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Multi Rate Output Feedback control of Doubly-fed Induction Motor

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***Abstract*—**The problem of output feedback control of doubly fed induction motor (DFIM) is considered in this paper. In particular the technique of multirate output feedback (MROF) has been employed. The challenge in control of DFIM is the nonlinear nature of torque and speed dynamics which prevents direct application of MROF techniques. We have proposed a novel strategy to achieve the torque and speed tracking via state reference tracking. The linear equations of doubly fed induction motor are utilized for application of MROF and the state reference commands are computed from torque and speed reference commands separately. The proposed output feedback controller is shown to be tracking given torque and speed commands.

***Keywords*—** Doubly-fed Induction Motor; Output Feedback; Multirate Output Feedback; Fast Output Sampling; Sensorless Control.

I. INTRODUCTION

Induction motors have been the workhorse of the automation industry since many decades. The simplicity of construction, availability of detailed mathematical models and sophisticated control methods have propelled the use of induction motors in the industries. The doubly-fed induction motors (DFIM) have been studied since over four decades [8]. Doubly-fed induction motor is an asynchronous electric machine with wound rotor drawing three-phase supply in addition to the stator. The power drawn by the rotor (slip power) is proportional to the slip so the drive requires a rotor-side power converter which consumes only a small fraction of the overall system power. Hence, DFIM is quite attractive for both high power drive applications as well as energy generation [1], [2], [12]. Also, mass production of cheap power electronic devices and digital control techniques have brought DFIMs into prominence. The DFIM preserves the simplicity and reliability of induction motors additionally providing better control of power consumption. The availability of supply on both the stator and rotor makes the utilization of power more efficient by giving precise control of active and reactive power drawn by the motor [4], [9].

A. Contributions

The major contribution in this paper is sensorless torque and speed control of DFIM using multirate output feedback technique. Although, the torque equation nonlinear we have adopted a novel approach to achieve sensorless control using measurement of only stator currents. A state feedback tracking controller is proposed and implemented using Fast Output Sampling (FOS), a type of MROF technique. To the best of authors' knowledge the research work proposed here is new and does not exist in literature.

B. Organization of the Paper

The paper is organised is the standard manner. The II section on mathematical model of DFIM follows the Introduction. The III section describes some preliminaries of MROF. The IV section contains our main contribution of proposing the state tracking controller using MROF. The numerical design of the controller and simulations are discussed in the V section. Finally, the conclusions are described in the last section.

II. RELATED WORK

Moreover the rich literature available for direct torque control (DTC), vector control and sensorless control of induction machines provides a fertile basis for new avenues in the control of DFIM. The sensorless control has reduced the cost of drives increasing ruggedness of induction drives. The double rotor flux oriented control offers unique advantage by providing simple mathematical model [3]. The vector control method proposed in [10] is shown to be effective in both the motoring mode and generation mode. The authors in [14] used a state-observer for achieving sensorless vector control of DFIM.

A lot of literature on the control of DFIM, considers the nonlinear model and employs the techniques suitable for such models. For example, [11], [13] and [7] have proposed innovative nonlinear approaches like feedback linearizing control and adaptive back stepping control for DFIM. The sliding mode control has also been applied for control of DFIM [13], [17]. The field oriented control of DFIM with position encoder has been well explored. However, the sensorless control of DFIM is relatively less explored and we have attempted to perform investigation on sensorless field oriented control for DFIM using multi-rate output feedback technique [16].

III. METHODOLOGY

A. Mathematical Model of DFIM

We consider the line connected stator with a standard 3-phase supply and rotor being fed via a 3-phase inverter which is to be used as input to control motor speed and torque. We assume 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 [13]

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

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

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

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

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

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

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

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

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,

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

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

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.

B. 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.

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

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

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

$$T_e(k) = \frac{3P}{2}\frac{L_m}{L_r}(\psi_{dr}(k) i_{qs}(k) - \psi_{qr}(k) i_{ds}(k)) \quad (13)$$

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

$$J\frac{\omega_m(k+1) - J\omega_m(k)}{\tau_s} = \delta T_{e\omega_m}\omega(k) + \delta T_{e\omega_m}\omega(k) \quad (14)$$

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,

$$\omega(k+1) = \left(1 + \tau_s \delta T_{e\omega_m}\right)\omega(k) \tag{15}$$

C. Brief Review of Multirate Output Feedback Controller and Observer

The multirate sampling of continuous-time systems is well-explored in literature [5], [16]. It has several distinct advantages over uniform sampling such as possibility of arbitrary pole-placement using output feedback [15].

In general the output feedback puts restriction on the location of poles that can be assigned to the closed-loop system. However, if the input and output are sampled at different rates, hence the name multirate, then it is possible to mimic the state feedback (arbitrary pole placement) using output feedback. Here, we briefly review the technique before applying it for sensorless control of DFIM.

Consider the discrete-time system described by (11). Let (A_d, B_d, C) be the system representation when sampled at interval τ and let (A_Δ, B_Δ, C)be the same system sampled at the interval $\Delta = \tau / N$, $N \geq \nu$, where ν is the observability index of the system. Then the combined system dynamics can be represented as below [16], [6].

$$x(k+1) = A_d x(k) + B_d u(k) \tag{16}$$

$$y_{k+1} = C_0 x(k) + D_0 u(k) \tag{17}$$

where the matrices C_0 and D_0 are as derived in [16]. The vector y k+1 is called the output stack which contains the stack of the outputs sampled at Δ interval. $y_{k+1} = [y_{kr} y_{kr+\Delta} \dots \dots y_{kr+N\Delta}]^T$

$$C_0 = \begin{pmatrix} C \\ CA_\Delta \\ \vdots \\ CA_\Delta^{N-1} \end{pmatrix}, \quad D_0 = \begin{pmatrix} 0 \\ CB_\Delta \\ \vdots \\ C\sum_{i=0}^{N-2} A_\Delta^i B_\Delta \end{pmatrix} \tag{18}$$

Let us define boldface $\mathbb{C}$, a fictitious measurement matrix, as

$$\mathbb{C} = (C_0 + D_0 F)(A_d + B_d F)^{-1} \tag{19}$$

The assumption that the state feedback matrix F does not place any eigenvalue at origin is to be enforced to ensure the invertibility of ($\Phi_\tau + \Gamma_\tau F$). Also, F being a design variable it can always be chosen such as to ensure existence of $\mathbb{C}$. Then the controller given as,

$$u_k = [L_0 L_1 \ \dots L_{N-1}] y_k = L y_k \tag{20}$$

mimics the state feedback $u(k) = Fx(k)$provided L satisfies following equation

$$L\mathbb{C} = F \tag{21}$$

The multirate sampled output can not only be used for constructing the state feedback controller but also for estimating states. As shown in [6], the states can be estimated as,

$$x(k) = (C_0^T C_0)^{-1} C_0^T (\, y_{k+1} \ - D_0 u(k)) \tag{22}$$

These estimated states can be used to compute the states at the next instant exactly which in turn can be used to compute the control.

$$x(k+1) = A_d (C_0^T C_0)^{-1} C_0^T \big(y_{k+1} \ - D_0 u(k)\big) + B_d u(k) \tag{23}$$

$$= A_d (C_0^T C_0)^{-1} C_0^T y_{k+1} + (B_d - A_d (C_0^T C_0)^{-1}) C_0^T D_0) u(k) \tag{24}$$

We propose to use this strategy for achieving the sensorless control of DFIM. However, note that the above analysis is valid only for linear systems and we propose a novel strategy for applying this technique for DFIM which has a nonlinear dynamics.

D. Multirate Output Feedback Based Tracking Controller Design

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.

Fast Output Sampling based Output Feedback Controller for Discrete-time Systems

Most controllers in literature require measurement of both the stator currents and the rotor fluxes. Also, if the speed is considered as a state then its measurement is also needed. In this section we propose the output feedback control which uses only the measurement of only outputs which are stator currents for our application. The output feedback control uses the fast output sampling technique discussed in Section-3.3.

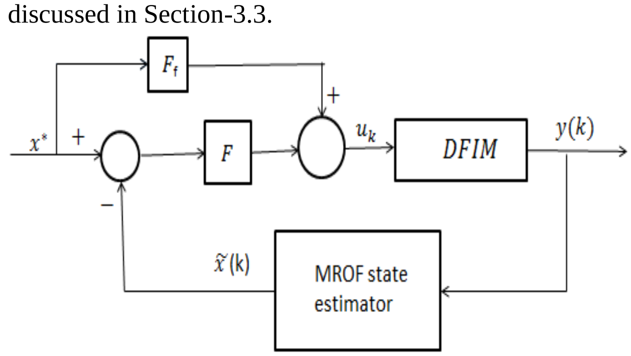

Figure-1 The block diagram of proposed controller

Let's discuss first a tracking control for discrete-time systems, using the FOS based state observer. Consider the discrete-time control system described by following equations

$$x(k+1) = A_d x(k) + B_d u(k) \tag{25}$$

$$y(k) = C_d x(k) \tag{26}$$

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 as x^*. The design objective for the controller is to make the system states track the prescribed final value. This brings us to propose the output feedback controller as follows.

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

$$u(k) = Fx^* - FL_n y_k - FL_u u(k-1) + u^* \tag{27}$$

Where,

$$u^* = (B_d^T B_d)^{-1} B_d^T (I_n - A_d) x^* \tag{28}$$

$$L_y = A_d (C_0^T C_0)^{-1} C_0^T \tag{29}$$

$$L_u = (B_d - A_d (C_0^T C_0)^{-1}) C_0^T D_0 \tag{30}$$

y_k is the MROF output stack and F is a stabilizing state feedback gain matrix. It is important to note here that the controller is using only output information and previous input. Although F is the state feedback gain matrix, the states are not measured rather estimated using fast output sampling.

Let us assume the state tracking error as $\tilde{x}$ then,

$$\tilde{x}(k+1) = x^*(k+1) + x(k+1) \tag{31}$$

$$= x^* - A_d x(k) - B_d u(k) \tag{32}$$

Using the output feedback controller (27) in (32),

$$\tilde{x}(k+1) = x^* - A_d x(k) \\ -B_d (x^* - FL_n y_k - FL_u u(k-1) + u^*) \tag{33}$$

Next substituting the values of L_y and L_u,

$$\tilde{x}(k+1) = \\ x^* - A_d x(k) - B_d F A_d (C_0^T C_0)^{-1} C_0^T y_k \\ -B_d F x^* + B_d F - B_d u^* \\ -(B_d F A_d (C_0^T C_0)^{-1}) C_0^T D_0 u(k-1) \tag{34}$$

Rearranging and collecting the terms with pseudo-inverse of C_0 and using (23)

$$\tilde{x}(k+1) = x^* - A_d x(k) - B_d F x^* + B_d F x(k) \\ - B_d u^* \tag{35}$$

Finally, equation we get,

$$\tilde{x}(k+1) = x^* - A_d x(k) - B_d F x^* + B_d F x(k) \\ + A_d x^* - x^* \tag{36}$$

$$= (A_d - B_d F)\tilde{x}(k) \tag{37}$$

Thus, the state tracking errors become zero asymptotically using multirate output feedback based control.

In the following section we carry out numerical design of the controllers and simulations to support the proposed theory.

IV RESULTS AND DISCUSSION

A. Numerical Simulations

Let us now design the controller proposed in previous section for the doubly fed induction motor. The numerical simulations in this section are carried out using MATLAB. The next subsection describes the design of the controller using the parameters in Table-1.

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	$\boldsymbol{\omega_r}$	**3000rpm**

B. Controller Design

Following is the step-by-step procedure followed to design the proposed controller.

Step-1: Determine the observabilty index and controllability of the system.

Step-2: Compute the A_Δ, B_Δ and C_Δ matrices.

Step-3: Compute the state reference commands from torque and speed reference commands.

Step-4: Compute the state-feedback gain F according to desired closed-loop dynamics and u^*.

Step-5: Compute the MROF output feedback gains.

The test for the controllability and computation of observability is trivial. The system is controllable and observability index is found to be 2. Thus, the fast output sampling multiplier can be chosen as N = 2. The Δ sampled system matrices are computed as shown below.

$$A_d = \begin{pmatrix} 0.9912 & 0 & 0 & 0.002 \\ 0 & 0.9912 & -0.002 & 0 \\ 0 & 0 & 0.9505 & -0.3088 \\ 0 & 0 & 0.3088 & 0.9505 \end{pmatrix} \tag{38}$$

$$B_d = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0.0098 & -0.0016 \\ 0.0016 & 0.0098 \end{pmatrix} \quad (39)$$

$$y = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix} x \quad (40)$$

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 eigenvalues at $\pm 0.5 \pm j0.5$. Corresponding statefeedback gain is

$$y = \begin{pmatrix} -15.46 & 11.34 & 159.96 & -181.35 \\ -4.73 & -21.35 & 147.60 & 140.51 \end{pmatrix} \quad (41)$$

Figure-2 shows the step changes in torque are applied periodically. The motor torque tracks the demanded load torque quickly and with very small overshoot.
The tracking of load torque cause the motor speed to deviate from 3000rpm but the controller can quickly steer the speed back to the desired value.

Figure-4 shows the stator current remains at the rated value of 40A since stator is connected to grid. The rotor voltage is shown in Figure-5.

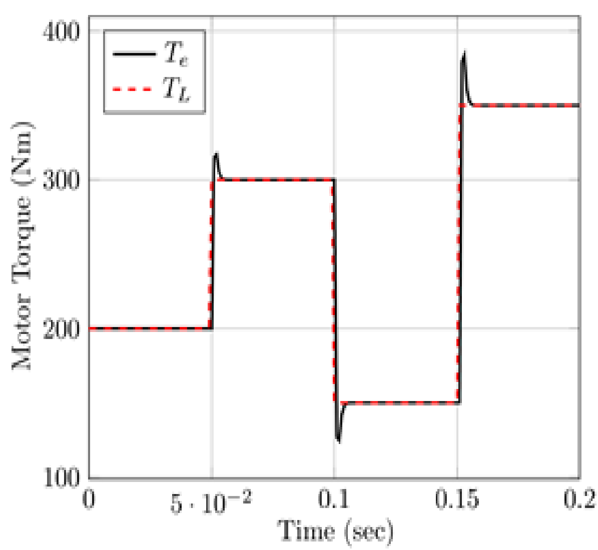

Figure-2 Motor torque tracks load torque

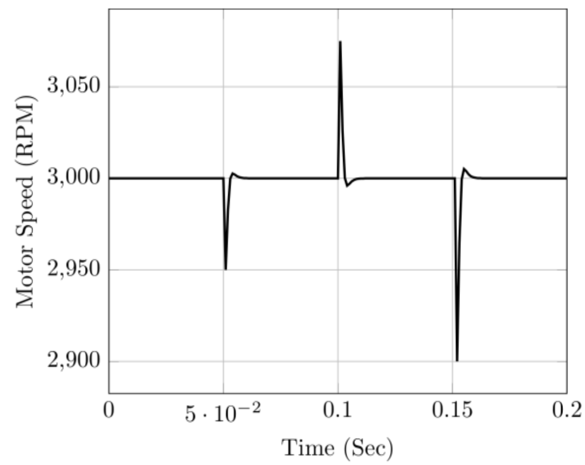

Figure-3 Motor speed is maintained at rated value

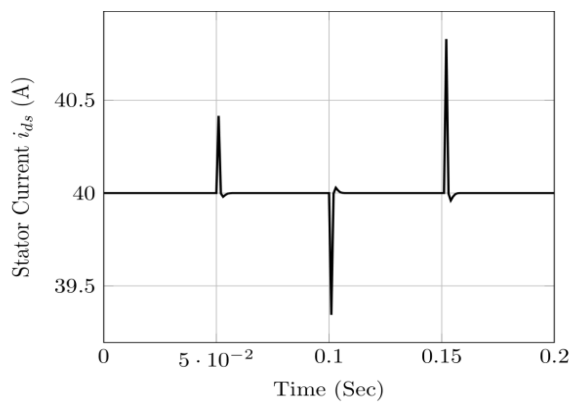

Figure-4 The stator current is maintained at rated value

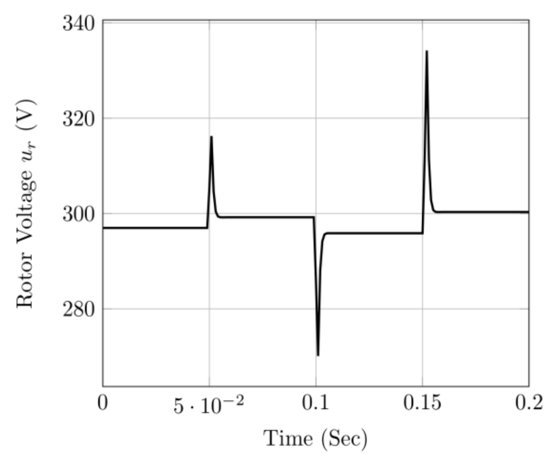

Figure-5 The rotor voltage variations are also small

IV. Conclusion and Future scope

We have studied the output feedback control of doubly fed induction motor. The DFIM is useful for it precise control over speed and torque due to availability of input on rotor. The well-known technique of multirate output feedback is used to achieve desired tracking performance of speed and torque. A new approach is proposed in this paper to track the state commands derived from torque and speed commands using the measurement of only stator currents. The simulations are shown to strengthen the proposed theory. We can consider advance controller design for greater performance.

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