Real- time Sensorless Torque Control of Doubly-fed Induction Motor

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Abstract—This paper considers the problem of real-time output feedback torque control of doubly fed induction motors (DFIM). We have considered the discrete-time model of a DFIM with its stator connected to the grid supply and the rotor is fed via and inverter. The controller-observer scheme is proposed to achieve the sensorless torque control. The speed and flux measurements are not used, instead an observer based strategy is proposed. This strategy uses the stator currents to estimate the states which are then used to compute the control. The state estimation is done in real-time and the estimated states are used to implement are real-time controller for achieving desired speed.

Keywords—Doubly Fed Induction Motor (DFIM), Output feedback control, sensorless control.

I. INTRODUCTION

THE inductions motors are the undisputed leader in the motion control and automation industry. No other motor currently available can match the ruggedness, simplicity in manufacturing and ease of construction offered by the induction motors. The only drawback is torque and speed control is not as simple as separately excited DC motors. However, this drawback has been well overcome since the modern power electronics devices have become widespread [1], [2]. The success of squirrel cage induction motors is well augmented by the doubly-fed induction motors. The squirrel cage motors, although very rugged and simple to manufacture, suffer from complexity of vector control methods. The Doubly-Fed Induction Motor (DFIM), provide a means to supply power to the rotor and thus providing the high performance capability via a simpler control [2]. The control of DFIM is usually achieved via varying the rotor voltage keeping the stator connected to the grid. This allows maintaining better power quality on the grid without drawing too much reactive power [3], [4]. We are following similar grid connection in this paper i.e., stator connected to grid and maintains unit power factor while rotor fed via an inverter to obtain desired speed and torque. The detailed analysis of DFIM mathematical model using MATLAB is carried out in [5] where the authors have clearly characterized various operating regions for DFIM. A field oriented control using speed sensors is shown in [6] which is one of the early attempts to operate the DFIM like vector controlled induction motor. Although there is numerous literatures available on control of DFIM, we are especially interested in the literature that deals with sensorless or output feedback control of DFIM e.g., [7], [8]. The dynamics output feedback is exploited in [7] to achieve sensorless control of DFIM while the [8] uses state observer based technique. The authors in [9] have proposed a unique approach combining the Sliding Mode Control with RBF network while [10] have proposed another approach for variable speed control of DFIM. Also, the DFIM is used as high torque low speed applications in [11] and [12]. A novel maximum power point tracking strategy is used in [13]. The controller structure we proposed is novel and not touched upon in any of the existing literature we have surveyed. The novelty of our contribution is described as follows.

A. Contributions

The major contributions of this paper concern the sensorless control of the Doubly-Fed Induction Motor. We have proposed a deadbeat observer which combined with a state feedback controller constitute an output feedback control of DFIM. The state dynamics are linear although the speed and torque equations are nonlinear in nature. Thus, there is a unique strategy devised to achieve nonlinear output tracking via the linear state tracking.

B. Organisation of the Paper

The paper is organized in six sections, Introduction and literature review being the first section. The second section discusses mathematical model of the DFIM along with its differential equations and state-space representation. Third section describes briefly the deadbeat observer for discrete time systems. The main result about state reference tracking is proved in section four. The proposed scheme is shown to be effective in section five through numerical simulations. Finally, the paper is concluded in section six.

II. DFIM MATHEMATICAL MODEL

We have considered the stator connected to line with a standard 3-phase supply. The rotor is being fed via a 3-phase inverter which is used as input to control motor speed and torque. We have assumed the linear magnetic circuits and balanced operating conditions. The electro-magnetic equations of the DFIM in standard d-q frame referred to stator are given as follows [14].

$$\frac{d}{dt}i_{ds} = -\left(\frac{R_s}{L_\sigma} + \frac{R_r L_m^2}{L_r^2 L_\sigma}\right) i_{ds} + \left(\frac{R_r L_m}{L_r^2 L_\sigma}\right)\psi_{dr} + \frac{u_{ds}}{L_\sigma} + \left(\frac{\omega_m L_m}{L_r L_\sigma}\right)\psi_{qr} - \frac{L_m}{L_r L_\sigma}u_{dr} \quad (1)$$

$$\frac{d}{dt}i_{qs} = -\left(\frac{R_s}{L_\sigma} + \frac{R_r L_m^2}{L_r^2 L_\sigma}\right) i_{qs} + \left(\frac{R_r L_m}{L_r^2 L_\sigma}\right)\psi_{qr} + \frac{u_{qs}}{L_\sigma} + \left(\frac{\omega_r L_m}{L_r L_\sigma}\right)\psi_{dr} - \frac{L_m}{L_r L_\sigma}u_{qr} \quad (2)$$

$$\frac{d}{dt}\psi_{dr} = \frac{R_r L_m}{L_r} i_{ds} - \frac{R_r}{L_r}\psi_{dr} - \omega_r\psi_{qr} + u_{dr} \quad (3)$$

$$\frac{d}{dt}\psi_{qr} = \frac{R_r L_m}{L_r} i_{qs} - \frac{R_r}{L_r}\psi_{qr} - \omega_r\psi_{dr} + u_{qr} \quad (4)$$

The differential equation describing the relationship between generated electro-magnetic torque, load torque and motor speed is given as

$$\frac{d}{dt}\omega_m = -\frac{B}{J}\omega_m + \frac{1}{J}T_e - \frac{1}{J}T_L \quad (5)$$

The electro-magnetic torque generated by the motor is given by,

$$\mathrm{T_e} = \frac{3P}{2}\frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right) \quad (6)$$

$$a_1 = \frac{Rs}{L_\sigma} + \frac{R_r L_m^2}{L_r^2 L_\sigma};\ a_2 = \frac{R_r L_m}{L_r^2 L_\sigma};\ a_3 = \frac{\omega_m L_m}{L_r L_\sigma} \quad (7)$$

$$a_4 = \frac{L_m}{L_r L_\sigma};\ a_5 = \frac{R_r L_m}{L_r};\ a_6 = \frac{R_r}{L_r} \quad (8)$$

We aim to design a sensorless control which do not require speed or flux sensor so we designate the stator currents as output. We shall design an MROF based observer to obtain information of states. Thus, defining the states $x_1 = i_{ds}, x_2 = i_{qs}, x_3 = \psi_{dr}, x_4 = \psi_{qr}$, outputs $y_1 = i_{ds}, y_2 = i_{qs}$ and inputs $u_1 = u_{dr}, u_2 = u_{qr}$, the linear state-space representation of the DFIM can be written as follows,

$$\dot{x} = \begin{pmatrix} -a_1 & 0 & a_2 & a_3 \\ 0 & -a_1 & -a_3 & a_2 \\ -a_1 & 0 & -a_5 & \omega_r \\ 0 & a_4 & \omega_r & -a_5 \end{pmatrix} x + \begin{pmatrix} -b & 0 \\ 0 & -b \\ 1 & 0 \\ 0 & 1 \end{pmatrix} u \quad (9)$$

$$y = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} x \quad (10)$$

Remark 1**:** *The model of DFIM in (9) is surely incomplete without the speed and torque equations (5) and (6). However, owing to the nonlinearity of these equations we have not included them in the state-space model. This does not impede controller design because we intend to employ a tracking controller to follow the given state references and the state references will be generated from speed and torque commands.*

A. *Discretization of DFIM Model*

A discrete-time model is required to employ the multirate output feedback techniques. Hence, we describe briefly the discretization of the continuous time model derived in previous section. We choose the sampling frequency f_s = 1kHz giving the sampling time of τ_s = 1mS. This choice is based on the parameter values described in Table-1 and ensure that the Nyquist theorem is satisfied. Since our objective is to track step changes in the speed and torque reference, the most suitable discretization scheme is step invariance method (also called “ZOH” method). The discretized DFIM state-space model is described below.

$$x(k+1) = A_d x(k) + B_d u(k) \quad (11)$$

$$y(k) = C_d x(k) \quad (12)$$

Where,

$$A_d = \begin{pmatrix} 0.9912 & 0 & 0 & 0.002 \\ 0 & 0.9912 & -0.002 & 0 \\ 0 & 0 & 0.9505 & -0.3088 \\ 0 & 0 & 0.3088 & 0.9505 \end{pmatrix} (13)$$

$$B_d = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0.0098 & -0.0016 \\ 0.0016 & 0.0098 \end{pmatrix} \quad (14)$$

$$y = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} x \quad (15)$$

Finally let us discretize the speed and torque equation round an operating point. Since the torque equation is algebraic, it can be written immediately as,

$$T_e(k) = \frac{3P}{2}\frac{L_m}{L_r}(\psi_{dr}(k) i_{qs}(k) - \psi_{qr}(k) i_{ds}(k)) \quad (16)$$

The speed equation about an operating point can be written in discrete-time as follows,

$$J\frac{\omega_m(k+1) - J\omega_m(k)}{\tau_s} = \delta T_{e\omega_m}\omega(k) + \delta T_{e\omega_m}\omega(k) \quad (17)$$

where, $\delta T_{e\omega m}$ denotes variation of torque w.r.t speed. Since we are considering the tracking of constant load torques its variation with speed is zero, i.e, $\delta TL_{\omega m}\omega(k) = 0$. Thus, the speed dynamics in discretetime about an operating point can be described as,

$$\omega(k+1) = \left(1 + \tau_s \delta T_{e\omega_m}\right)\omega(k) \tag{18}$$

III. BRIEF REVIEW OF REAL TIME DEADBEAT OBSERVER FOR DIGITAL SYSTEMS

The outputs of the motor are speed and torque. However, speed and torque measurement is expensive and intrusive. Thus, the sensorless drives consider the stator currents as outputs and observe the states for the control purpose. This observation (estimation) has to be performed in real-time since the observed states are Use a deadbeat observer based on theory of nilpotent matrices. The nilpotent matrix as its all eigen values placed at zero. This property allows the designer to achieve the observation errors to become zero in finite time in minimum time steps. We describe in the following the deadbeat observer which exploit the nilpotent matrices. Consider the discrete-time system described by (11). Let (A_d, B_d, C_d) be the system representation when sampled at interval τ . We assume the pair { A_d, C_d } to be observable

$$x(k+1) = A_d x(k) + B_d u(k) \tag{19}$$

$$y(k) = C_d x(k) \tag{20}$$

The deadbeat observer is the replication of these system equations which are simulated in real-time with the correction terms.

$$\hat{x}(k+1) = A_d\hat{x}(k) + B_d u(k) + LC\left(x(k) + \hat{x}(k)\right) \tag{21}$$

Let us define the state observation error at each step as

$$e(k) = x(k) - \hat{x}(k) \tag{22}$$

The error dynamics can be computed as

$$e(k+1) = x(k+1) - \hat{x}(k+1) \tag{23}$$

$$= Ax(k) + Bu(k) - A\hat{x}(k) - Bu(k) - LCe(k) \tag{24}$$

$$= (A - LC)\, e(k) \tag{25}$$

From the equation (25) and the assumption of observability, it is clear that the observation gain matrix L can be designed to assign arbitrary eigen values to the matrix $\hat{A} = (A - LC)$. Here, in this work we propose to assign all the eigen values Of A to zero. It is well-known that the time response of the state estimation errors is given as

$$e(k) = \hat{A}^k\, e(0) \tag{26}$$

The proposed nilpotency of the matrix$\hat{A}$makes the matrix $\hat{A}^k$ equivalent to zero for k ≥ 4 (since n = 4). Thus, the initial observation error vanishes to zero in 4 time steps. The observed states are exactly equal to the real states after 4 time steps and the controller designed using the observed states gives the correct desired response.

IV. A TRACKING CONTROLLER FOR NONLINEAR OUTPUTS VIA STATE TRACKING

This is the major contributory section where we propose the tracking controller for the DFIM which uses only stator current measurements. The MROF output feedback technique as described in previous section is directly usable for linear systems. However, for the DFIM, the model contains some nonlinearity in torque and speed equation. Hence, we are proposing a novel strategy for utilizing the MROF technique for the DFIM. In the proposed technique, the torque and speed references are translated into the state references for the linear model (13)and the state references are tracked using the MROF technique. We first propose a state tracking state-feedback controller in following subsection and in latter section we develop an output feedback controller which mimics the state-feedback controller.

B. *Tracking Controller for Digital Systems*

Let's discuss first a tracking control for discrete-time systems using state-feedback. This same controller will be implemented, in the next subsection, using the FOS based state observer. Consider the discrete-time control system described by following equations.

$$x(k+1) = A_d x(k) + B_d u(k) \tag{27}$$

$$y(k) = C_d x(k) \tag{28}$$

The state vector$x \in \mathbb{R}^n$, input$u \in \mathbb{R}^m$and output $y \in \mathbb{R}^p$. The matrices are assumed to be of appropriate size. Also, the system is assumed to be in the controllable canonical form. The system is required to track the desired final value of the states prescribed asx^*. The design objective for the controller is to make the system states track the prescribed final value. A state feedback controller is proposed next for this purpose.

Proposition 1**:***The state feedback controller designed as follows provides the tacking of the desired state final values with steady state error approaching zero asymptotically.*

$$u(k) = F\tilde{x}(k) + u^* \quad (29)$$

$$u^* = (B_d^T B_d)^{-1} B_d^T (I_n - A_d) x^* \quad (30)$$

where$\tilde{x} = x^*(k) - x(k)$ is the state error at each instant, u^* feed-forward control magnitude, and F is a stabilizing state feedback gain matrix.

Proof: The final value of $x(k)$ at steady-state is prescribed as x^*so it is a fixed point of the dynamic equation (28). Thus,

$$x(k+1) = A_d x^*(k) + B_d u^*(k) \quad (31)$$

$$x(k) = A_d x^*(k) + B_d u^*(k) \quad (32)$$

$$B_d \; u^*(k) = (I_n - A_d) x^*(k) \quad (33)$$

Since $x^*(k)$ and $u^*(k)$ are fixed, not changing with k, the argument k can be dropped.

$$u^* = (B_d^T B_d)^{-1} B_d^T (I_n - A_d) x^* \quad (34)$$

The matrix $B_d^T B_d$ is invertible because it is assumed to be in controllable canonical form. Thus, using the desired steady state value of x(k), we have derived the final value the input must have at steady state. Next, let us define the error between desired final value of state and instantaneous value of state as$\tilde{x} = x^* - x(k)$and the error between the final vale of input and instantaneous value of input as $\tilde{u} = u(k) - u^*$.

The error dynamics can now be written as

$$\tilde{x}(k+1) = x^*(k+1) + x(k+1) \quad (35)$$

$$= x^*(k) - A_d x(k) - B_d u(k) \quad (36)$$

Substituting, the control from (30) in (37) and dropping the argument k from steady-state values,

$$\tilde{x}(k+1) = x^* - A_d x(k) - B_d F\tilde{x} + B_d u^* \quad (37)$$

$$= x^* - A_d x(k) - B_d F\tilde{x} + A_d x^* - x^* \quad (38)$$

$$= (A_d - B_d F)\tilde{x} \quad (39)$$

Here, the last equation follows by substituting (34) in (37).Thus, from (39) it is clear that $\tilde{x}$ tends to zero asymptotically and the system states track the desired final value. This completes the proof of the proposition.

The proposed state tracking controller is to be used with the deadbeat observer discussed in previous section. The deadbeat observer computes the exact value of states in four time steps and then the proposed controller tracks the states to reference values.

Remark 2:*The controller-observer closed loop is stable here due to the well-known separation principle for closed loop systems. Also, the deadbeat nature of the observer means that the controller acts on the true states after a finite-time as opposed to the asymptotic observer where the observation errors approach zero only asymptotically.*

Table 1. DFIM parameters, symbols and values

Parameter name	*Symbol*	*values*
Stator Resistance	R_s	0.0073 Ω
Stator Inductance	L_s	0.0126 H
Rotor Resistance	R_s	0.0073 Ω
Rotor Inductance	L_s	0.01255 H
Mutual Inductance	L_s	0.01218 H
Pole Pair	P	2
Rotor Inertia	J	20Kgm^2
Synchronous Speed	ω_r	3000rpm

V. NUMERICAL SIMULATIONS

This section validates the proposed controller-observer via the numerical simulations. All the simulations are carried out on the MATLAB software using the discretization approach described in Section-2. The next subsection describes the design of the controller using the parameters in Table-I

A. Controller Design

The test for the controllability and computation of observability is trivial. The system is controllable and observable. The system matrices according to the DFIM parameters are computed as shown below.

$$A_d = \begin{pmatrix} 0.9912 & 0 & 0 & 0.002 \\ 0 & 0.9912 & -0.002 & 0 \\ 0 & 0 & 0.9505 & -0.3088 \\ 0 & 0 & 0.3088 & 0.9505 \end{pmatrix} \quad (40)$$

$$B_d = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0.0098 & -0.0016 \\ 0.0016 & 0.0098 \end{pmatrix} \quad (41)$$

$$y = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} x \quad (42)$$

To compute the state reference commands, some basic requirements of the Induction motor drive have to recall. such as for unity power factor operation$i_{qs}^* = 0$ and $i_{ds}^* = 40$A, rated current. For the stability of speed dynamics torque variation is chosen as 0.5ωm. Thus, $\psi_{qr}^* = 0.5\omega_m$. To ensure $\psi_{dr}^2 + \psi_{qr}^2$ = 1 the command for $\psi_{dr}^* = \sqrt{1 - 0.25\omega_m^2}$.

The state feedback gains are calculated to place the eigen values at $\pm 0.5 \pm j0.5$. Corresponding statefeedback gain is

$$F = \begin{pmatrix} -15.46 & 11.34 & 159.96 & -181.35 \\ -4.73 & -21.35 & 147.60 & 140.51 \end{pmatrix}$$

The observer gain L to place the observer eigen values on zero is computed as

$$L = \begin{pmatrix} -.1211 & 0 & -0.3217 & 252.3059 \\ 0 & -0.1211 & -252.3059 & -0.3217 \end{pmatrix}$$

The large values of some of the gains are due to the deadbeat nature of the observer. Such large values can be difficult to realize for controllers but for observer which is software, these large values do not affect realizability.

B. Simulation Results

The torque commands are given to the motor varying from250Nm to 350Nm. The Figure-1 shows that the given torque commands are attained by the motor quickly without much overshoot.

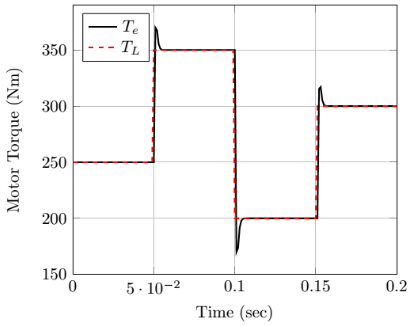

Fig.1. The Torque Commands are tracked

The speed is to be regulated at the rated 3000rpmwhich is shown in Figure-2. The Figure-3 shows that the stator current is maintained at the rated value with unity power factor. The rotor voltage is plotted in Figure-4 to show that the slight variations in rotor voltage input are used to obtain the required torque demand variations.

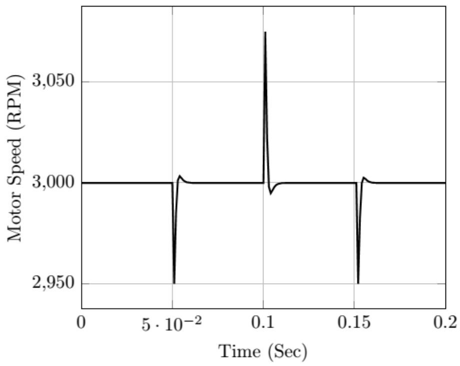

Fig.2. The Motor Speed is regulated at 3000rpm

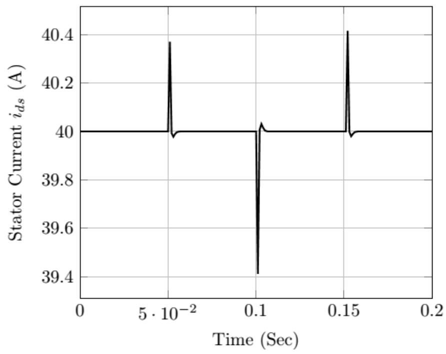

Fig.3. The stator current is regulated at the rated 40A

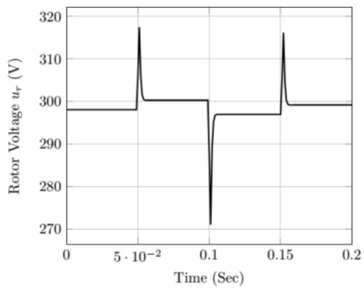

Fig.4. The rotor voltage varies slightly to contribute to varying torque demand

VI. CONCLUSION

We have considered sensorless output feedback real-time control of a Doubly-fed induction motor. A unique strategy for tracking nonlinear outputs of a linear discrete-time system is proposed. We have also proposed a deadbeat observer and a linear state tracking controller for achieving the desired speed and torque output. The state dynamics being linear the usual separation principle is admissible. The strategy is shown to be quite effective in regulating motor speed at rated value while adjusting the generated torque to the demanded load torque.

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