A Comparative Study of a Luenberger Observer and Adaptive Observer-Based Variable Structure Speed Control System Using a Self-Controlled Synchronous Motor

PRADEEP K. NANDAM, AND PARESH C. SEN, FELLOW, IEEE

Abstract—**This paper presents an analysis of the state observer-based robust speed control of a self-controlled synchronous motor (SCSM). A variable structure control (VSC) technique is utilized to achieve robust (parameter-insensitive) characteristics. The speed and acceleration signals required for the implementation of the variable structure speed control (VSSC) are dynamically estimated with state observers. Two kinds of observers—the Luenberger full-order observer and an adaptive observer—are explored in this paper. The results obtained illustrate that Luenberger observers do not estimate the system states accurately when the system parameters vary. This inaccuracy in the state estimation results in a deteriorated performance of the VSSC. Therefore, the possibility of using an adaptive state observer (ASO) is investigated. As expected, the ASO estimates the system parameters and the system states simultaneously, thus making VSSC possible. The design methods and the simulation results presented demonstrate the potential of the proposed scheme.**

I. Introduction

A SYNCHRONOUS motor equipped with an electronic commutator (dc-to-ac inverter) and a rotor position sensor (RPS) is known as a self-controlled synchronous motor (SCSM) [1]. The input supply (voltage or current) frequency to the motor is forced to be always in synchronism with the output speed. This is accomplished by varying the switching frequency of the inverter switches based on the position information obtained by the RPS. This feature of the SCSM makes it possible to have a wide range of speed control, and it also provides stable operation. Moreover, the armature and field mmf's are maintained at 90 electrical degrees (on an average) to provide independent control of torque and flux. Therefore, a SCSM has the useful features of a dc motor with the additional advantage of not having a mechanical commutator. These desirable properties and the precise speed control characteristics of the SCSM make it suitable for high-performance variable-speed drives.

Many industrial applications require robust or parameter-insensitive speed control [2], [3]. Traditional techniques, such as proportional-integral control, phase-locked loop control, etc. are highly sensitive to system parameter variations. Fortunately, a technique known as variable structure control (VSC) possesses parameter-insensitive properties, and it can provide robust operation [4], [5].

Manuscript received August 28, 1988.

The authors are with the Department of Electrical Engineering, Queen's University, Kingston, Ontario, Canada K7L 3N6.

IEEE Log Number 8933868.

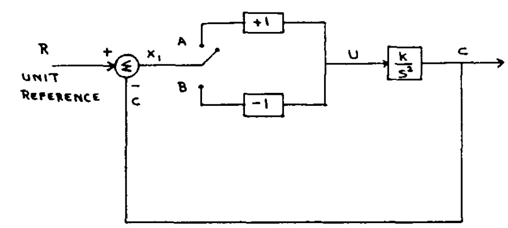

Fig. 1. Variable structure control system.

In a variable structure system (VSS), the controller is switched between two different control structures. A VSS exploits the characteristics of different control structures and achieves a fast, robust, and stable operation. Variable structure position control (VSPC) requires the position and speed signals [6], [8]–[11]. On the other hand, variable structure speed control (VSSC) needs speed and acceleration [7]. However, accurate dynamic measurement of acceleration is a difficult task. Hence, VSSC is more complex than VSPC.

State observers can be employed to estimate acceleration to overcome the above difficulty. Hence, a full-order observer (Luenberger observer) [12]–[14] is designed to estimate the system states. However, because of the sensitivity of the observer to system parameter variations, the state estimation becomes inaccurate under varying parameter conditions. Consequently, the speed control performance deteriorates, and this factor renders ordinary state observers unsuitable for robust control.

Therefore, an adaptive observer [14], which can estimate the system states and parameters simultaneously, is designed. The simulation results show a significant improvement in the robustness of the variable speed drive when the adaptive state observer (ASO) is used.

II. Variable Structure Control

An example of a variable structure controller [5] is briefly discussed in this section. The second-order system shown in Fig. 1 has a switch that can be used to connect the system in

0278-0046/90/0400-0127$01.00

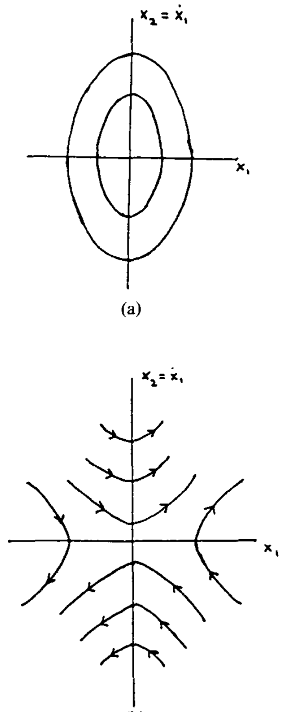

Fig. 2. Phase-plane portraits for the system in Fig. 1: (a) Negative feedback; (b) positive feedback.

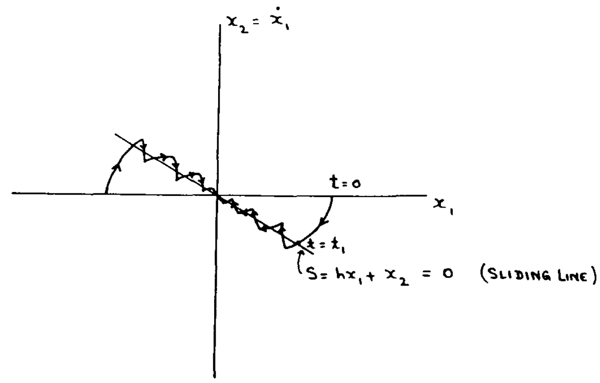

Fig. 3. Sliding-mode control trajectory of the system in Fig. 1.

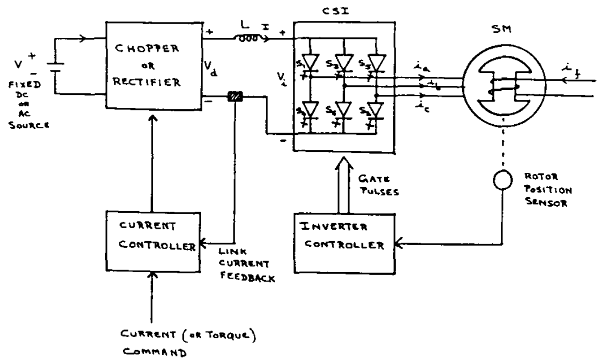

Fig. 4. Schematic block diagram of the CSI-fed SCSM.

the negative-feedback mode or the positive-feedback mode. To configure a negative-feedback structure, the switch is thrown to position A. The system response for this negative-feedback configuration is illustrated in Fig. 2(a) in the form of a phase plane portrait. The figure shows that the aforementioned second-order system is not asymptotically stable in the negative-feedback mode.

On the other hand, when the switch in Fig. 1 is thrown to position B, a positive-feedback system can be obtained. The system response for this configuration is displayed in Fig. 2(b), and it clearly shows that the system is unstable. Moreover, the responses in both Fig. 2(a) and Fig. 2(b) depend on the parameter K of the system.

A remarkable property of VSC is that by switching appropriately between different control structures, a stable and parameter-insensitive system can be synthesized [5]. For example, in the above system, by switching between the negative and positive feedback configurations, a stable and robust response can be obtained, as is displayed in Fig. 3. Because of the sliding motion of the system trajectory, this is generally known as sliding mode control (SLMC). These useful features of VSC make it very attractive for many applications where robust control is imperative.

III. State-Space Model of the Variable-Speed Drive

A schematic block diagram of the current source inverter (CSI)-fed self-controlled synchronous motor (SCSM) is given in Fig. 4. The inverter switching frequency is changed according to the position information obtained from the rotor position sensor. The armature and field are decoupled, and their mmf's are kept orthogonal to one another.

A simplified dynamic model of the overall observer-based drive system is shown in Fig. 5. The integrator is introduced to reduce the steady-state error and the chattering effect of the controller. The machine electrical time constant is small in comparison with the mechanical time constant, and it is therefore neglected to simplify the design.

From the earlier discussion, it is evident that the speed and acceleration signals play an important part in the implementation of VSSC. The observer in Fig. 5 estimates these two signals.

The state-space model of the system in Fig. 5 is given by (1) and (2):

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -a \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -b \end{bmatrix} U \tag{1}$$

$$y = [1 \quad 0] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{2}$$

where

$$x_1 = \omega - \omega^* \text{ (speed error)}$$

$$x_2 = \frac{d\omega}{dt} \text{ (acceleration)}$$

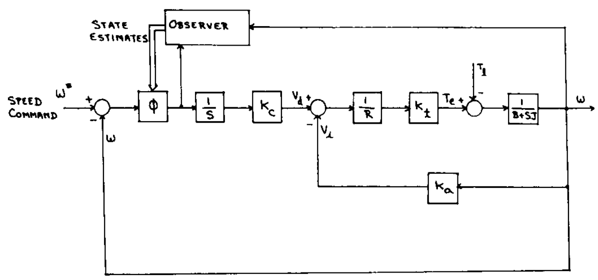

Fig. 5. Block diagram of the dynamic model of the drive system.

$$a = \frac{(RB + K_g^2)}{RJ}$$

$$K_g = K_t = K_a$$

$$b = \frac{K_g K_C}{RJ}$$

$$U = \text{control input.}$$

A VSC law to provide sliding-mode operation is as follows:

$$U = \phi x_1 \tag{3}$$

where

$$\begin{aligned} \phi &= +1; \ \text{if } x_1 S > 0 \\ &= -1; \ \text{if } x_1 S < 0 \end{aligned} \tag{4}$$

where

$$S = hx_1 + x_2 \tag{5}$$

is the switching line about which the sliding-mode action occurs. The value of ϕ is selected such that the existence condition is always satisfied, i.e., $S\dot{S} < 0$ as $S \to 0$. To ensure asymptotic stability of the sliding-mode control, h is always positive ($h > 0$) in (5).

IV. Luenberger Observer Design

In this section, a Luenberger observer is designed for the estimation of system states. State equations (1) and (2) can be written as given below:

$$\dot{X} = AX \text{ and } y = CX \tag{6}$$

where

$$X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad A = \begin{bmatrix} 0 & 1 \\ -b\phi & -a \end{bmatrix} \quad C = [1 \quad 0].$$

To estimate states x_1 and x_2, the observer equation is

$$\dot{\bar{X}} = A\bar{X} + F(y - \bar{y}) \tag{7}$$

where $\bar{X}$ and $\bar{y}$ represent estimates of X and y, respectively, and F is the design matrix. The observer poles can be placed anywhere in the left half plane because the system is observable. The observer poles are generally chosen such that they are faster than the system poles. From (6) and (7)

$$\dot{\tilde{X}} = \dot{X} - \dot{\bar{X}} = A\tilde{X} - FC(X - \bar{X}) \tag{8}$$

i.e.

$$\dot{\tilde{X}} = (A - FC)\tilde{X} \tag{9}$$

where $\tilde{X}$ is the error between the actual and the estimate of the states.

Therefore, if eigenvalues of $(A - FC)$ are stable, as $t \to \infty$ $\tilde{X} \to 0$, i.e., the steady-state error between the states and their estimates is zero.

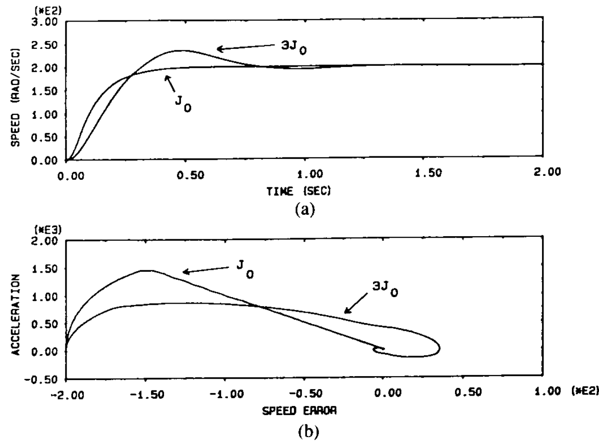

Fig. 6. (a) Speed response of the SCSM with sliding-mode control for J_0 and $3J_0$ using a Luenberger observer; (b) corresponding phase-plane portraits.

V. Sliding-Mode Speed Control with the Luenberger Observer

Sliding-mode speed control of the SCSM is obtained by applying the Luenberger observer design for state estimation. The controller and the observer are designed for the system parameters of which the inertia is equal to J_0. The speed-versus-time plot in Fig. 6(a) shows an excellent response for inertia equal to J_0 when the parameter remains unchanged from its design value. However, Fig. 6(a) also shows that the system experiences an undesirable speed overshoot when the inertia changes to three times J_0. This is because of the sensitivity of the Luenberger observer to changes in parameters. The actual acceleration of the machine with inertia $3J_0$ is computed and is compared with the estimated acceleration, which is shown in Fig. 7. This figure confirms that a Luenberger observer is sensitive to system parameter variations and is unsuitable for applications where the parameters may change, such as the variable inertia in robotics.

VI. Adaptive Observer Design

In this section, an adaptive observer is designed to estimate the system states as well as the system parameters to encounter the inadequacy of a Luenberger observer. The input and output of the system are the only measurable variables available to the ASO. The state-space equations (1) and (2) can be written

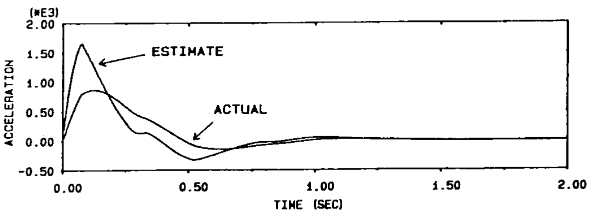

Fig. 7. Comparison of actual acceleration and estimate of acceleration with the Luenberger observer when $J = 3J_0$.

as (10) and (11):

$$\dot{X} = AX + HU \tag{10}$$

$$y = CX. \tag{11}$$

The triple (A, H, C) is controllable and observable.

For the sake of simplicity and brevity, only the essential steps in the adaptive observer design are given here.

Step 1: Perform a similarity transformation on systems (10) and (11) with a transformation matrix T:

$$A_{new} = \begin{bmatrix} -a & 1 \\ 0 & 0 \end{bmatrix} \quad H_{new} = \begin{bmatrix} 0 \\ -b \end{bmatrix} \quad C_{new} = [1 \quad 0]$$

where

$$A_{new} = T^{-1}AT, \quad H_{new} = T^{-1}H, \quad C_{new} = CT$$

$$X_{new} = T^{-1}X, \quad T = \begin{bmatrix} 1 & 0 \\ -a & 1 \end{bmatrix}.$$

Step 2: Let

$$P = \begin{bmatrix} a \\ 0 \end{bmatrix} \text{ and } M = \begin{bmatrix} 0 \\ -b \end{bmatrix}.$$

The unknown parameter vectors are P and M. Both a and b involve the system inertia (1) and are unknown. Therefore, the ASO will have to estimate or identify vectors P and M along with the states.

Step 3: The adaptive observer equation is given below:

$$\dot{Z} = KZ + [G - \bar{P}(t)]x_1 + \bar{M}(t)U + W + R \tag{12}$$

where Z is the estimate of the transformed state vector X_{new}, and $\bar{P}(t)$ and $\bar{M}(t)$ are system parameter vectors whose elements are adjusted adaptively. These are the estimates of P and M. $K = \begin{bmatrix} & 1 \\ -G & \\ & 0 \end{bmatrix}$ is a stable matrix, and $G = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix}$ is a design vector that adjusts the observer poles. W and R are feedback signals, which are needed to stabilize the adaptive observer. As the error between the actual output and the output from the estimated states tends to zero, W and R also tend to zero.

Step 4: The main objective of the ASO is to achieve

$$\lim_{t \to \infty} \bar{P}(t) = \begin{bmatrix} a \\ 0 \end{bmatrix} \qquad \lim_{t \to \infty} \bar{M}(t) = \begin{bmatrix} 0 \\ -b \end{bmatrix}$$

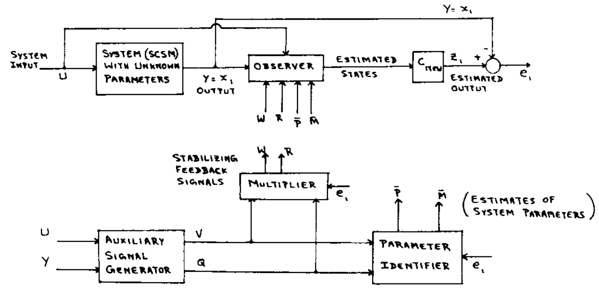

Fig. 8. Schematic of the adaptive observer-based system.

$$\lim_{t \to \infty} [Z(t) - X_{new}(t)] \to 0.$$

Fig. 8 shows an overall schematic diagram of the system with the adaptive observer.

Step 5: One important point in the adaptive procedure is the generation of two auxiliary signal vectors V and Q from the known input and output of the system. These signals obtain the adaptive signals to dynamically adjust the observer parameters and obtain the feedback signals W and R to make the observer stable [14].

Step 6: The set of conditions for the conditions for the various signals is given below.

Auxiliary Signals

$$\dot{V}_2 = x_1 - d_2V_2 = V_1; \qquad \dot{Q}_2 = U - d_2Q_2 = Q_1$$

$d = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$ is chosen such that $[K, d]$ is controllable and $C_{new}(sI - K)^{-1}d$ is positive real.

Stabilizing Feedback Signals

$$W = -e_1 \begin{bmatrix} 0 \\ V^T F_1 F_3 V \end{bmatrix} \quad R = -e_1 \begin{bmatrix} 0 \\ Q^T F_2 F_3 Q \end{bmatrix}$$

where V^T and Q^T are transposes of vectors V and Q. F_1 and F_2 are diagonal positive definite matrices. $F_3 = \begin{bmatrix} 0 & -d_2 \\ 0 & 1 \end{bmatrix}$ and $e_1 = z_1 - x_1$.

Adaptive Laws

$$\dot{\bar{P}}(t) = \begin{bmatrix} \dot{\bar{P}}_1(t) \\ \dot{\bar{P}}_2(t) \end{bmatrix} = F_1 e_1 V, \quad \dot{\bar{M}}(t) = \begin{bmatrix} \dot{\bar{M}}_1(t) \\ \dot{\bar{M}}_2(t) \end{bmatrix} = -F_2 e_1 Q.$$

The observer poles (eigenvalues of K) should be made quite fast so that both the estimation of parameters and states is quick enough. The diagonal matrices F_1, F_2 and the vector $G = \begin{bmatrix} g_1 \\ g_2 \end{bmatrix}$ and $d = \begin{bmatrix} 1 \\ d_2 \end{bmatrix}$ are the design variables available to the designer. The auxiliary signal generator poles should also be made fast so that parameter estimation converges quickly. This is done by adjusting d_2.

VII. Sliding-Mode Speed Control with the Adaptive Observer

The adaptive observer estimates the system parameters a and b as illustrated in Fig. 9(a) and (b). This estimation goes

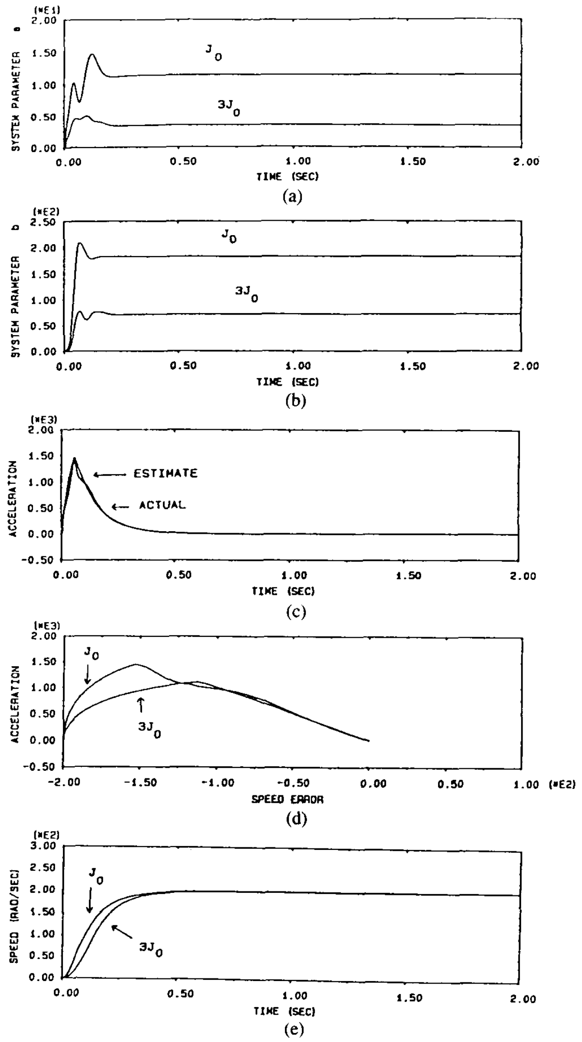

Fig. 9. (a) Parameter a estimation; (b) parameter b estimation; (c) comparison of actual acceleration and estimate of acceleration at $J = 3J_0$; (d) corresponding phase-plane portraits; (e) speed response with the ASQ-based sliding-mode control.

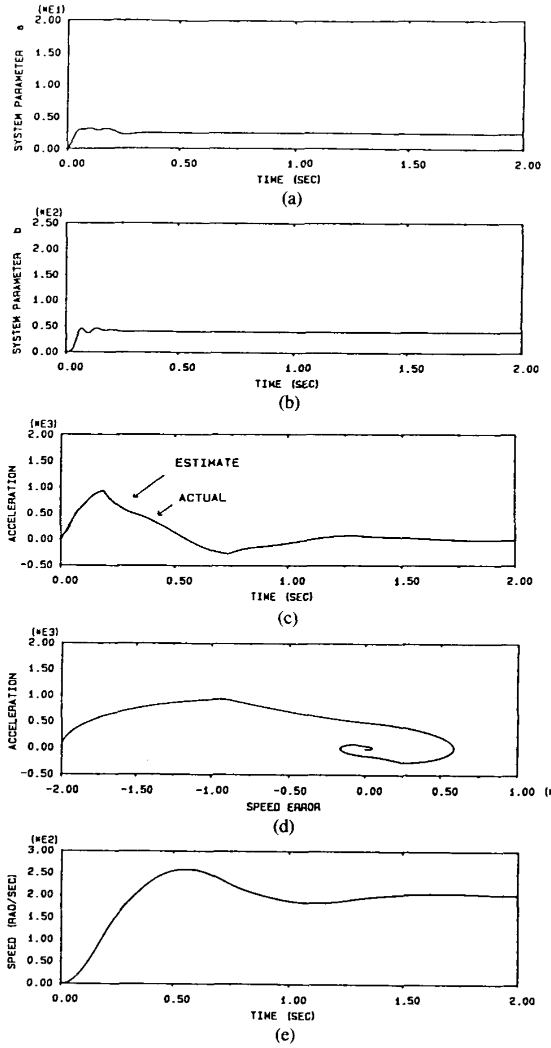

Fig. 10. (a) Parameter a estimation; (b) parameter b estimation; (c) comparison of actual acceleration and estimate of acceleration at $J = 5J_0$; (d) corresponding phase-plane portraits; (e) speed response with the ASO-based sliding-mode control.

through a transient period before converging on the corresponding system parameters, both when inertia is equal to J_0 and $3J_0$. The oscillations in the transient region of the parameter estimation are more pronounced for the lower inertia (J_0) as seen in Fig. 9(a) and (b). This is expected because at a lower inertia, the machine accelerates rapidly, and it is more difficult for the ASO to estimate the parameters.

The accuracy of the estimation of acceleration is shown in Fig. 9(c). The actual acceleration of the system when inertia is $3J_0$ is computed and is compared with the acceleration estimated by the adaptive observer (Fig. 9(c)). It is obvious from this figure that the state estimation is quite accurate when the ASO is used, even when the inertia changed from J_0 to $3J_0$. In contrast, the Luenberger observer is highly sensitive to system parameter variations, as is shown in Fig. 7, where the actual and estimated accelerations were compared when system inertia changed to $3J_0$.

However, when inertia is increased to $3J_0$, the system needs more time to reach the sliding line, as is seen in Fig. 9(d). Before the system trajectory hits the sliding line, the response is sensitive to parameter variations. The speed response of the VSC when used in conjunction with the ASO is shown in Fig. 9(e). It is observed that the response is almost parameter insensitive. The small difference in the speed response for J_0 and $3J_0$ is because of the transient error in parameter estimation by the ASO and the fact that the system spends more time in reaching the sliding line when inertia is $3J_0$.

Nonetheless, the overall improvement in performance of VSC with the ASO is clear when speed responses in Fig. 9(e) are compared with those in Fig. 6(a). The effects of further increases in J_0 are also studied. Fig. 10 shows the results for inertia $5J_0$. The system trajectory takes more time to hit the sliding line (Fig. 10(d)). As a result, the speed response shows a high speed overshoot (Fig. 10(e)).

The study shows that when the ASO is used, the estimation of states is accurate, and sliding-mode speed control can provide a nearly parameter-insensitive performance within a certain range of parameter variation. On the other hand, a Luenberger observer can only perform well when system parameters remain constant. However, its design is relatively simple, and it can be used in applications where a system is parameter invariant. An adaptive observer is useful for VSSC if system parameter variation is within a certain range.

VIII. Conclusions

This paper discusses the state observer-based, robust, parameter-insensitive, speed control of a self-controlled synchronous motor. The parameter-insensitive characteristics are obtained by employing a variable structure speed control (VSSC) method known as sliding-mode control (SLMC). The state observers are introduced into the overall system to estimate the acceleration of the drive. The speed and acceleration signals are needed for the implementation of VSSC.

Two kinds of state observers—the Luenberger observer and an adaptive state observer (ASO)—have been used to achieve the objective of robust control with VSSC. The Luenberger observer is simple to design. It estimates the acceleration accurately as long as the system parameters remain constant. Consequently, Luenberger observers can be used only for parameter-invariant systems. However, variable structure speed control is primarily meant for applications where the parameters vary, such as in robotics, paper mills, etc. Therefore, Luenberger observers are unsuitable for all such applications.

In striking contrast, an ASO estimates the states (acceleration, in this case) accurately in spite of parameter variations. An ASO estimates the system parameters and the system states simultaneously. Therefore, an ASO is ideally suited for VSSC to provide robust speed control in high-performance drives.

Because of its potential advantages, investigations are warranted to resolve some persisting problems in adaptive observer-based variable structure speed control. The parameter estimation has to be made as fast as possible by optimizing the convergence time of the adaptive observer. One other significant problem is that despite accurate estimation by the ASO, the VSSC fails to provide a robust performance when the parameter variation is too large. This difficulty can be solved by minimizing the time taken by the state trajectory in hitting the sliding line. By doing this, the system can be made highly robust, and the full potential of the ASO can be exploited.

Further studies are being conducted to resolve the aforementioned problems and to synthesize a high-performance, robust variable-speed drive system.

References

[1] T. Kataoka and S. Nishikata, "Transient performance of SCSMs," in *IEEE-IAS Conf. Rec.*, 1980, pp. 626-633.

[2] M. F. Brosnan, "New trends in servo control systems," in *Proc. First Euro. Conf. Power Electron. App.* (EPE) (Brussels), 1985, vol. 2, pp. 5.1-5.6.

[3] C. Namuduri and P. C. Sen, "Variable structure control of a SCSM drive," in *IEEE-IAS Conf. Rec.*, 1985, pp. 503-509.

[4] B. Drazenovic, "The invariance conditions in VSS," *Automatica*, vol. 5, no. 3, pp. 287-295, 1969.

[5] V. I. Utkin, "Variable structure control systems with sliding modes," *IEEE Trans. Automat. Contr.*, vol. AC-22, no. 2, pp. 210-222, 1977.

[6] M. O. Kaynak *et al.*, "Microprocessor controlled position servo system with a sliding mode," in *Proc. ETG Conf. Microelectron. Power Electron. Electrical Drives*, 1982, pp. 273-279.

[7] Y. Dote *et al.*, "Variable structure control with sliding mode for DC drive speed regulation," in *IEEE PESC*, 1982, pp. 123-127.

[8] A. Sabonovic *et al.*, "Sliding modes in controlled motor drives," in *Proc. IFAC Contr. Power Electron. Electrical Drives* (Lausanne, Switzerland), 1983, pp. 133-138.

[9] F. Harashima *et al.*, "MOSFET converter-fed position servo system with sliding mode control," *IEEE Trans. Ind. Electron.*, vol. IE-32, no. 3, pp. 238-244, Aug. 1985.

[10] B. K. Bose, "Sliding mode control of induction motor," in *IEEE-IAS Conf. Rec.*, 1985, pp. 479-486.

[11] C. Namuduri and P. C. Sen, "A servo-control system using a SCSM with sliding mode controller," in *IEEE-IAC Conf. Rec.*, 1986, pp. 56-65.

[12] D. G. Luenberger, "An introduction to observers," *IEEE Trans. Automat. Contr.*, vol. AC-16, no. 6, pp. 596-602, Dec. 1971.

[13] T. Kailath, *Linear Systems*. Englewood Cliffs, NJ: Prentice-Hall, 1980.

[14] J. O'Reilly, Observers for Linear Systems. London: Academic, 1983.