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A Novel Observer Design for Sensorless Sampled Output Measurement: Application of Variable Speed Doubly Fed Induction Generator

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Abstract: This paper presents a novel exponentially convergent nonlinear observer design for variable speed doubly fed induction generators (DFIG). The main feature of the proposed observer lies in the use of sampled-data without necessitating mechanical sensors, making the observer more reliable. A main component of the observer is an inter-sampled predictor of the output current vector. The observer exponential convergence is established and analyzed using Lyapunov stability technique and the small gain theorem. The proposed observer combines the advantage of a high-gain structure in terms of convergence speed and the continuity of the estimated state trajectory. One difficulty of the present observer design problem is that the electromagnetic torque is not related to the output by an injective map. The simulation results in variable speed DFIG operation are provided to confirm the theoretical results.

Keywords: DFIG; High - gain observer; Sampled - data; Sensorless measurements; ISS stabilization.

1. INTRODUCTION

It is widely recognized that the induction machine has become one of the main actuators for industrial use. Indeed, as compared to the DC machine, it provides a better power/mass ratio, simpler maintenance (as it includes no mechanical commutators), and a relatively lower cost.

It is largely agreed that these machines have promising perspectives in the industrial actuator held. This has motivated an intensive research activity on induction machine control, especially over the last 15 years (Giri, 2013; El Fadili et al., 2013).

Doubly-fed induction machines (DFIM) have recently entered into common use. This is due almost exclusively to the advent of wind power technologies for electricity generation.

Doubly-fed induction generator (DFIG) are by far the most widely used type of doubly-fed electric machine, and are one of the most common types of generator used to produce electricity in wind turbines. Doubly-fed induction generators have a number of advantages over other types of generators when used in wind turbines. The primary advantage is that they allow the amplitude and frequency of their output voltage to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor. Because of this, doubly-fed induction generator can be directly connected to the ac power network and remain synchronized at all times with the ac power network. Other advantages include the ability to control the power factor (e. g., to maintain the power factor at unity), while keeping the power electronics devices in the wind turbine at a moderate size (Boldea and Nasar, 2010, Lajouad et al., 2014).

Measuring mechanical quantities is always a challenge for control and visualization of the states of the system under studies. In fact the synthesis of an observer for the system is still beneficial to measure inaccessible magnitudes and quantities or requiring high-end sensors as claimed by (Bastin and Gevers, 1988, Marino and Tomei, 1996, Gildas, 2007, Zhang, 2002, Besancon et al., 2006).

Much research work has been done around the synthesis observers for doubly fed induction machine. For example in (Li et al., 2010) the author suggests an adaptive estimate of rotor currents of the machine. This estimate depends on the time varying of the machine parameters.This estimate has applications where measurement of rotor currents is practecally difficult.

In (Lascu et al., 2013) the paper investigates a family of stator and rotor flux observers of doubly-fed induction generators (DFIG). Four stator flux observer topologies are described and compared. All proposed schemes use the voltage and current models connected in parallel or in series. In this structure no mechanical quantity is estimated.

In (Beltran et al., 2011), the paper deals with the sensorless control of a doubly-fed induction generator (DFIG) based wind turbine. The sensorless control scheme is based on a high-order sliding mode (HOSM) observer to estimate only the DFIG rotational speed.

All these design methods provide continuous-time observers that need discretization for practical implementation purpose (Laila et al, 2006). The point is that exact discretization is a highly complex issue due to the strong nonlinearity of the observer. On the other hand, there is no guarantee that

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approximate discrete-time versions can preserve the performances of the original continuous-time adaptive observers. This explains why quite a few studies have, so far, focused on designing sampled-data adaptive observers that apply to nonlinear systems subject to parametric uncertainty. In (Deza et al., 1992), discrete-continuous time observers have been designed on the basis of the system continuous-time model. The proposed observers include in effect two parts: an open-loop state estimator (with zero innovation term) operating between two successive sampling times and a feedback state estimator operating at the sampling times. The output estimation error is shown to be exponentially vanishing under ad hoc assumptions.

Another approach has been proposed by (Raff et al., 2008) that consisted in using a single hybrid continuous-discrete observer with a ZOH sampled innovation term. The observer is applicable to a class of systems with Lipschitz nonlinearity in the state and linear matrix inequalities (LMIs) are established to meet global stability. In (Kravaris, 2013) a hybrid continuous-discrete observer involving an inter-sample output predictor has been proposed. Only the output predictor is reinitialized at each sampling time, while the state estimate is continuously updated by a standard structure observer where the (unavailable) inter-sample output measurement is replaced by the output prediction. The observer is applicable to triangular globally Lipschitz systems and features exponential convergence of the state observation.

This rest of this paper is organized as follows: the reduced model of the DFIG system is described in Section 2. In Section 3 we deal with the candidate observer of the designated system. The fundamental theorem describing the proposed observer dynamic performances is presented in Section 4; all results are validated by numerical simulation throught MATLAB/SIMULINK environment, as given in Section 5. Finally, conclusions and remarks is given in Sections 6.

2. REDUCED MODEL OF THE DFIG

It is important to initiate with a good and appropriate model of the DFIG when designing the observer. The model of doubly fed induction generator, in d-q coordinates, is defined by the following equations given in (El Fadili et al., 2013, 2012):

$$v_{sd} = R_s i_{sd} + \dot{\phi}_{sd} - \omega_s \phi_{sq} \quad (1a)$$

$$v_{sq} = R_s i_{sq} + \dot{\phi}_{sq} - \omega_s \phi_{sd} \quad (1b)$$

$$v_{rd} = R_r i_{rd} + \dot{\phi}_{rd} - (\omega_s - p\omega)\phi_{rq} \quad (1c)$$

$$v_{rq} = R_r i_{rq} + \dot{\phi}_{rq} - (\omega_s - p\omega)\phi_{rd} \quad (1d)$$

$$\begin{bmatrix}\phi_{sd}\\ \phi_{sq}\\ \phi_{rd}\\ \phi_{rq}\end{bmatrix} = \begin{bmatrix} L_s & 0 & M_{sr} & 0\\ 0 & L_s & 0 & M_{sr}\\ M_{sr} & 0 & L_r & 0\\ 0 & M_{sr} & 0 & L_r\end{bmatrix}\begin{bmatrix} i_{sd}\\ i_{sq}\\ i_{rd}\\ i_{rq}\end{bmatrix} \quad (1e)$$

$$\dot{\omega} = \left(T_{em} - T_g - f_v\omega\right)/ J \quad (1f)$$

where R_s, L_s, R_r and L_r are, respectively the stator and rotor resistances and self-inductances, and M_{sr} is the mutual inductance between the stator and the rotor windings. $\phi_{sd}, \phi_{sq}, \phi_{rd}$ and ϕ_{rq} denote the rotor and stator flux components. $(i_{sd}, i_{sq}, i_{rd}, i_{rq})$ and $(v_{sd}, v_{sq}, v_{rd}, v_{rq})$ are the stator and rotor components of the current and voltage respectively. p is the number of pole-pair, ω_s is the stator angular frequency, ω represents the generator speed. f_v, J and T_g are, respectively the viscuous friction coefficient, the total moment of inertia for lumped mass model (rotor blades, hub, and generator), and generator torque.

Equation (1a-1f) can be re-written as follows:

$$v = \begin{bmatrix} R_s I_2 & O_2\\ O_2 & R_r I_2\end{bmatrix} i + \frac{d\Phi}{dt} + \begin{bmatrix}\omega_s J_2 & O_2\\ O_2 & (\omega_s - p\omega)J_2\end{bmatrix}\Phi \quad (2a)$$

$$\Phi = \begin{bmatrix} L_s I_2 & M_{sr} I_2\\ M_{sr} I_2 & L_r I_2\end{bmatrix} i \quad (2b)$$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(T_{em} - T_g - f_v\omega\right) \quad (2c)$$

T_{em} is the electromagnetic torque represented by:

$$T_{em} = pM_{sr}\left(i_{rd}i_{sq} - i_{rq}i_{sd}\right) = pM_{sr} i^T T_0 i \quad (3a)$$

$$T_0 = \begin{bmatrix} O_2 & J_2\\ O_2 & O_2\end{bmatrix} \quad (3b)$$

$i = \left[i_{sd}\ i_{sq}\ i_{rd}\ i_{rq}\right]^T$, $v = \left[v_{sd}\ v_{sq}\ v_{rd}\ v_{rq}\right]^T$ and $\Phi = \left[\phi_{sd}\ \phi_{sq}\ \phi_{rd}\ \phi_{rq}\right]^T$ denote, respectively the state vector of stator and rotor current, voltage and flux in (d-q) reference coordinate, where

$J_2 = \begin{bmatrix} 0 & -1\\ 1 & 0\end{bmatrix}$, $I_2 = \begin{bmatrix} 1 & 0\\ 0 & 1\end{bmatrix}$ and $O_2 = \begin{bmatrix} 0 & 0\\ 0 & 0\end{bmatrix}$

Then the model of DFIG in the (d; q) coordinates system (El Fadili et al., 2013, 2012) can be given by the following equations:

$$i = \gamma M_1 v + M_{23} i - p\gamma M_4 \omega i \quad (4a)$$

$$\dot{\omega} = \left(pM_{sr} i^T T_0 i - T_g - f_v\omega\right)/J \quad (4b)$$

$$\dot{T}_g = 0 \quad (4c)$$

Equation (4c) is motivated by the fact that, in numerous applications, the generator torque T_g is assumed bounded, derivable and its derivative is also bounded. Indeed, the generator torque T_g is actually infrequent, that is, the input generator torque takes a value with slowly varying.

with $\gamma = \frac{1}{\varrho L_s L_r}$, $\varrho = 1 - \frac{M_{sr}^2}{L_s L_r}$, M_1, M_2, M_3, M_{23} and M_4 are constant matrices that can be represented as follows:

$$M_1 = \begin{pmatrix} L_r I_2 & -M_{sr} I_2\\ -M_{sr} I_2 & L_s I_2\end{pmatrix} \quad (5a)$$

$$M_2 = \begin{pmatrix} R_s L_r I_2 & -M_{sr} R_r I_2\\ -M_{sr} R_s I_2 & R_r L_s I_2\end{pmatrix} \quad (5b)$$

$$M_3 = \begin{pmatrix} J_2 & O_2\\ O_2 & J_2\end{pmatrix} \quad (5c)$$

$$M_{23} = -M_3\omega_s - \gamma M_2 \quad (5d)$$

$$M_4 = \begin{pmatrix} M_{sr}^2 J_2 & M_{sr} L_r J_2\\ -M_{sr} L_s J_2 & -L_s L_r J_2\end{pmatrix} \quad (5e)$$

Now, let us introduce the following state variables representation:

$x_{11} = i_{sd},\ x_{12} = i_{sq},\ x_{13} = i_{rd},\ x_{14} = i_{rq},\ x_2 = \omega, x_3 = T_g$ and let's $x_1 = [\,x_{11}\ x_{12}\ x_{13}\ x_{14}]^T$. Then the system (4) can be re - written in the reduced form as :

$$\dot{x} = f(v, x) \quad (6a)$$

$$y = h(x) = x_1 \quad (6b)$$