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T-S Fuzzy Observer and Controller of Doubly-Fed Induction Generator

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ABSTRACT

This paper aims to ensure a stability and observability of doubly fed induction generator DFIG of a wind turbine based on the approach of fuzzy control type T-S PDC (Parallel Distributed Compensation) which determines the control laws by return state and fuzzy observers. First, the fuzzy TS model is used to precisely represent a nonlinear model of DFIG proposed and adopted in this work. Then, the stability analysis is based on the quadratic Lyapunov function to determine the gains that ensure the stability conditions. The fuzzy observer of DFIG is built to estimate non-measurable state vectors and the estimated states converging to the actual statements. The gains of observatory and of stability are obtained by solving a set of linear matrix inequality (LMI). Finally, numerical simulations are performed to verify the theoretical results and demonstrate satisfactory performance.

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1. INTRODUCTION

The doubly fed induction generator has been popular because of its higher energy transfer capability, low investment and flexible control [1]. The control of the DFIG is well known to be difficult owing to the fact that the dynamic model is nonlinear and some states cannot be measured. For this, it is important to know the evolution of the state of the nonlinear system (DFIG).

A considerable research has been done on the modeling and control of DFIG [2]-[8]. For monitoring, decision making and feedback control of the DFIG, very interesting approach were done in the fuzzy modeling and control, especially with Takagi-Sugeno (T-S) fuzzy [9] and related parallel distributed compensation (PDC) control algorithm [10].

The Takagi-Sugeno (TS) fuzzy modeling framework with parallel-distributed compensation (PDC) technique [11] offers a viable way to control and approximate a wide class of nonlinear dynamical systems [12] by providing a generic nonlinear state-space model. To ensure global system stability and observability of DFIG, a quadratic Lyapunov function common to all subsystems is found by solving a set of linear matrix inequalities LMIs [10], [13]. Then using powerful computational tool boxes, such as Matlab LMI Toolbox. We obtain the controller and observers gains for local fuzzy models.

This paper is organized as follows. In Section II, the dynamic model of doubly fed induction generator is presented. In Section III, study of T-S fuzzy modelling, method PDC and Fuzzy state observer.

In Section IV, describes LMI-based design procedures for the augmented system, finally an application of fuzzy TS method on DFIG with the results obtained and simulation.

2. MODEL OF DOUBLY FEED INDUCTION GENERATOR

The state space of the DFIG dynamics model in d-q coordinates can be expressed by following nonlinear equations [2]-[4] :

$$\begin{cases} x(t) = A\,x(t) + B\,u(t) \\ y(t) = C\,x(t) \end{cases}$$

where

$$x(t) = [I_{sd}, I_{sq}, I_{rd}, I_{rq}]^T$$
$$u(t) = [V_{rd}, V_{rq}, V_{sd}, V_{sq}]^T$$

$$A = \begin{bmatrix} \frac{-R_s}{\sigma L_s} & p\left(\omega_s + \frac{M^2}{\sigma L_s L_r}\omega_r\right) & \frac{R_r M}{\sigma L_s L_r} & \frac{pM}{\sigma L_s}\omega_r \\ -p\left(\omega_s + \frac{M^2}{\sigma L_s L_r}\omega_r\right) & \frac{-R_s}{\sigma L_s} & \frac{-pM}{\sigma L_s}\omega_r & \frac{R_r M}{\sigma L_s L_r} \\ \frac{R_s M}{\sigma L_s L_r} & \frac{-pM}{\sigma L_s}\omega_r & \frac{-R_r}{\sigma L_r} & p\left(\omega_s - \frac{\omega_r}{\sigma}\right) \\ \frac{pM}{\sigma L_r}\omega_r & \frac{R_s M}{\sigma L_s L_r} & -p\left(\omega_s - \frac{\omega_r}{\sigma}\right) & \frac{-R_r}{\sigma L_r} \end{bmatrix}$$

$$B = \begin{bmatrix} -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_s} & 0 \\ 0 & -\frac{M}{\sigma L_s L_r} & 0 & \frac{1}{\sigma L_s} \\ \frac{1}{\sigma L_r} & 0 & -\frac{M}{\sigma L_s L_r} & 0 \\ 0 & \frac{1}{\sigma L_r} & 0 & -\frac{M}{\sigma L_s L_r} \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 & 0 & -\frac{MV_s}{L_s} \\ 0 & 0 & \left(\frac{V_s^2}{w_s L_s}\frac{1}{I_{rd}} - \frac{MV_s}{L_s}\right) & 0 \end{bmatrix}$$

where

L_s, L_r, M	: Stator, Rotor and Mutual inductance
R_s, R_r	: Stator and Rotor resistances.
ω_s, ω_r	: Stator and Rotor speed
I_{sq}, I_{rq}	: Stator and Rotor currents in axis q
I_{sd}, I_{rd}	: Stator and Rotor currents in axis d
$x(t), u(t)$	: The state system and the control vector
L_i, K_i	: The gains matrices of the fuzzy observer and fuzzy regulator
r	: The number of local models.
p	: The Number of pole
Vs	: Stator voltage magnitude

3. TAKAGIE-SUGENOSYSTEM WITH OBSERVER AND CONTROLLER

3.1. A Fuzzy Dynamic Model Takagie-Sugeno

A Takagi-Sugeno fuzzy model for a dynamic system consists of a finite set of fuzzy IF ... THEN rules expressed in the form [11], [12], and [13]:

Model rule i:

If $z_1(t)$ is $F_1^i((z_1(t))$ and … and $z_p(t)$ is $F_p^i((z_1(t))$ THEN

$$\begin{cases} \dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))\ (A_i\ x(t) + B_i\ u(t)) \\ y(t) = \sum_{i=1}^{r} h_i(z(t))\ (C_i\ x(t)\ ) \end{cases} \quad (2)$$

F_1^i (j=1, 2... p) the fuzzy membership function associated with the i^{th} rule and j^{th} parameter component $z_1(t)...z_p(t)$ are known premise variables.

with $w_i(z(t)) = \prod_{j=1}^{p} F_j^i(z_j(t))$; $h_i(z(t)) = \dfrac{w_i(z(t))}{\sum_{i=1}^{r} w_i(z(t))}$; $\sum_{i=1}^{r} h_i(z(t)) = 1$ and $h_i(z(t)) \geq 0$.

3.2. Parallel-Distributed Compensation (PDC)

We use the concept of PDC to design fuzzy controllers to stabilize fuzzy system (2). For each rule, we utilize linear control design techniques.

Model Rule i:

If $z_1(t)$ is $F_1^i((z_1(t))$ and … and $z_p(t)$ is $F_p^i((z_1(t))$ THEN

$$u(t) = -\sum_{i=1}^{r} h_i(z(t)) K_i\, x(t) \quad (3)$$

Replacing (3) in (2), we obtain the following equation for the closed loop system:

$$\dot{x}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} h_i(z(t))\ h_j(z(t))\ (A_i - B_i K_j) x(t) \quad (4)$$

3.3. Fuzzy State Observer

The T-S observer can be designed by using PDC technique [14] to estimate the non-measurable state variables of the T-S model (1). A fuzzy observer is designed by fuzzy IF-THEN rules, the i^{th} observer rule is of the following form [11] [14] [16]:

Observator rule i:

If $z_1(t)$ Is $F_1^i((z_1(t))$ and … and $z_p(t)$ is $F_p^i((z_1(t))$ THEN

$$\begin{cases} \dot{\hat{x}}(t) = A_i \hat{x}(t) + B_i u(t) + L_i(y(t) - \hat{y}(t)) \\ \hat{y}(t) = C_i \hat{x}(t) \end{cases} \quad , For\ i = 1.2..r$$

The fuzzy observer is represented with all the premises variables are measurable [13], the observer output $\hat{y}(t)$ and estimated state vector $\hat{x}(t)$ as follows:

$$\begin{cases} \dot{\hat{x}}(t) = \sum_{i=1}^{r} h_i(z(t))\ [A_i \hat{x}(t) + B_i u(t) + L_i (y(t) - \hat{y}(t))] \\ \hat{y}(t) = \sum_{i=1}^{r} h_i(z(t))\, C_i \hat{x}(t) \end{cases} \quad (5)$$

If the fuzzy observer exists, the controller used is

$$u(t) = -\sum_{i=1}^{r} h_i(z(t)) F_i \, \hat{x}(t) \tag{6}$$

Combining the equations (5), (6) and the estimation error $\varepsilon(t) = x(t) - \hat{x}(t)$, the augmented system is represented as follows:

$$\dot{x}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} h_i(z(t)) \, h_j(z(t)) \, [(A_i - B_i K_j) x(t) - B_i F_j \varepsilon(t)] \tag{7}$$

Using the observer (5), the error dynamics $\dot{\varepsilon}(t)$ can be written as:

$$\dot{\varepsilon}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} h_i(z(t)) \, h_j(z(t)) \, (A_i - L_i C_j) \, \varepsilon(t)] \tag{8}$$

We require that the estimated error $\varepsilon(t)$ converge to zero when $t \to \infty$
The augmented system is given by combining (8) and (7) as follows:

$$\dot{X}_a(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} h_i(z(t)) \, h_j(z(t)) \, G_{ij} \; X_a(t) \tag{9}$$

where

$$X_a(t) = \begin{bmatrix} x \\ e \end{bmatrix} \quad \text{and} \quad G_{ij} = \begin{bmatrix} A_i - B_i K_j & B_i K_j \\ 0 & A_i - L_i C_j \end{bmatrix}$$

4. LMI-BASED DESIGN FOR AUGMENTED SYSTEM

LMI-based design [15] [16], procedures for augmented system containing fuzzy controllers and fuzzy observers are constructed using the PDC and quadratic stability conditions. We propose that the premises variables are measurable. The augmented systems (9) can be represented as follows:

$$\dot{X}_a(t) = \sum_{i=1}^{r} h_i(z(t))^2 \, G_{ii} \; X_a(t) + 2 \sum_{i<j}^{r} h_i(z(t)) \, h_j(z(t)) \frac{G_{ij} + G_{ji}}{2} X_a(t) \tag{10}$$

The equilibrium of the augmented system described by (10) is asymptotically stable in the large if there exists a common positive definite matrix P such as these two conditions [14] [17]:

$$G_{ii}^T P + P G_{ii} < 0 \tag{11}$$

$$\frac{(G_{ij} + G_{ji})^T}{2} \; P + P \frac{(G_{ij} + G_{ji})}{2} < 0, \quad i < j \tag{12}$$

The separation principle holds and the method of linear matrix inequality LMI have been used in order to calculate the gains K_i and L_i. The Conditions (11) and (12) can be transformed into LMIs by introducing matrices X and Y with appropriate dimensions:

For regulator $X = P_c^{-1}$ and $M_i = K_i X$

For observatory $Y = P_o^{-1}$ and $N_i = L_i Y$

where P_c and P_o are the positives matrices of lyaponuv for controller and observatory respectively

5. APPLICATION TAKAGIE-SUGENO IN THE DFIG

We have two non-linear term $z_1(t)$ and $z_2(t)$ of the matrices $A(x(t))$ and $C(x(t))$ as shown in the DFIG system (1):

$$z_1(t) = \omega_r(t) \text{ And } z_2(t) = \frac{1}{I_{rd}}(t)$$

We consider that the minimum and maximum values of $z_1(t)$ and $z_2(t)$ are:

$$z_1 \in [0, \alpha] \text{ And } z_2 \in [-\beta, \beta] \text{ with } \alpha, \beta > 0$$

The membership functions for fuzzy sets of the premise variable $z_1(t)$ and $z_2(t)$ are:

$$F_1^1(z_1(t)) = \frac{z_1(t)}{a},\ F_1^2(z_1(t)) = \frac{a - z_1(t)}{a}, F_2^1(z_2(t)) = \frac{z_2(t) + \beta}{2\beta} \text{ And } F_2^2(z_2(t)) = \frac{\beta - z_2(t)}{2\beta}$$

with $\begin{cases} F_1^1(z_1(t)) + F_1^2(z_1(t)) = 1 \\ F_2^1(z_2(t)) + F_2^2(z_2(t)) = 1 \end{cases}$

The Takagi-Sugeno fuzzy model of the doubly fed induction generator DFIGcan berewritten by introducing 4 sub models are described respectively by the matrices Ai, Ci, i=1,..,4. As follows:

The four state matrix A_i :

$$A_1 = \begin{bmatrix} -8.902 & 917.911 & 0 & 2.937 \\ -917.911 & -8.902 & -2.937 & 0 \\ 0.0003 & -2.937 & -7.948 & 300.624 \\ 0.378 & 0.0003 & -300.624 & -7.948 \end{bmatrix}$$

$$A_2 = \begin{bmatrix} -8.902 & 628.318 & 0 & 0 \\ -628.318 & -8.9023 & 0 & 0 \\ 0.0003 & 0 & -7.948 & 628.318 \\ 0 & 0.0003 & -628.318 & -7.948 \end{bmatrix}$$

with $\begin{cases} A_4 = A_1 \\ A_3 = A_2 \end{cases}$

The four output matrix C_i :

$$C_1 = \begin{bmatrix} 0 & 0 & 0 & -77.6074 \\ 0 & 0 & -249.7804 & 0 \end{bmatrix}$$

$$C_3 = \begin{bmatrix} 0 & 0 & 0 & -77.6074 \\ 0 & 0 & 94.5657 & 0 \end{bmatrix}$$

with $\begin{cases} C_1 = C_2 \\ C_3 = C_4 \end{cases}$

6. SIMULATION RESULTS

The feedback control law has been tested in simulation. The three-phase 1.5Mw Doubly Fed Induction Generator is characterized by the following parameters:

$$L_s = 0.163\,H;\ L_r = 0.021\,H;\ M = 0.055\,H;\ R_s = 1.417\,\Omega;\ R_r = 0.163\,\Omega;\ V_s = 230\,\text{V} \text{ and } p = 2$$

Using the LMI approach and the conditions of quadratic stability for Calculate the feedback and the observer's gains of the fuzzy control law (6) and (3) gives the followings result:

The feedback gains:

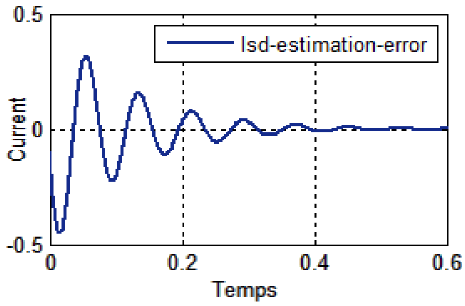
$$L_1 = \begin{bmatrix} -0.0472 & 0.0002 \\ -0.0013 & -0.0021 \\ -1.9331 & -0.0043 \\ 0.0116 & 0.6002 \end{bmatrix} \quad L_2 = \begin{bmatrix} -0.0262 & -0.0003 \\ -0.0025 & 0.0075 \\ -1.9340 & -0.0039 \\ 0.0170 & 0.6004 \end{bmatrix}$$

$$L_3 = \begin{bmatrix} -0.0074 & 0.0000 \\ -0.0018 & -0.0023 \\ 0.7304 & 0.0076 \\ 0.0149 & 0.6003 \end{bmatrix} \quad L_4 = \begin{bmatrix} -0.0283 & -0.0004 \\ -0.0006 & 0.0252 \\ 0.7311 & 0.0093 \\ 0.0095 & 0.6006 \end{bmatrix}$$

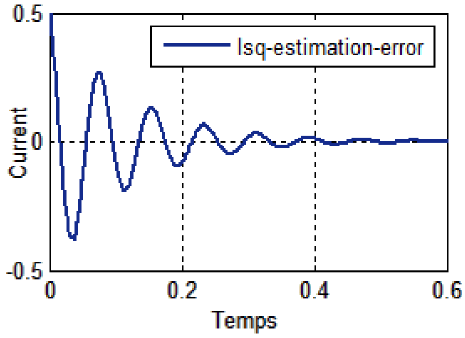
The observer's gains

$$K_1 = \begin{bmatrix} -14.7658 & -2.1031 & -356.5371 & -37454 \\ 2.1983 & -10.1304 & -1.2083 & -361.4230 \\ -51.6382 & 1.0443 & -0.6483 & 19.5403 \\ 0.9556 & -52.0411 & -34.9358 & -15.8320 \end{bmatrix} \quad K_2 = \begin{bmatrix} -14.7658 & -2.1031 & -356.5371 & -37454 \\ 2.1983 & -10.1304 & -1.2083 & -361.4230 \\ -51.6382 & 1.0443 & -0.6483 & 19.5403 \\ 0.9556 & -52.0411 & -34.9358 & -15.8320 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} -16.3700 & -0.0234 & -356.4706 & 0.2630 \\ 1.9334 & -30.4829 & -0.3456 & -360.5793 \\ -51.6400 & -0.9199 & -0.4416 & -0.2073 \\ 1.0000 & -52.8848 & -0.0494 & -13.2108 \end{bmatrix} \quad K_4 = \begin{bmatrix} -13.7564 & -9.2865 & -356.5790 & -4.4856 \\ 3.4307 & -34.7875 & -0.2078 & -360.4008 \\ -51.6370 & 1.9695 & -0.7783 & 19.3441 \\ -1.8380 & -53.0632 & -33.9306 & -12.6562 \end{bmatrix}$$

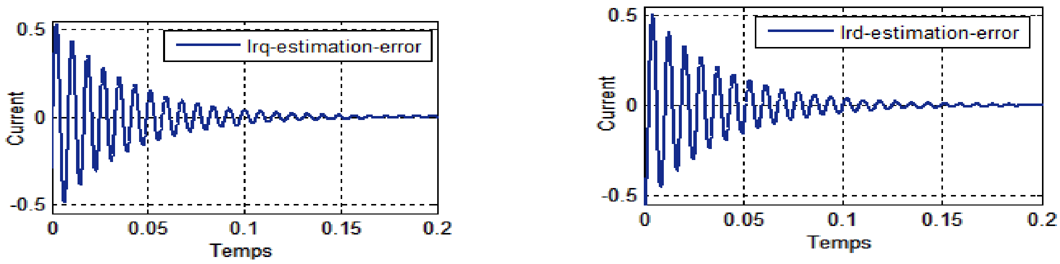


(a)



(b)

Figure 1. Simulation results, (a) I_{sd} estimation error, (b) I_{sq} estimation error



(a) (b)

Figure 2. Simulation results, (a) I_{rd}estimation error, (b) I_{rq} estimation error.

A trajectory of each estimation error of I_{sd} , I_{sq} , I_{rd} and I_{rq} using the observer gains above are shown in Figure 1 and 2, respectively. For this particular trajectory, the true initial states were $(0.3\ \ 0.1\ \ 1\ \ 1)^T$ and the estimated initial states were $(0.2\ \ 0.6\ \ 0.8\ \ 0.8)^T$. As can be seen, the estimation error converges to zero. The type of membership used for linerizedthe two premises variables of the system (1) is “sigmoidal”, the minimum and maximum values of $z_1(t)$ and $z_2(t)$ are respectively are $\alpha = 160$ and $\beta = \frac{1}{6}$. Comparing our result of the current I_{rd} of DFIG 1.5 MW showing in Figure 2-b by another obtained by method "A High-Order Sliding Mode Observer" [18]. It’s noted that the responsetime is more important than one referenced in [18], following Table 1 shows the comparison between the two methods:

Table 1. The comparison

Variable	Fussy observer type Takagie- sugeno method	A High-Order Sliding Observer method
Response time (sec)	t = 0.2	1.5 < t < 2

7. CONCLUSION

In this paper, a fuzzy controller and fuzzy observer based on fuzzy Takagie-sugeno theorem for double fed induction generator (DFIG) is developed. First, we transform the nonlinear model of DFIG into a T-S fuzzy representation, which derived from the sector nonlinearity approach. Then, LMI based design procedures for fuzzy controller have been constructed using the parallel distributed compensation PDC. Next, the stability conditions are expressed in terms of Linear Matrix Inequalities LMI’s. Finally, a design algorithm of fuzzy control system containing fuzzy regulator and fuzzy observer has been constructed. The simulation results are provided to verify the validity of the proposed approach.

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