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Unknown Input Observer for a Doubly Fed Induction Generator Subject to Disturbances

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ABSTRACT

This paper deals with the problem design of an unknown input observer (UIO) for a Doubly Fed Induction Generator (DFIG) subject to disturbances. These disturbances can be considered as unknown inputs (UI). The state space model of the DFIG is obtained from the voltage equations of the stator and rotor. Then, this latter is used for the design of an unknown input observer (UIO) in order to estimate both the state and the unknown inputs of the DFIG. Furthermore, the UIO gains are computed by solving a set of linear matrix inequalities (LMIs). Simulations results are given to show the performance and the effectiveness of the proposed method.

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1. INTRODUCTION

Induction generators are one of the most popular electric machines used in wind turbines. Wind turbines based on the doubly fed induction generator (DFIG) has received increasing attention in the recent years, due to its remarkable advantages over other wind turbine systems [1], the increase of power capture [2], their capacity to operate at different range of the wind speed, the ability to control active and reactive powers [3].However, DFIG-based wind turbines can be subject to disturbances which can have as source: measurement noises, sensors and actuators faults, especially to voltage dips [4]. These disturbances, can be considered as unknown inputs, have adverse effects on the normal behavior of the real system and their estimates can be used to conceive systems of diagnostic and control [5]. Robust observers are proposed to estimate simultaneously states and actuator faults for various class of linear and nonlinear systems [6]-[10].

Recently, diagnosis and estimation faults are becoming very important to ensure a good supervision of the systems and guarantee the safety of human operators and equipment's, even if systems are becoming more and more complex. In this respect, a large number of diagnostic methods for sensors of induction machines have proposed in [11]-[13].

Fault diagnosis and State estimation of induction machines has attracted considerable interest, as they are often used in practical control systems [14]. FDI in sensor faults of induction machines is necessary since control systems rely on the information provided by measured signals. In [15], the authors have studied the FDI problem of induction machines. Since DFIG can be subject to different kinds of faults as studied in [16]. Authors in [17]-[19], focus on current sensor fault detection and isolation (FDI) and control reconfiguration current for DFIG. They have used two Luenberger observers to generate residuals for the current sensors. A proposed algorithm for fault identification is designed to isolate current sensor faults instator or in rotor. In [20]-[21], have studied the effect of current sensor fault on a doubly fed induction machine (DFIM). In [22], a new FDI algorithm of stator current sensors and speed sensor faults detection problem has proposed for Permanent Magnet synchronous machine drives where simulation and experimental results are reported. In [23] presents a signal-based approach to detect and isolate the fault in stator current and voltage sensors of the DFIG.

The contribution of this paper focuses on the design of the UIO to estimate both of state and unknown inputs. These unknown inputs are considered in this work, as faults affecte the stator voltages of the DFIG and their estimates can be used to conceive systems of diagnostic and control.

This work is organized as follows. In Section 2, system description and modeling are presented. In Section 3, formulation problem is discussed. Then, in Section 4, simulation results are conducted to evaluate the performance of the proposed observer. Finally, the conclusions and future works are given in Section 5.

2. SYSTEM DESCRIPTION AND MODELING

In a DFIG-based wind turbine, as shown in Fig. 1, the generator is coupled to the wind turbine rotor through a gearbox. The stator of the DFIG is directly connected to the grid and the rotor side is connected to a back-to-back converter via slip-rings [24].

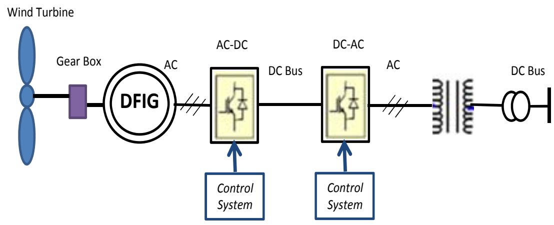

Figure 1.Model of DFIG-based wind turbine.

2.1. DFIG model

For the DFIG, the dynamic voltages of the stator ($V_{\alpha s}$ and $V_{\beta s}$) and those of the rotor ($V_{\alpha r}$ and $V_{\beta r}$) in the general $(\alpha-\beta)$ reference frame are respectively expressed as [25]:

$$\begin{cases} V_{\alpha s} = R_s I_{\alpha s} + \dfrac{\mathrm{d}}{\mathrm{d}t}\Phi_{\alpha s} - \omega_s \Phi_{\beta s} \\ V_{\beta s} = R_s I_{\beta s} + \dfrac{\mathrm{d}}{\mathrm{d}t}\Phi_{\beta s} + \omega_s \Phi_{\alpha s} \\ V_{\alpha r} = R_r I_{\alpha r} + \dfrac{\mathrm{d}}{\mathrm{d}t}\Phi_{\alpha r} - \omega_r \Phi_{\beta r} \\ V_{\beta r} = R_r I_{\beta r} + \dfrac{\mathrm{d}}{\mathrm{d}t}\Phi_{\beta r} + \omega_r \Phi_{\alpha r} \end{cases} \tag{1}$$

The stator and rotor $(\alpha-\beta)$ fluxes, $\varphi_{\alpha s}$, $\varphi_{\beta s}$, $\varphi_{\alpha r}$ and $\varphi_{\beta r}$ are given by:

$$\begin{cases} \Phi_{\alpha s} = L_s i_{\alpha s} + L_m i_{\beta r} \\ \Phi_{\beta s} = L_s i_{\beta s} + L_m i_{\beta r} \\ \Phi_{\alpha r} = L_r i_{\alpha r} + L_m i_{\alpha s} \\ \Phi_{\beta r} = L_r i_{\beta r} + L_m i_{\beta s} \end{cases} \tag{2}$$

Where, $V_{\alpha s}$, $V_{\beta s}$, $V_{\alpha r}$ and $V_{\beta r}$ stator and rotor in $(\alpha-\beta)$ voltages; $I_{\alpha s}$, $I_{\beta s}$, $I_{\alpha r}$ and $I_{\beta r}$ stator and rotor in $(\alpha-\beta)$ currents; , $\varphi_{\alpha s}$, $\varphi_{\beta s}$, $\varphi_{\alpha r}$ and $\varphi_{\beta r}$ stator and rotor in $(\alpha-\beta)$ fluxes; R_s, R_r stator and rotor per phase resistance; L_s, L_r cyclic stator and rotor inductances.

2.2. DFIG State space model

In this paper, themathematical model developed of the DFIG is derived from the voltage equations of the stator and rotor (for more details see ([17-19]). Based on (1), (2) and (3), the DFIG model is expressed in the reference $(\alpha-\beta)$ frame, as the following:

$$
\begin{cases}
\dfrac{d\,I_{\alpha s}}{dt} = -\dfrac{R_s}{\sigma L_s} I_{\alpha s} + (\omega_s + \dfrac{L_m^2\, p\,\Omega_m}{\sigma L_s\, L_r}) I_{\beta s} + \dfrac{R_r\, L_m}{\sigma L_s\, L_r} I_{\alpha r} + \dfrac{L_m\, p\Omega_m}{\sigma L_s} I_{\beta r} + \dfrac{1}{\sigma L_s} u_{\alpha s} - \dfrac{L_m}{\sigma L_s\, L_r} u_{\alpha r} \\
\dfrac{d\,I_{\beta s}}{dt} = -(\omega_s + \dfrac{L_m^2\, p\,\Omega_m}{\sigma L_s\, L_r}) I_{\alpha s} - \dfrac{R_s}{\sigma L_s} I_{\beta s} - \dfrac{L_m\, p\Omega_m}{\sigma L_s} I_{\alpha r} + \dfrac{R_r\, L_m}{\sigma L_s\, L_r} I_{\beta r} + \dfrac{1}{\sigma L_s} u_{\beta s} - \dfrac{L_m}{\sigma L_s\, L_r} u_{\beta r} \\
\dfrac{d\,I_{\alpha r}}{dt} = -\dfrac{L_m R_s}{\sigma L_s\, L_r} I_{\alpha s} - \dfrac{L_m\, p\,\Omega_m}{\sigma\, L_r} I_{\beta s} + \dfrac{R_r}{\sigma\, L_r} I_{\alpha r} + (\omega_s - \dfrac{p\,\Omega_m}{\sigma}) I_{\beta r} - \dfrac{L_m}{\sigma L_s\, L_r} u_{\alpha s} + \dfrac{1}{\sigma L_r} u_{\alpha r} \\
\dfrac{d\,I_{\beta r}}{dt} = \dfrac{L_m\, p\,\Omega_m}{\sigma L_r} I_{\alpha s} + \dfrac{L_m R_s}{\sigma L_s\, L_r} I_{\beta s} - (\omega_s - \dfrac{p\,\Omega_m}{\sigma}) I_{\alpha r} - \dfrac{R_r}{\sigma\, L_r} I_{\beta r} + \dfrac{L_m}{\sigma L_s\, L_r} u_{\beta s} + \dfrac{1}{\sigma L_r} u_{\beta r}
\end{cases} \tag{3}
$$

The state space model of the DFIG is given by:

$$
\begin{cases}
\dot{x}(t) = A(\Omega_m) x(t) + B\, u(t) + R\, u_{in}(t) \\
y(t) = C\, x(t)
\end{cases} \tag{4}
$$

Where, Ω_m is the mechanical speed of the rotor, p is the number of pole pairs, and the matrices $A(\Omega_m)$, B and C are expressed as follows :

$$
A(\Omega_m) = \begin{bmatrix} -\left(\dfrac{R_s}{\sigma L_s} I_2 + \left(\omega_s + \dfrac{L_m^2\, p\,\Omega_m}{\sigma L_s\, L_r}\right) J\right) & \left(\dfrac{R_r\, L_m}{\sigma L_s\, L_r} I_2 - \dfrac{L_m\, p\Omega_m}{\sigma L_s} J\right) \\ \left(\dfrac{R_s\, L_m}{\sigma L_s\, L_r} I_2 + \dfrac{L_m\, p\Omega_m}{\sigma L_s} J\right) & -\left(\dfrac{1}{\sigma\, L_r} I_2 + (\omega_r - \dfrac{p\,\Omega_m}{\sigma}) J\right) \end{bmatrix},\ B = \begin{bmatrix} \dfrac{L_m}{\sigma L_s L_r} I_2 \\ -\dfrac{1}{\sigma L_r} I_2 \end{bmatrix},\ C^T = \begin{bmatrix} 0_{2\times 2} \\ I_2 \end{bmatrix}\ J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}
$$

The state vector $x = \left[I_{\alpha s}\ I_{\beta s}\ I_{\alpha r}\ I_{\beta r}\right]^T$, consists of the stator currents and rotor current components. The control inputs $u = \left[u_{\alpha s}\ u_{\beta s}\right]^T$ are the rotor voltage components. The measured disturbances (Unknown inputs) $u_{in} = \left[u_{\alpha r}\ u_{\beta r}\right]^T$ are the stator voltage components. It is clear from the representation as in (4), that the system matrix A is varying time and depends on the mechanical rotor speed Ω_m. In this paper, letus consider that the DFIG operates at a fixed-speed ($\Omega_m = \Omega_{mec}$).

3. PROBLEM FORMULATION

UIO's goal is to estimate the system states where some inputs are unknown. Authors in [26], demonstrated that the conventional Luenberger observer is not suitable to overcome unknown inputs. Using the estimated states and the known inputs, the unknown inputs are reconstructed [3]. The block diagram of a UIO with reconstruction of the unknown inputs is given in Figure 3. For the system as in (1), the UIO is as follows[27]:

$$
\begin{cases}
\dot{z}(t) = N\, z(t) + G\, u(t) + L\, y(t) \\
\hat{x}(t) = z(t) - E\, y(t)
\end{cases} \tag{5}
$$

Where z is a new state of the observer, y the output vector, u the known input vector, N is a stable matrix. Matrices N, G, L and E are the observer gains. The matrices N, K, G and E have to be designed in such a way that $\hat{x}(t)$ converges asymptotically to $x(t)$. As a consequence, the observer error will converge to zero.

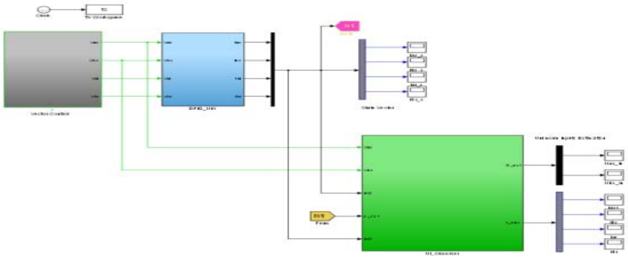

Figure 2. Unknown Input Observer for a DFIG subject to disturbances.

Let us define the state estimation error as:

$$e(t) = x(t) - \hat{x}(t) \tag{6}$$

By using (5) and (6), the state estimation error e(t) becomes:

$$e(t) = z(t) - (I_{nx} + EC)x(t) \tag{7}$$

By setting $P = (I_{nx} + EC)$, the dynamics of the estimation error is given by the following equation:

$$e(t) = N\,e(t) + (G - P\,B)u(t) + (P\,N - L\,C - N\,P)x(t) - PR\,u_{in} \tag{8}$$

Theorem.1 . The necessary and sufficient conditions for the existence of UIO (5) of system (4) are [27-28]:

a) N is stable (eig (N) <0);
b) rank(CR) = rank(R) = dim(y);
c) The pair ((Inx + EC)A,C) is observable.

If the following relations are satisfied:

$$L\,C = P\,A - N\,C \tag{9a}$$

$$G = PB \tag{9b}$$

$$(I_{nx} + E\,C)R = 0 \tag{9c}$$

Based on (9c) yield to:

$$E = -R(C\,R)^{+} \tag{10}$$

where (CR)+ is the generalized inverse matrix of (CR) and can be given as :

$$(C\,R)^{+} = \left((C\,R)^{T}(C\,R)\right)^{T}(C\,R)^{T} \tag{11}$$

Finally, all matrices N, K, G and E are defined in the following equations :

$$E = -R\left((C\,R)^{T}(C\,R)\right)^{-1}(C\,R)^{T} \tag{12a}$$

$$P = I_{nx} - R\left((C\,R)^{T}(C\,R)\right)^{-1}(C\,R)^{T} \tag{12b}$$

$$G = P\,B \tag{12c}$$

$$N = P\,A - K\,C \tag{12d}$$

$$L = K - N\,E \tag{12e}$$

The state estimation error is then refined as:

$$\dot{e}(t) = N\,e(t) \tag{13}$$

3.1. Stability and convergence conditions

Based on the above UI observer, the following theorem will give the fault estimation algorithm and the conditions that guarantee the stability of error system (13).

Theorem. 2. The UIO (5) for a DFIG system with inputs unknown (4) exists and their estimation error (13) converges asymptotically to zero, if and only if, the pair (A,C) is detectable . This observer is asymptotically stable if exists a positive definite symmetric matrix P and matrices $W_i = P\,K_i$ such that the following LMI holds:

$$A_i^{T}P + P\,A_i - C^{T}W_i^{T} - W_i\,C < 0, \forall i \in \{1,...,r\} \tag{14}$$

The solution of the inequality (14) can then be obtained usingLMI conditions. Observer gains can becalculated from $K_i = P^{-1}W_i$. Then, consequently $\hat{x}(t)$ will asymptotically converge to $x(t)$ and $u_{in}(t)$ to $\hat{u}_{in}(t)$.

3.2. Unkown input estimation

In order to obtain the unknown inputs $\hat{u}_{in}(t)$, we combining (4) and (15), the unknown inputs are expressed as the following:

$$\frac{d\,\hat{x}(t)}{dt} = N\,z(t) + L\,y(t) + G\,u(t) - E\,\dot{y}(t) \tag{15}$$

$$\hat{u}_{in}(t) = R^{+}N + R^{+}(G-B)u + R^{+}Ly - R^{+}E\,\dot{y} - R^{+}A\,\hat{x}(t) \tag{16}$$

4. SIMULATION AND DISCUSSION RESULTS

In order to validate the proposed approache, the model (4) with the parameters in [9-10] is used as a controlled system in the simulation studies. The studies were conducted in Matlab using 4th-order Runge-Kutta method with the fixed step size of 0.01 s.Figure. 3 represents the measured stator and rotor currents of the DFIG and their estimated based on the UIO, and in Figure. 4 is represented the dynamic errors of the states.

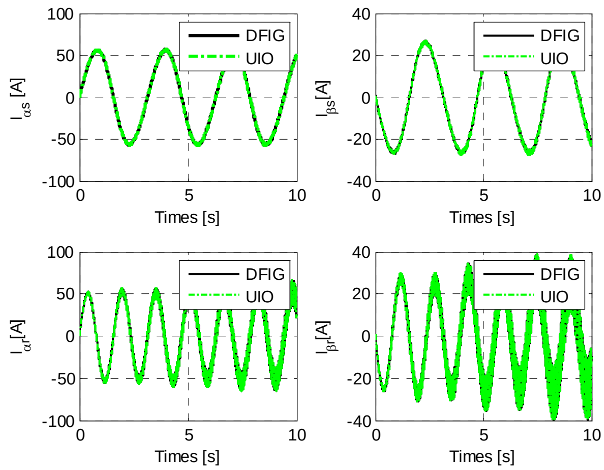

Figure 3. Simulation results of original states and their estimated.

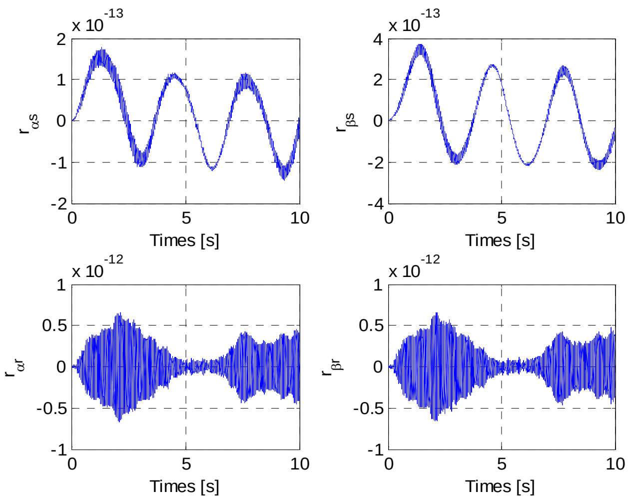

Figure 4. The errors between states and their estimated.

It can be clearly observed from the simulation results that the states estimation generated from the UIO converge rapidly to those simulate by the DFIG system. In addition, we can see in Figures 4, that the estimation errors are very weak.

4.1. Unknown Input Estimation

Figures. 5 and 6 represent the unknown inputs and their estimates, with their dynamic errors . The simulation results show the good estimation of these unknown inputs.

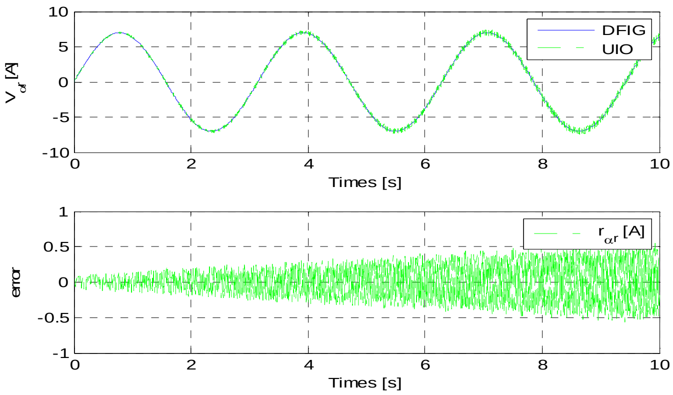

Figure 5.Unknown input $V_{\alpha s}$ and its estimated $\hat{u}_{in\alpha s}$.

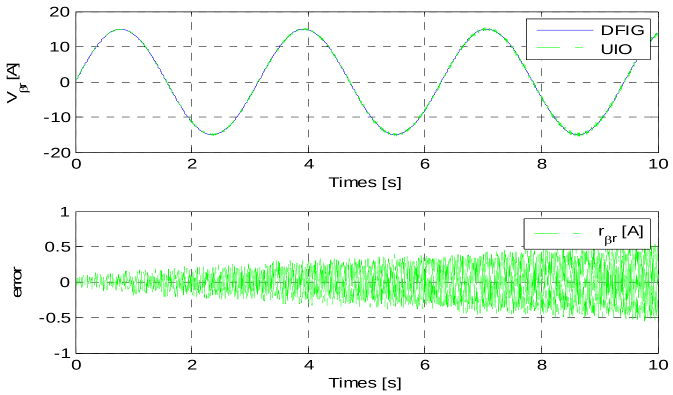

Figure 6.Unknown input $V_{\beta s}$ and its estimated $\hat{u}_{in\beta s}$.

The simulation results show a good estimation of both state and unknown inputs by using the UIO.

5. CONCLUSION

In this paper, the problem of designing the unknown input observer (UIO) for a DFIG which subject to disturbance is treated. These unknown inputs affects the states of the DFIG. The Unknown Input Observer (UIO) design problem is formulated as a set of linear constraints which can be easily solved using linear matrix inequalities (LMIs) technique. Solving a set of LMIs, the UIO can be designed. An application based on a DFIG is presented to evaluate the performance and the effectiveness of the proposed observer. The observer is applied to estimate both stator and rotor currents with unknown inputs which described by the stator voltages. The simulation results show a good estimation of both state and unknown inputs.

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