method as

$$\hat{\ddot{\theta}}_e(t) = (\dot{\theta}(t) - \dot{\theta}(t-h))/h \tag{21}$$

The control gain g_1 and g_2 as design parameters in (20) should be chosen to force the sliding surface to be bounded by γ in order to validate the assumption in Theorem 1.

By differentiating $s(t)$ with respect to time and substituting into (17)-(20), the real dynamics of the sliding surface in the proposed control finally becomes

$$\dot{s}(t) = n_1(t) - (g_1 \cdot s(t) + g_2 \cdot s(t)/(|s(t)| + \delta) \tag{22}$$

where $n_1(t)$ is a resultant disturbance vector given as

$$n_1(t) = J^0 \cdot \Delta\ddot{\theta} - \Delta i_{qs}(t)$$

and $\Delta\ddot{\theta}$ is the acceleration information error from the real acceleration value and $\Delta i_{qs}(t)$ is the control input delay error resulting from the digital implementation. These two errors are defined as

$$\Delta\dot{\theta}=\dot{\theta}(t)-\dot{\theta}_e(t),\quad \Delta i_{qs}(t)=i_{qs}(t)-i_{qs}(t-h)$$

As shown in (22), the original tracking problem is converted to a first order simple stabilization problem under the resultant disturbance by the proposed sliding mode tracking control algorithm. Due to g_1 and g_2, there are two degrees of freedom to stabilize (22) with γ accuracy.

For the positive constants ε_1 and ε_2 defined in (16), let the constant N be defined as follows:

$$N=\max_t\{n_1(\Delta\dot{\theta}(t),\Delta i_{qs}(t))|;\ \theta(t)\in B(\varepsilon_1,\theta_s(t)) \text{ and } \dot{\theta}(t)\in B(\varepsilon_2,\dot{\theta}_s(t))\} \tag{23}$$

where $B(x,y)$ is defined as the ball with a x radius and a y center. The choice of N is based on the definition of N (23). The stability property of the controlled BLDD SM in (5) with the control laws in (17)-(20) is investigated in the next theorem.

Theorem 2: *Consider a BLDD SM in (8) with the control given by (17)-(20). For some positive* γ $|s(0)|\le\gamma$ *and* $|\overline{X}(0)|\le\gamma/x$ *is assumed to be satisfied at the initial time. If* g_1 *and* g_2 *satidfies*

$$g_2\ge N-g_1\cdot\delta \tag{24}$$

for a given δ *then the closed loop control system is uniformly bounded. In other words, the solution* $\overline{X}(t)$ *is uniformly bounded to the sliding surface for all* $t\ge 0$ *until* $|s(t)|\ge\eta$, *i.e. for all time* t *where* η *is defined as*

$$\eta=\sqrt{\alpha^2+\beta}-\alpha,\quad \alpha=\delta/2+(g_2-N)/2,\quad \beta=(\delta\cdot N)/g_1 \tag{25}$$

Proof: If one takes a Lyapunov candidate as $V(t)=1/2\cdot s^2(t)$ and differentiates it with respect to time, it follows

(26)

By the vector norm inequality and $N\ge|n_1(t)|$ from the definition of N it summarized as

(27)

The right hand side of the last equation of (27) becomes a second function. if the gains g_1 and g_2 satisfy the condition (24), then (27) leads to

$$dV(t)/dt<0,\quad \text{if}\quad |s(t)|>\eta,\quad t\ge 0. \tag{28}$$

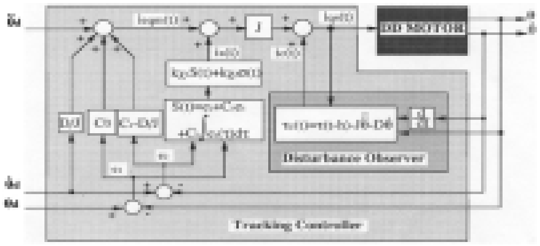

Fig. 1 Block diagram of proposed algorithm
그림 1 제안된 알고리듬의 블록 다이어그램

If one designs the value of η smaller than the value of γ then the sliding surface is bounded by the value of γ which makes the assumption of Theorem 1 valid. Therefore by Theorem 1, the solution $\overline{X_1}$ and $\overline{X_2}$ is uniformly bounded to the sliding trajectory which completes the proof of Theorem 2.

Using the results of Theorems 1 and 2, the prescribed tracking performance is guaranteed by the proposed control algorithm. For the detailed design procedure, one can refer [16]. The schematic block diagram of the proposed algorithm is shown in Fig. 1. The comparative studies for the conventional SMC, previous IVSS[16], and the proposed algorithm are carried out through the computer simulations.

IV. Simulation Studies

The specifications of a BLDDSM used in the simulations are summarized in Table 1.
The planned desired trajectory, $\theta_d(t)$, $\dot{\theta}_d(t)$, and $\ddot{\theta}_d(t)$ of (7) are shown in Fig.2

Table 1. Characteristics of a BLDDSM
표 1 전동기의 규격

Item	value	unit
Rated power	120	[Watt]
Rated torque	11.0	[Nm]
Rated voltage	70.0	[volt]
Rotor inertia	0.00156	[Kgm2]
Viscous friction	1.418	[Nm/s]
Current constant	3.038	[Nm/A]
Number of pole	16	

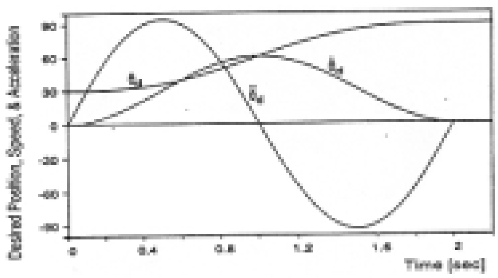

Fig. 2 Desired $\theta_d(t)$, $\dot{\theta}_d(t)$, and $\ddot{\theta}_d(t)$
그림 2 원하는 궤적 $\theta_d(t)$, $\dot{\theta}_d(t)$, and $\ddot{\theta}_d(t)$

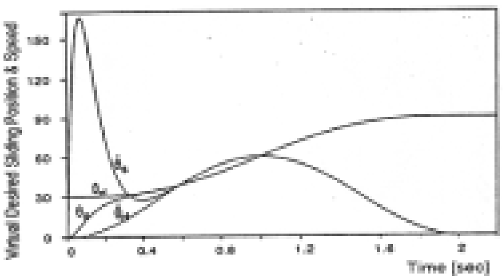

Fig.3 Ideal sliding trajectory($\theta_s(t)$) and speed($\dot{\theta}_s(t)$)
그림 3 이상 슬라이딩 궤적($\theta_s(t)$)과 속도($\dot{\theta}_s(t)$)

starting from an initial position $\theta_i=30^\circ$ to a final position $\theta_f=90^\circ$. The execution time, T is 2 $[sec]$ for this example, and a sampling time is $1\,[msec]$. For the design of the VSS controller, the coefficient of the proposed sliding surface C_0 and C_1 is selected as 225 and 30 so that the matrix Λ has the double poles at -15. The initial
condition of the integral $e_0(0)$ in (9) becomes -0.1333. Fig.3 shows the virtual sliding trajectory $\theta_s(t)$ and $\dot{\theta}_s(t)$ predetermined by the selected integral sliding surface with respect to Fig. 2. The K and χ are also found to be 11.2 and 7.5, respectively. Thus, based on theorem 1, the bounds on the tracking error and its derivative become from (15) as

$$|e_1(t)|<1.492\cdot\gamma=\varepsilon_1 \text{ and } |e_2(t)|<227\cdot\gamma=\varepsilon_2 \tag{29}$$

For a $\varepsilon_1=0.2^\circ$ maximum tracking error, γ is selected as 0.134. Also, N defined in (23) becomes 2. Using the results of Theorem 2, the controller gains, g_1, g_2, and δ are designed as 100, 20, and 0.05, respectively. On the other hand, the coefficients of the sliding surface, C_0 and C_1 for the conventional SMC, are selected as *0* and *990* to have a simple pole. The corresponding control input for the conventional SMC is expressed as follows:

$$i_{qs}(t)=g_1\cdot sign(e_1\cdot s)\cdot e_1+g_2\cdot sign(e_2\cdot s)\cdot e_2 +g_3\cdot sign(s)+u(t) \tag{30}$$

Its gains are selected as $g_1=0.09$, $g_2=0.09$, and $g_3=0.32$. For the algorithm of [16], the design parameters are the same as in this paper. A load disturbance is given as a function of the rotor position and expressed as

$$T_L(t,\theta(t))=1.601\cdot M\cdot L\cdot\sin(\theta(t)) \tag{31}$$

The simulations are carried out under three different conditions of load disturbance, i.e., M=0.0, 0.5, and 1.0 [kg]. The simulation results of the conventional VSS, algorithm of [16], and the proposed SMC are shown in Fig. 4 through Fig. 8. The position responses by the three algorithms are depicted in Fig. 6 for the three load cases. As can be seen, the outputs of Fig. 4(a) are disturbed during the reaching phase, and in Fig. 4(b) the robustness is much improved by means of an integral action while the overshoot problems occur because of the simple integral for an extended tracking problems. However, the output responses in Fig 4(c) exactly follow the predetermined virtual ideal sliding trajectory. Because of this, the output is accurately predictable. No overshoot and no steady state error performance is exhibited. The small box in Fig.4(a), (b), and (c) is the macrograph showing the improvement of robustness by means of the integral. The control inputs for q-axis current commands are depicted in Fig. 5. The varying reaching time can be seen in Fig. 5(a), and are much reduced in Fig.5(b). The continuous components of the proposed control input for the case of M=1.0[Kg] are depicted in Fig 6. In Fig. 7, the sliding surfaces by the suggested algorithm for three cases are within the designed allowable bound $\gamma=0.134$ so that the assumption of Theorem 1 is validated, As a consequence, the $\varepsilon_1=0.2^{\circ}$ prescribed tracking performance is guaranteed by the proposed algorithm. The output responses of the proposed algorithm or other three different sliding surfaces are depicted in Fig. 8.

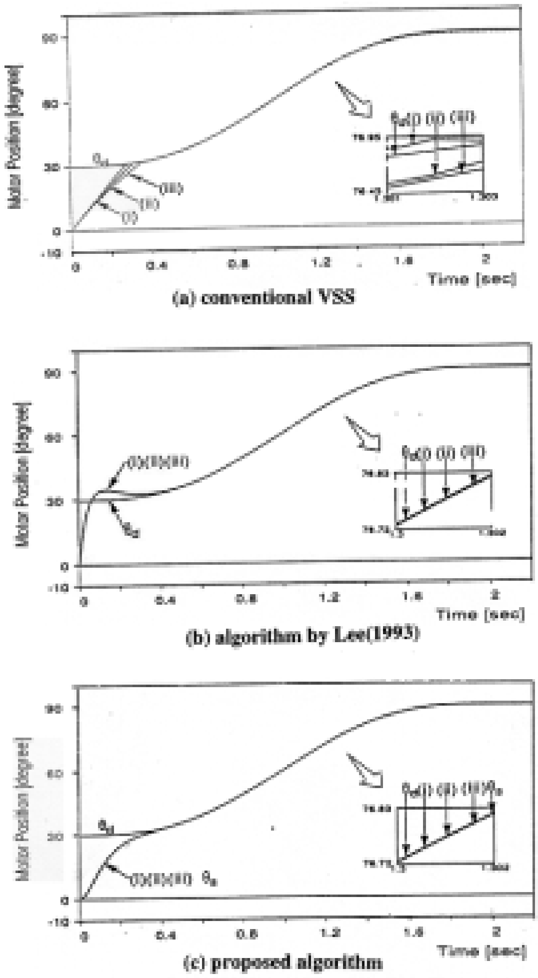

Fig. 4 Position responses for three cases (i) M=0[kg](no load), (ii)M=0.5, and (iii)M=1.0[kg]

그림 4 세가지 경우의 위치 응답

(i) M=0[kg](no load), (ii)M=0.5, and (iii)M=1.0[kg]

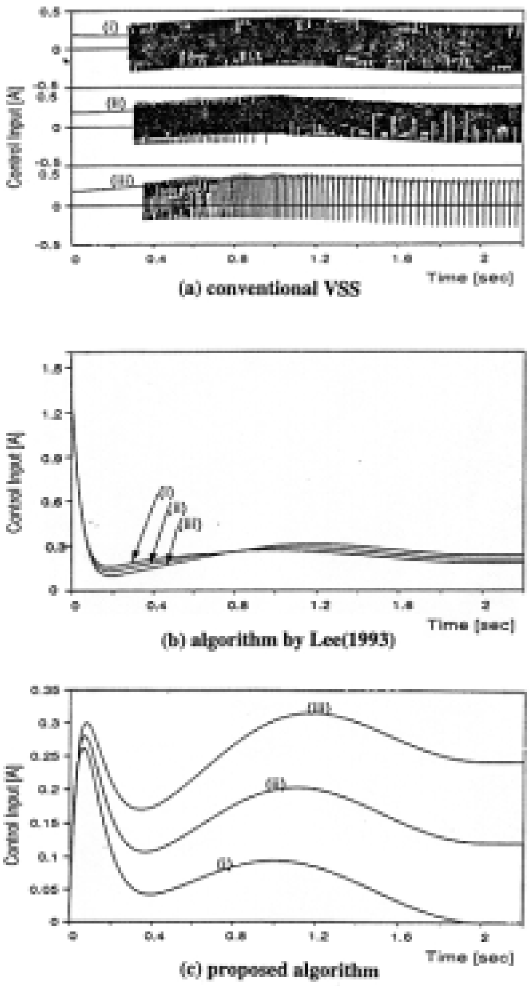

Fig. 5 Control inputs for three cases
(i) M=0[kg](no load), (ii)M=0.5, and (iii)M=1.0[kg]

그림 4 세가지 경우의 제어입력
(i) M=0[kg](no load), (ii)M=0.5, and (iii)M=1.0[kg]

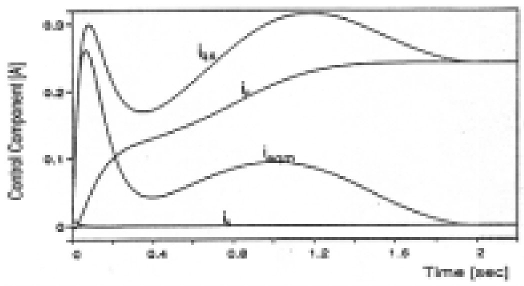

Fig 6 Proposed control input components for case (iii)

그림 6 Case (iii) 경우의 제안된 제어입력 구성요소

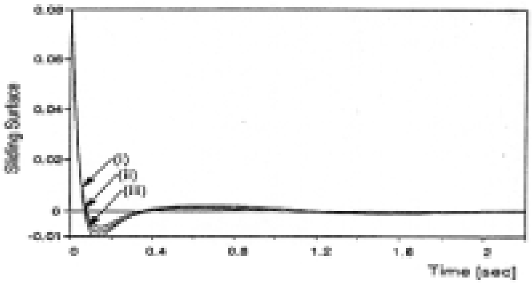

Fig. 7 Sliding surfaces of proposed algorithm for three cases

그림 7 제안된 알고리듬의 세 가지 경우의 슬라이딩 면

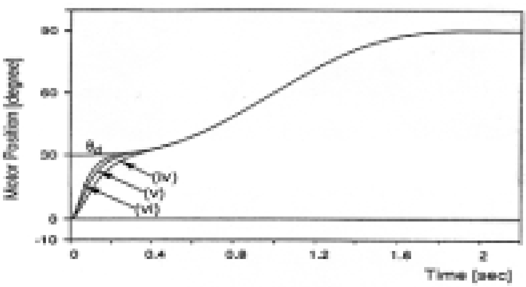

Fig. 8 Outputs of proposed VSS for another 3 different sliding surfaces
((iv) $C_0 = 400$ $C_1 = 40$, (v) $C_0 = 625$ $C_1 = 50$, (vi) $C_0 = 900$ $C_1 = 60$)

그림 8 세가지 다른 슬라이딩 면에 대한 제안된 제어기의 출력

V. Conclusions

In this paper, an improved continuous SMC is proposed for an accurately prescribed tracking control of a BLDDSM under the load variations for the extended tracking problems. With the presented algorithm, the virtual ideal sliding trajectory is predetermined from the initial position of motors to the planned desired trajectory by the modified integral sliding surface for removing the reaching phase as in Definition 1. The maximum tracking error from the virtual prescribed sliding trajectory is derived as a function of the maximum bound of the sliding surface in Theorem 1. The continuous control input based on a compensation technique using the disturbance observer is presented so that the sliding surface remains within a given prescribed bound γ. The stability of the closed loop control systems is analyzed in detail in Theorem 2. Combining the results of Theorem 1 and 2, the ε_1 prescribed tracking performance to the virtual sliding trajectory can be guaranteed under the load variations. The comparative simulation studies are carried out to verify the improved performance of the proposed algorithm. The developed algorithm is widely applicable to the tracking problems not only for BLDD SM but also general motors and dynamic plants. As a further study, the analysis of the effect of current saturation to the suggested algorithm is pointed out.

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