Speed Nonlinear Control of DC Motor Drive With Field Weakening

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***Abstract*—In this paper, we show that it is feasible to apply nonlinear multiple-input multiple-output feedback linearization technique to a separately excited dc motor system that is operated in the high-speed field-weakening regime. Load-adaptive and sensorless control techniques to improve dynamic speed performance are proposed and compared. Also, application results are presented to verify theoretical ones.**

***Index Terms*—DC motor drive, field weakening, nonlinear control.**

I. Introduction

TOGETHER with the invention of low-cost and reliable induction motors and their power semiconductor converter-based power supplies equipped with field-oriented types of controllers, it was believed that dc motors would become obsolete in industry applications. However, contrary to popular belief, dc motor drives are still widely used in many industries such as rolling mills, paper machines, and unwinding and rewinding machines [1]–[5]. In a separately excited dc motor (SEDCM) drive system, linear control techniques are easily applied to the system represented by linear equations in the armature control region. However, system nonlinearities begin to appear once the motor is operated in the field-weakening region due to the electromagnetic torque being a product of field flux and armature current, the back electromotive force (EMF) being a product of field flux and speed, and magnetic saturation. The traditional way of circumventing such nonlinearities is by linearizing the system equations around an operating point and designing linear controllers based on the linearized system equations. Recent advances in nonlinear control systems, however, resulted in the development of more sophisticated controllers based on the feedback linearization techniques [6]–[10]. Regardless of being computing intensive in real-time control, the applicability of these techniques has been justified particularly in motion control. This factor explains the surge of research interest in nonlinear control applicable to motion control, especially where a high dynamic performance is required in the closed-loop control design of motor drives. This paper contributes to carrying out nonlinear speed control design of an SEDCM drive in the field-weakening mode.

It is shown that the single-input single-output (SISO) feedback linearization for the motor system taking the field voltage as the control input has one stable equilibrium point [11]. Unfortunately, the armature current drawn at this point has been found to be much larger than the nominal armature current, thus, this method has not been considered as a feasible controller candidate.

In this paper, several nonlinear field weakening control techniques for speed tracking of an SEDCM system are investigated. We first show it is feasible to apply nonlinear multiple-input multiple-output (MIMO) feedback linearization technique to such a system that is operated in high-speed field-weakening regimes. To improve speed performance in the presence of load torque disturbance, a load-adaptive control design is then proposed, which can be implemented at any desired field weakening point of operation. The control scheme with speed and load torque observer is, further, in particular, presented for speed-sensorless operation. Finally, application examples are shown to verify theoretical ones.

II. Dynamical System Modeling

An SEDCM system is characterized by the three interconnected differential equations as follows [1]:

$$\begin{aligned} \frac{di_r}{dt} &= \frac{1}{L_r}\left(u_r - R_r i_r - E\right) \\ \frac{di_s}{dt} &= \frac{1}{L_s}\left(u_s - R_s i_s\right) \\ \frac{d\omega}{dt} &= \frac{1}{J}\left(T_e - T_L - B\omega\right) \end{aligned} \tag{1}$$

where $T_e = K i_s i_r$ is the developed torque and $E = K i_s \omega$ the back EMF. u_r and u_s are armature and field voltages, and i_r and i_s armature and field currents, respectively. R_r and R_s denote armature and field resistances, L_r and L_s armature and field inductances, and K, B, and J back-EMF constant (or torque constant), viscous damping coefficient, and inertia, respectively.

To facilitate the controller design, model (1) is rewritten in the compact state-space form as follows:

$$\dot{x} = f(x) + u_r g_r + u_s g_s + dm \tag{2}$$

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where $x = [i_r \ \ i_s \ \ \omega]^T$ is the state vector. $f(x)$ is the function of i_r, i_s, and ω,

$$f(x) = \begin{bmatrix} \frac{1}{L_r}(-R_r i_r - K i_s \omega) \\ -\frac{R_s}{L_s} i_f \\ \frac{1}{J}(K i_s i_r - B\omega - T_{LN}) \end{bmatrix}$$

$g_r = [1/L_r \ \ 0 \ \ 0]^T$, $g_s = [0 \ \ 1/L_s \ \ 0]^T$, and $m = [0 \ \ 0 \ \ 1/J]^T$ are coefficient vectors, T_{LN} is the normal load torque, and $d = T_L - T_{LN}$ the load torque disturbance.

This model, which is nonlinear because it involves the product of two variables, will be applied to speed tracking design in the field-weakening region. Generally speaking, all of the parameters change to some extent with the motor operating conditions. However, we assume here that the variations of these parameters are negligible for the controller design except when dealing with unknown load torque disturbance.

III. Input–Output Linearization

The objective here is to develop a field-weakening controller, which can effectively stabilize and track the desired speed reference ω_{ref} over the range $\omega \geq \omega_n$, and reject load torque disturbance. To do so, the control outputs are selected to be $h_1(x) = E$ and $h_2(x) = \omega$, and we define

$$\begin{aligned} e_E &= E - E_{\text{ref}} \\ e_\omega &= \omega - \omega_{\text{ref}} \end{aligned} \tag{3}$$

where E_{ref} represents the set point of field weakening, which is chosen to be between 0.85–0.95 of the rated armature voltage [1], and the reference speed ω_{ref} is required to be twice differential.

By means of Lie derivative, we introduce the following change of coordinates:

$$\begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{bmatrix} = \begin{bmatrix} h_1(x) \\ h_2(x) \\ L_f h_2(x) \end{bmatrix} = \begin{bmatrix} E \\ \omega \\ \frac{1}{J}\left(T_e - B\omega - T_{LN}\right) \end{bmatrix} \tag{4}$$

which is one to one in $s = \{x \in R^3 : l_s \neq 0 \text{ and } \omega \neq 0\}$, and its inverse transformation is

$$\begin{bmatrix} i_r \\ i_s \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{\eta_2}{\eta_1}\left(J\eta_3 + B\eta_2 + T_L\right) \\ \frac{\eta_1}{K\eta_2} \\ \eta_2 \end{bmatrix}. \tag{5}$$

In the new coordinates, the motor dynamics with normal load torque ($d = 0$) can be rewritten as

$$\begin{bmatrix} \dot{\eta}_1 \\ \ddot{\eta}_2 \end{bmatrix} = \begin{bmatrix} L_f h_1(x) \\ L_f^2 h_2(x) \end{bmatrix} + D(x) \begin{bmatrix} u_r \\ u_s \end{bmatrix} \tag{6}$$

where $D(x)$, the decoupling matrix, is

$$D(x) = \begin{bmatrix} L_{g_r} h_1(x) & L_{g_s} h_1(x) \\ L_{g_r} L_f h_2(x) & L_{g_s} L_f h_2(x) \end{bmatrix}$$

and the Lie derivatives are expressed as

$$\begin{aligned} L_f h_1 &= -\frac{R_s}{L_s} E + \frac{K}{J} i_s \left(T_e - B\omega - T_L\right) \\ L_f h_2 &= \frac{1}{J}\left(T_e - B\omega - T_L\right) \\ L_f^2 h_2 &= \frac{K}{JL_r} i_s \left(-R_r i_r - E\right) - \frac{R_s}{JL_s} T_e \\ &\quad - \frac{B}{J^2}\left(T_e - B\omega - T_{LN}\right) \\ L_{g_r} h_1 &= 0 \\ L_{g_s} h_1 &= \frac{K}{L_s}\omega \\ L_{g_r} L_f h_2 &= \frac{K}{JL_r} i_s \\ L_{g_s} L_f h_2 &= \frac{K}{JL_s} i_r. \end{aligned}$$

Note that $D(x)$ is nonsingular in field-weakening regimes since det $D(x) = -K i_s \omega / L_r L_s \neq 0$ holds. Letting

$$\begin{bmatrix} u_r \\ u_s \end{bmatrix} = D^{-1}(x) \begin{bmatrix} -L_f h_1(x) + v_a \\ -L_f^2 h_2(x) + v_f \end{bmatrix} \tag{7}$$

and inserting it into (6) results in

$$\begin{aligned} \dot{\eta}_1 &= v_a \\ \dot{\eta}_2 &= \eta_3 \\ \dot{\eta}_3 &= v_f \end{aligned} \tag{8}$$

where $v = [v_a \ \ v_f]^T$ is the input vector of the linearized system of the well-known Brunovski canonical form (8). The relative degree of the system ($1 + 2 = 3$) is equal to the original (no zero dynamics).

To ensure desirable tracking of the reference speed ω_{ref} and back EMF E_{ref}, v_a and v_f are designed as follows:

$$\begin{aligned} v_a &= \dot{E}_{\text{ref}} - k_a\left(E - E_{\text{ref}}\right) \\ v_f &= \ddot{\omega}_{\text{ref}} - k_{f1}\left(\dot{\omega} - \dot{\omega}_{\text{ref}}\right) - k_{f0}\left(\omega - \omega_{\text{ref}}\right) \end{aligned} \tag{9}$$

where the parameters k_a, k_{f1}, and k_{f2} can be suitably chosen to make the linear systems

$$\begin{aligned} \dot{e}_E + k_a e_E &= 0 \\ \ddot{e}_\omega + k_{f1}\dot{e}_\omega + k_{f0} e_\omega &= 0 \end{aligned} \tag{10}$$

asymptotically stable. The selection of these parameters is also limited by the motor operation conditions and the feasible realization using power electronics.

To enable the rejection of load torque disturbance d, an integrator is inserted into the linear control law as

$$\begin{aligned} v_a &= \dot{E}_{\text{ref}} - k_a\left(E - E_{\text{ref}}\right) - k_{a1}\int \left(E - E_{\text{ref}}\right) dt \\ v_f &= \ddot{\omega}_{\text{ref}} - k_{f1}\left(\dot{\omega} - \dot{\omega}_{\text{ref}}\right) - k_{f0}\left(\omega - \omega_{\text{ref}}\right) \\ &\quad - k_{f2}\int \left(\omega - \omega_{\text{ref}}\right) dt. \end{aligned} \tag{11}$$

IV. Load-Adaptive Control Design

The motor system with load torque disturbance T_L is written as

$$\begin{aligned}\dot{\eta}_1 &= L_f h_1 + dL_m h_1 + L_{g_r} h_1 u_r + L_{g_s} h_1 u_s\\ \dot{\eta}_2 &= \eta_3 + dL_m h_2\\ \dot{\eta}_3 &= L_f^2 h_2 + dL_m L_f h_2 + L_{g_r} L_f h_2 u_r + L_{g_s} L_f h_2 u_s. \end{aligned} \quad (12)$$

It is clear that the complete feedback linearization design of the model (2) cannot be achieved due to the presence of load torque disturbance. Inserting an integrator in the control law shown in (11) to enable the rejection of constant unmeasured disturbance will result in degraded output response, which is not acceptable. To overcome these problems, this paper will apply a load-adaptive control design to estimation of the unknown disturbance torque [12].

Defining a time-varying change of coordinates with the estimate of load torque disturbance $\hat{d}$

$$\begin{aligned} z_1 &= \eta_1 = E\\ z_2 &= \eta_2 = \omega\\ z_3 &= \eta_3 + \hat{d} L_m h_2 \end{aligned} \quad (13)$$

we then have

$$\begin{aligned} \dot{z}_1 &= L_f h_1 + dL_m h_1 + u_r L_{g_r} h_1 + u_s L_{g_s} h_1\\ \dot{z}_2 &= z_3 + \Delta d L_m h_2\\ \dot{z}_3 &= L_f^2 h_2 + dL_m L_f h_2 + \hat{d} L_m h_2 + u_r L_{g_r} L_f h_2\\ &\quad + u_s L_{g_s} L_f h_2 \end{aligned} \quad (14)$$

where $\Delta d = d - \hat{d}$.

To linearize (14), let the control voltage inputs be as follows:

$$\begin{bmatrix} u_r \\ u_s \end{bmatrix} = D^{-1}(x) \begin{bmatrix} L_f h_1 - \hat{d} L_m h_1 + v_r \\ -L_f^2 h_2 - \hat{d} L_m L_f h_2 - \hat{d} L_m h_2 + v_s \end{bmatrix} \quad (15)$$

where

$$\begin{aligned} v_r &= -\alpha_a z_1 + v_{\mathrm{aref}}\\ v_s &= -\alpha_{f0} z_2 - \alpha_{f1} z_3 + v_{\mathrm{fref}} \end{aligned}$$

and

$$\begin{aligned} v_{\mathrm{aref}} &= \dot{E}_{\mathrm{ref}} + \alpha_a E_{\mathrm{ref}}\\ v_{\mathrm{fref}} &= \ddot{\omega}_{\mathrm{ref}} + \alpha_{f1}\dot{\omega}_{\mathrm{ref}} + \alpha_{f0}\omega_{\mathrm{ref}}. \end{aligned}$$

The Lie derivatives related to load torque disturbance are

$$\begin{aligned} L_m h_1 &= -\frac{K}{J} i_s\\ L_m h_2 &= -\frac{1}{J}\\ L_m L_f h_2 &= \frac{B}{J^2} \end{aligned}$$

where α_a, α_{f0}, and α_{f1} are constant gain parameters to be designed.

Using (14) and (15) results in

$$\begin{aligned} \dot{z}_1 &= \Delta d L_m h_1 - \alpha_a z_1 = v_{\mathrm{aref}}\\ \dot{z}_2 &= z_3 + \Delta d L_m h_2\\ \dot{z}_3 &= \Delta d L_m L_f h_2 - \alpha_{f0} z_2 - \alpha_{f1} z_3 + v_{\mathrm{fref}}. \end{aligned} \quad (16)$$

The unknown load torque disturbance d will be estimated by using model reference adaptive technique. The reference model is then selected as follows:

$$\dot{z}_m = A_m z_m + u \quad (17)$$

where

$$\begin{aligned} z_m &= [\, z_{1m} \quad z_{2m} \quad z_{3m} \,]^2\\ u &= [\, v_{ares} \quad 0 \quad v_{fres} \,]^T \end{aligned}$$

and

$$A_m = \begin{bmatrix} -\alpha_a & 0 & 0 \\ 0 & 0 & 1 \\ 0 & \alpha_{f0} & \alpha_{f1} \end{bmatrix}.$$

By subtracting (17) from (16), the model reference tracking error dynamics are obtained

$$\dot{e} = A_m e + w(x)\Delta d \quad (18)$$

where

$$e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} z_1 - z_{1m} \\ z_2 - z_{2m} \\ z_3 - z_{3m} \end{bmatrix}$$

$$w(x) = \begin{bmatrix} L_m h_1 \\ L_m h_2 \\ L_m L_f h_2 \end{bmatrix}.$$

Let V be the Lyapunov function given as

$$V = e^T P e + \lambda \Delta d^2 \quad (19)$$

where λ is a positive number, P is a positive-definite symmetric matrix, and the solution of the following Lyapunov equation:

$$A_m^T P + P A_m = -\mathcal{Q} \quad (20)$$

with Q a positive-definite symmetric matrix. By making the time derivative of V, we have

$$\dot{V} = -e^T \mathcal{Q} e + 2\Delta d (w^T P e + \lambda \Delta \dot{d}). \quad (21)$$

To make

$$\dot{V} = -e^T \mathcal{Q} e \quad (22)$$

we choose

$$w^T P e + \lambda \Delta \dot{d} = 0. \quad (23)$$

The following adaptation law, which describes the estimate dynamics of the unknown constant load torque disturbance $\hat{d}$ is then derived:

$$\dot{\hat{d}} = \frac{1}{\lambda} W^T P e. \quad (24)$$

A Lyapunov function (19) satisfying $\dot{V}(t) \leq 0$ has been found which guarantees that tracking error e and load torque estimation error Δd are bounded. Application of Barbalat's lemma allows the further conclusion that $e \rightarrow 0$ as $t \rightarrow \infty$, i.e., that the tracking error converges to zero asymptotically.

The obtained field-weakening controller for the speed control, which is based on nonlinear load-adaptive MIMO lineariza-

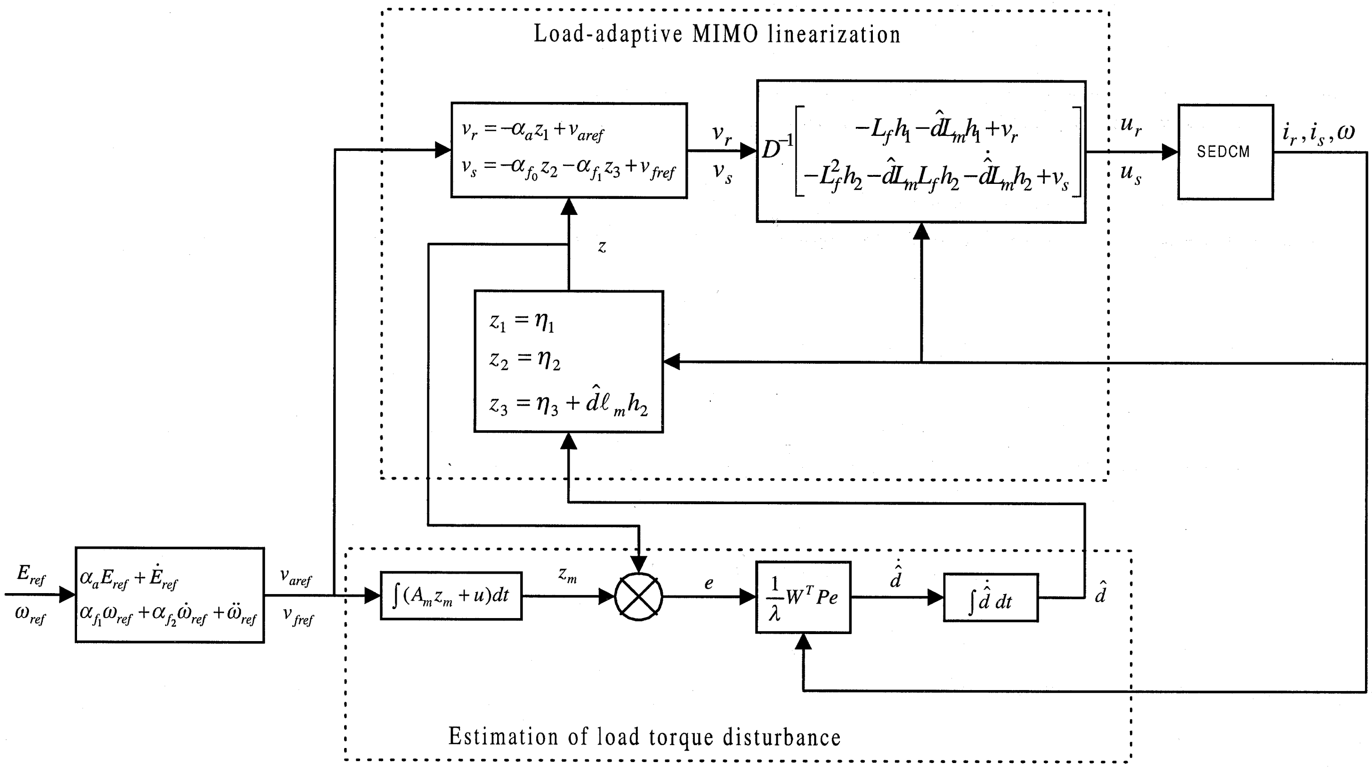

Fig. 1. Load-adaptive nonlinear MIMO speed-tracking controller.

tion design, is shown in Fig. 1. In this scheme, full state, i.e. i_r, i_s, and ω, measurements are required.

V. Speed-Sensorless Control

Measuring speed usually needs a mechanical speed sensor, which adds to the cost and the number of electrical connections to the motor drive system. Therefore, it would be desirable to eliminate the need for such a sensor. The nonlinear speed and load torque observer with linear error dynamics is then proposed.

To design such an observer via model (2), the key approximation made is that $L_r i_r$ is very small compared to $L_s i_s$. Based on this approximation, an accurate observer can still be obtained because the ratio L_r/L_s can be 10^{-4} [2].

Modeling the effect of the constant load torque T_L as the additional state variable results in

$$\begin{aligned}\frac{di_s}{dt} &= \frac{1}{L_s}\left(-R_r i_r - R_s i_s - K i_s \omega + u_r + u_s\right)\\ \frac{d\omega}{dt} &= \frac{1}{J}\left(K i_r i_s - B\omega - T_L\right)\\ \frac{dT_L}{dt} &= 0.\end{aligned} \tag{25}$$

Note that (25) is not linear in the measured state variables due to the term $K i_s \omega$ in the first equation as ω is not available. Based on the idea described in [7], we can find a coordinate transformation $\zeta = T(x)$, which will transform (25) into a system which is linear in the unmeasured state variables.

TABLE I
Parameters of the SEDCM

Rated power	3.7kW	Rated voltage	240V
Rated speed	1750rpm	Rated torque	18Nm
Field voltage	240V	Armature inductance	0.01H
Armature resistance	1.2 Ω	Field inductance	60H
Field resistance	60Ω	Motor constant	$0.3 Nm/A^2$
Inertia	0.208kgm2	Damping coefficient	$0.011 kgm^2 s^{-1}$

For $i_s > 0$, consider the change of coordinates

$$\begin{aligned}\zeta_1 &= \ln i_s\\ \zeta_2 &= \omega\\ \zeta_3 &= T_L.\end{aligned} \tag{26}$$

Using this change of coordinates, the system (25) becomes

$$\begin{aligned}\zeta_1 &= \frac{R_r i_r}{L_s i_s} - \frac{R_s}{L_s} - \frac{K}{L_s} z_2 + \frac{u_r + u_s}{L_s i_s}\\ \zeta_2 &= -\frac{B}{J} z_2 - z_3 + \frac{K i_r i_s}{J}\\ \zeta_3 &= 0\end{aligned} \tag{27}$$

which is now linear in the unmeasured state variable $\zeta_2 = \omega$.

Such an observer is then designed as

$$\begin{aligned}\dot{\hat{\zeta}}_1 &= -\frac{K}{L_s}\hat{\zeta}_2 + \frac{u_r + u_s}{L_s i_s} - \frac{R_r i_r}{L_s i_s} - \frac{R_s}{L_s} + l_1(\zeta_1 - \hat{\zeta}_1)\\ \dot{\hat{\zeta}}_2 &= -\frac{B}{L_s}\hat{\zeta}_2 - \hat{\zeta}_3 + \frac{K}{J} i_r i_s + l_2(\zeta_1 - \hat{\zeta}_1)\\ \dot{\hat{\zeta}}_3 &= l_3(\zeta_1 - \hat{\zeta}_1).\end{aligned} \tag{28}$$

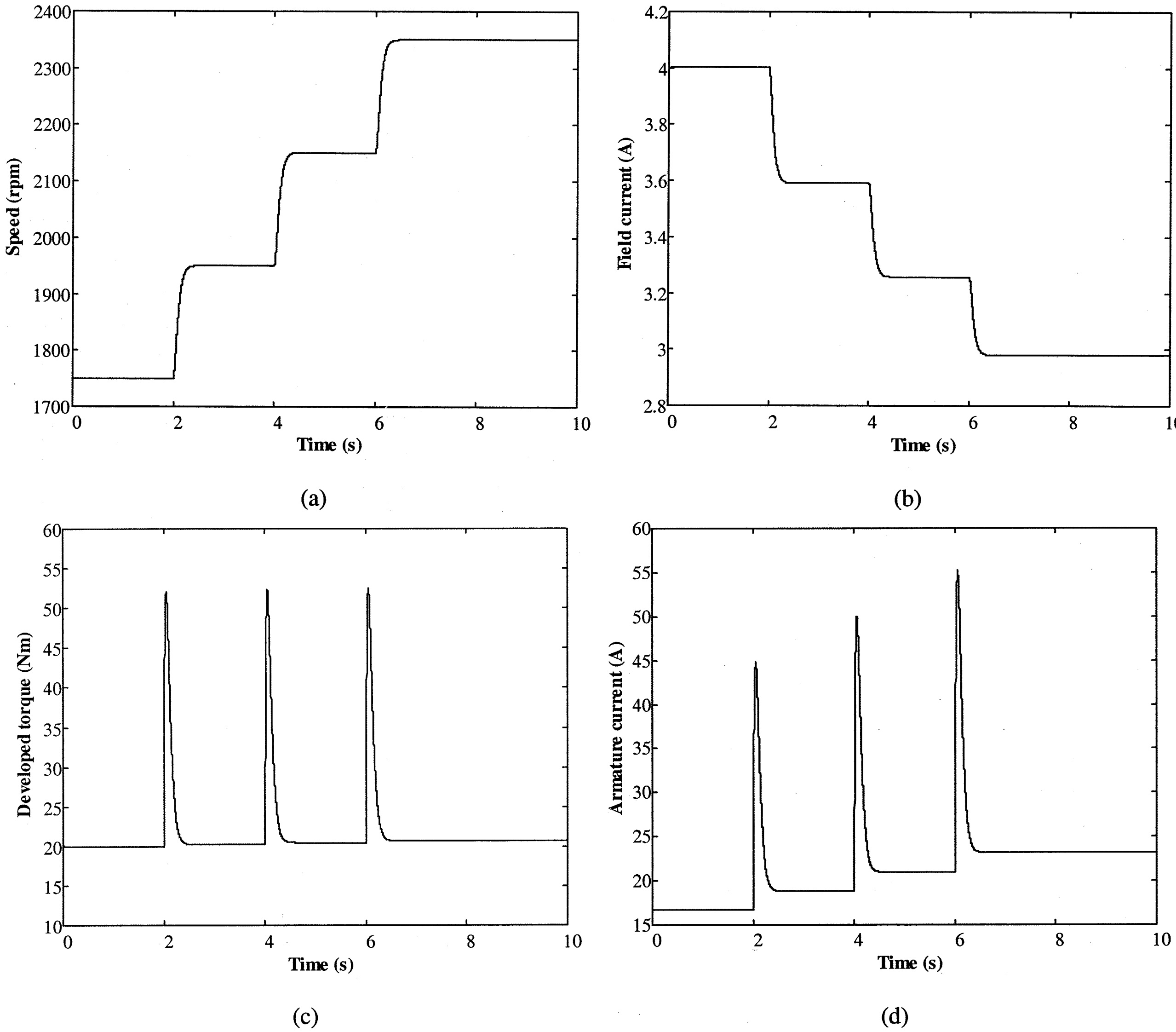

Fig. 2. System response with normal load torque.

The observer error system is found by subtracting (28) from (27), i.e.,

$$\begin{aligned}\dot{e}_1 &= -\frac{K}{L_s}e_2 - l_1 e_1\\ \dot{e}_2 &= -\frac{B}{J}e_2 - e_3 - l_2 e_1\\ \dot{e}_3 &= -l_3 e_1\end{aligned}$$

where

$$e_1 = \zeta_1 - \hat{\zeta}_1,\ e_2 = \zeta_2 - \hat{\zeta}_2 \text{ and } e_3 = \zeta_3 - \hat{\zeta}_3. \tag{29}$$

Choosing the gains l_1, l_2, and l_3 as

$$\begin{aligned}l_1 &= p_1 + p_2 + p_3 - \frac{B}{J}\\ l_2 &= -\frac{L_s}{K}\left(p_1p_2 + p_1p_3 + p_2p_3 - \frac{B}{J}l_1\right)\\ l_3 &= \frac{L_s}{K}p_1p_2p_3\end{aligned} \tag{30}$$

results in the characteristic equation of (29) being given by

$$s^3 + \left(\frac{B}{J} + l_1\right)s^2 + \left(\frac{B}{J}l_1 - \frac{K}{L_s}l_2\right)s + \frac{K}{L_s}l_3 = (s+p_1)(s+p_2)(s+p_3). \tag{31}$$

That is, these gains put the poles of the observer at $-p_1$, $-p_2$, and $-p_3$, where p_1, p_2, and p_3 are positive.

Such an observer is combined with the nonlinear MIMO field-weakening controller designed in Section III to obtain a sensorless control scheme, where only the current measurements (i_r, i_s) are needed and the speed feedback (ω) and load torque signal (T_L) are replaced by the estimated values $(\hat{\omega}, \hat{T}_L)$, respectively.

VI. Applications

To evaluate the performance of the several nonlinear speed control schemes proposed above, extensive simulation studies have been carried out using Matlab/Simulink. A converter-fed

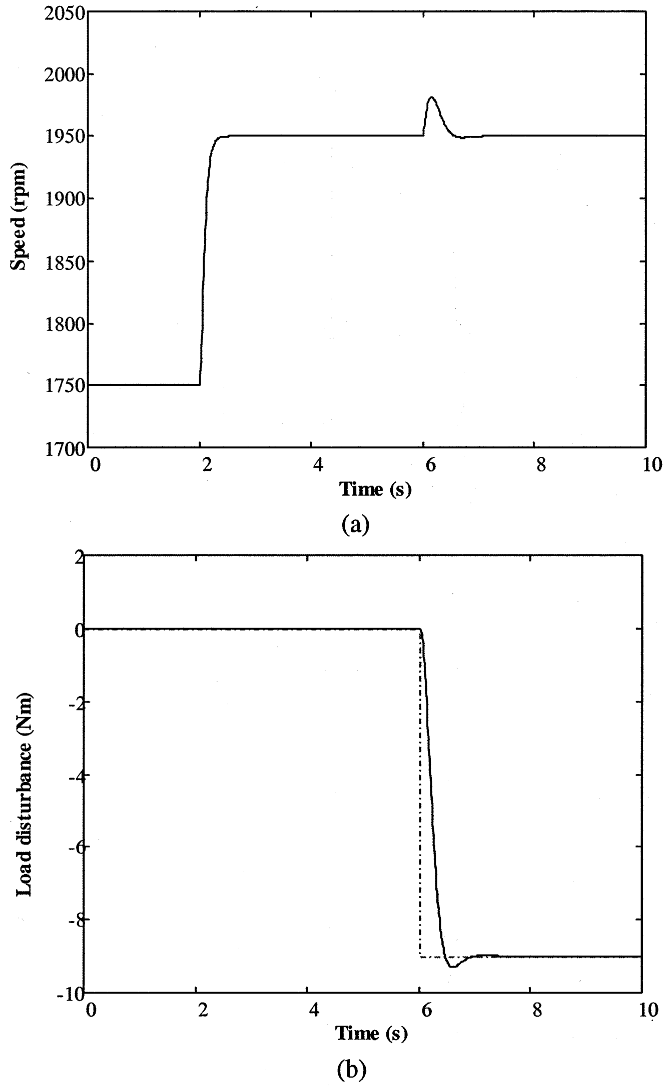

Fig. 3. Speed response with load torque disturbance.

3.7-kW SEDCM system is simulated for these studies. With the assumption that the mechanical time constant of the motor system is much larger compared to the process delay, the process delay is ignored and the firing angle change is considered instantaneous [3]. The system is operated at rated state before weakening field. The motor parameters are given in Table I.

The system performance of the nonlinear MIMO control algorithm is shown in Fig. 2. The gain parameters used are $k_a = 20$, $k_{f1} = 400$, and $k_{f2} = 40$ to place all the closed-loop system's poles at -20. The adaptive gain $\lambda = 3.8$, and normal load torque $T_{LN} = 18$ N $\cdot$ m.

Initially, the field-weakening point is set at $E = 220$ V, the motor is operated at base speed of 1750 r/min. Then, three step changes of 200 r/min in a reference speed is applied at t $= 2$, 4, and 6 s. When the speed ω increases (from 1750 to 2350 r/min) the field current i_s decreases (from 4.0 to 2.98 A), and $\omega \propto I/i_s$. The steady-state values of transient armature current i_r and developed torque T_e increase slightly.

In the case of load-adaptive control design, the responses of the motor speed are reported in Fig. 3. After reaching speed reference $\omega_{\text{ref}} = 1950$ r/min, a sudden change of load torque ($d = 9$ N $\cdot$ m) is applied at t $= 6$ s. It can be observed that the proposed load-adaptive controller demonstrates satisfactory performance with a short time transient of speed and no steady-state error [see Fig. 3(a)]. The actual and estimated load torque disturbances are given in Fig. 3(b) (dotted line represents actual, and solid line describes estimated dynamics).

It has also been shown that the proposed nonlinear MIMO speed-sensorless control scheme can be implemented with high control performance, even in the unknown load torque disturbance.

VII. Conclusion

Base on nonlinear MIMO feedback linearization, several nonlinear control techniques have been investigated for speed tracking of an SEDCM system modeled in interconnected differential equations. Under unknown load torque disturbance, the design with the linear control law obtained yields the steady-state errors as well as the degraded system responses as a result of the incomplete linearization. In addition, introducing an integrator cannot effectively deal with this problem. To overcome this limitation, load-adaptive control design has been developed to improve the dynamic control performance. The scheme with the nonlinear speed and load torque observer is proposed for speed-tracking control. The main advantage of the scheme is that it uses only current measurements, eliminating costly speed sensors. Because of the decoupling and linearization, control implementation of the motor speed ω and back EMF E is achieved independently. As a result, these designs can assure speed tracking at any desired field point.

Applications to a given specific SEDCM system show the proposed nonlinear speed control schemes have high dynamic tracking performance, even when the system with unknown load torque is operated in wide dynamic regimes of field weakening.

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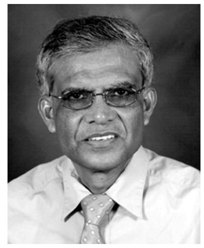

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