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$\mathcal{H}_\infty$ Fuzzy Integral Power Control for DFIG Wind Energy System

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***Abstract*—In order to maximize energy capturing from wind energy, controlling the doubly fed induction generator to have optimal power from the wind, generator speed and output electrical power control in wind energy system have a great importance due to the nonlinear behavior of wind velocities. In this paper purposes the design of a control scheme is developed for power control of wind energy system via $\mathcal{H}_\infty$ fuzzy integral controller. Firstly, the nonlinear system is represented in term of a TS fuzzy control design via linear matrix inequality approach to find the optimal controller to have an $\mathcal{H}_\infty$ performance are derived. The proposed control method extract the maximum energy from the wind and overcome the nonlinearity and disturbances problems of wind energy system which give good tracking performance and high efficiency power output of the DFIG.

***Keywords*—$\mathcal{H}_\infty$ fuzzy integral control, linear matrix inequality, wind energy system, doubly fed induction generator (DFIG).

I. Introduction

UNDER the deterioration of the world environment, the increased demand and the decline of petroleum resources, it is imperative to implement the source for a sustainable energy which is clean, cost effective and inexhaustible. Renewable energy can be used for an alternate resource; however, these alternative energies are non-dispatchable [1]. The power output cannot be controlled, thus, an individual country must consider the strategy in utilizing to deliver these energies in significant quantities. Remarkably, the wind power that many countries have conducted their researches has become a potential source for electricity generation. Wind energy can be generated into electrical power by using wind turbine. Nevertheless, the wind fluctuation is a major problem of power generating system that yields uncertainty [2].

In order to overcome this problem, the MPPT technique was used by several authors [3]-[6] to search for maximal power point. To optimal power extraction by MPPT approach, doubly fed induction generator (DFIG) is implemented to produce electricity in wind power system. The DFIG is the conventional three phase wound rotor induction generator fed AC current into both the stator and the rotor windings. Although the DFIG can support the variable speed operation, their efficiency and reliability draw heavily on the applied control approach [7]-[10].

Conventional PID control design is a widely used approach in most basic control systems for the output active and reactive power of wind turbine. However, the way of dealing with the uncertainty of dynamic behavior of DFIG and turbulence wind velocities during operation is very difficult to obtain the proper result by using the common conventional PID control method [11], [12].

Recently, MPPT control based on a fuzzy logic approaches have been introduced to some applications. Fuzzy PID gain scheduling control scheme is a very useful strategy for nonlinear process control [13]. This scheme produces a nonlinear global controller from a series of local controllers tuned at specific operation points. Nevertheless, this controller are not usually appropriate for nonlinear system due to the complicated mathematical models. In [14], an adaptive TSK fuzzy tracking control for maximum energy extraction was considered, which this method can be compensated the nonlinearities of the system. To evaluate stability of controllers, the design of $\mathcal{H}_\infty$ fuzzy for the complex nonlinear systems which can be represented by a Takagi-Sugeno (TS) fuzzy model has been considered by many researchers [15]-[17].

Many control theories have been used $\mathcal{H}_\infty$ control methods to verify stability of controllers to carry out nonlinear systems with guaranteed $\mathcal{H}_\infty$ performance while fuzzy control enables us to utilize qualitative, linguistic variables on the intricate nonlinear system to draw a mathematical model for it. In this TS fuzzy model, local dynamics in different state space parts are represented through local linear systems [18], [19]. For linear system modeling, a single function is used to describe the whole behavior of a system whereas the fuzzy modeling is an outstanding approach that integrated linear sub-models to explain the whole behavior of the systems.

In this paper, the $\mathcal{H}_\infty$ fuzzy integral controller for nonlinear DFIG wind energy system is considered. The combination of $\mathcal{H}_\infty$ control methods with TS fuzzy control can be solved the complex nonlinearity. However, dealing with the behavior of strongly nonlinear of the wind energy system can occur the output error. In order to closely obtain the maximum energy, this paper contributes the TS fuzzy integral technique to regulate the output error to be less or equal to the prescribed value with guaranteed $\mathcal{H}_\infty$ performance. The controller design is formulated by a linear matrix inequality (LMI) and the Lyapunov theory.

This paper is organized as follows. The dynamic model of wind energy system and the nonlinear fuzzy model are presented in Section II. In Section III, the proposed $\mathcal{H}_\infty$ fuzzy integral controller for DFIG wind energy system are explained. The proposed approaches are demonstrated through simulation results in Section IV and finally, the conclusion is given in Section VI.

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II. DFIG Wind Energy System Descriptions

Wind turbines are mechanical devices used in wind energy systems to generate electricity from the kinetic power of the wind. Wind turbines consist of different parts such as rotor blades (turbine), gearbox, doubly fed induction generator (DFIG). In this section, the modeling of the wind turbine and the modeling of DFIG are described.

A. Aerodynamic Model and Mechanical Torque Calculation

The tip speed ratio can be defined as the ratio of the rotor speed and the wind speed:

$$\lambda = R\frac{\omega_m}{V_w}. \tag{1}$$

Under the wind speed, the wind energy is generated by wind turbine can be expressed as follows:

$$P_w = \frac{1}{2}\rho_{air} A_R C_p\left(\lambda,\theta\right) {V_w}^3 \tag{2}$$

where λ is the tip speed ratio, R is the wind turbine rotor radius (m), V_w is the equivalent wind speed (m/s), ω_m is the wind turbine speed (rad/s), A_R is the swept area of the turbine, θ is the pitch angle of the rotor (deg) and C_p is the power coefficient.

The power coefficient can be reasonably approximated by the following equations [20]:

$$C_p(\lambda,\theta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta - 5.0\right)\exp\left(\frac{-12.5}{\lambda_i}\right) \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{(\lambda + 0.08\theta)} - \frac{0.035}{(\theta^3+1)}. \tag{4}$$

The mechanical power and torque of the wind turbine are:

$$P_w = T_m\omega_m \tag{5}$$

$$T_m = 0.5\rho\pi R^3 {V_w}^2 C_p\lambda \tag{6}$$

where T_m is the aerodynamic torque extracted from the wind. Thus, any change in the wind speed and the rotor speed induces the change in the optimal value of the tip speed ratio which brings about to the maximum value of the power coefficient $C_{p_{max}}$. In this way, the optimal torque is affected:

$$T_m = \kappa{\omega_m}^2 \tag{7}$$

where $\kappa = 0.5\rho\pi R^5 \frac{C_{p_{max}}}{{\lambda^2}_{opt}}$ is a factor determined by the wind turbine characteristics [21].

B. Modeling of the DFIG

The doubly fed induction generator is basically the three phase electric machines that are fed AC currents through both the stator and the rotor cores. The application of the Park transformation in the three phase electrical system (a,b,c) frame allows to convert a dynamic model in a dq frame as follows:

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\varphi_{ds} - \omega_s\varphi_{qs} \tag{8}$$

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\varphi_{qs} + \omega_s\varphi_{ds} \tag{9}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\varphi_{dr} - \left(\omega_s - P\omega_r\right)\varphi_{qr} \tag{10}$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\varphi_{qr} + \left(\omega_s - P\omega_r\right)\varphi_{dr}. \tag{11}$$

III. Proposed Control Strategy

A. Nonlinear Model of the Wind Energy System

The wind energy system is shown in Fig. 1. By considering the behavior of the input variables and pursuing the proper fuzzy membership functions and fuzzy rules of the proposed controller, the wind turbine speed control system can closely achieve the maximize operating point with a maximum value to the power coefficient; i.e., increasing output power. For obtaining an acceptable computation effort as well as measurable output quantities, the stator flux linkage, the rotor current and the rotor speed with the disturbance can be expressed by following nonlinear equations

$$\dot{x}(t) = A(x)x(t) + B(x)u(t) + B_w w(t) \tag{12}$$

$$z(t) = C_1(x)x(t) \tag{13}$$

$$y(t) = C_2(x)x(t) \tag{14}$$

where $x(t) = \begin{bmatrix} \varphi_{ds} & \varphi_{qs} & i_{dr} & i_{qr} & \omega_r \end{bmatrix}^T$ is the state vector of the system, $u(t) = \begin{bmatrix} v_{ds} & v_{qs} & v_{dr} & v_{qr} & T_m \end{bmatrix}^T$ is the control input signal, $z(t) = \begin{bmatrix} Q_s & P_s & \omega_r \end{bmatrix}^T$ is the controlled output, $y(t) = \begin{bmatrix} Q_s & P_s & \omega_r \end{bmatrix}^T$ is the measured output, $w(t)$ is the input disturbance and the matrices $A(x), B(x), B_w, C_1(x), C_2(x)$ are suitable matrices of the system,

$$A(x) = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_s & L_m\frac{R_s}{L_s} & 0 & 0 \\ -\omega_s & -\frac{R_s}{L_s} & 0 & L_m\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_r}{\sigma L_r} & -\omega_s + P\omega_r & 0 \\ (\omega_s - P\omega_r)\frac{L_m}{L_s} & 0 & \omega_s - P\omega_r & -\frac{R_r}{\sigma L_r} & 0 \\ -\frac{1}{J_t+GJ_r}\frac{L_m}{L_s}i_{qr} & 0 & 0 & 0 & -\frac{f}{J_t+J_r} \end{bmatrix}$$

$$B(x) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\sigma L_r} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{J_t+G^2 J_r} \end{bmatrix}$$

$$B_w = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0.01 & 0 & 0 \\ 0.01 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$C_1(x) = C_2(x) = \begin{bmatrix} \frac{1}{L_s L_m}D_s & 0 & -\frac{1}{\omega_s L_s}D_s & -\frac{R_s}{\omega_s {L_s}^2}D_s & 0 \\ 0 & 0 & 0 & \frac{L_m}{L_s}D_s & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

with $D_s = \left(\frac{\omega_s\varphi_{ds}}{L_m} - \frac{R_s i_{qr}}{L_s}\right)$.

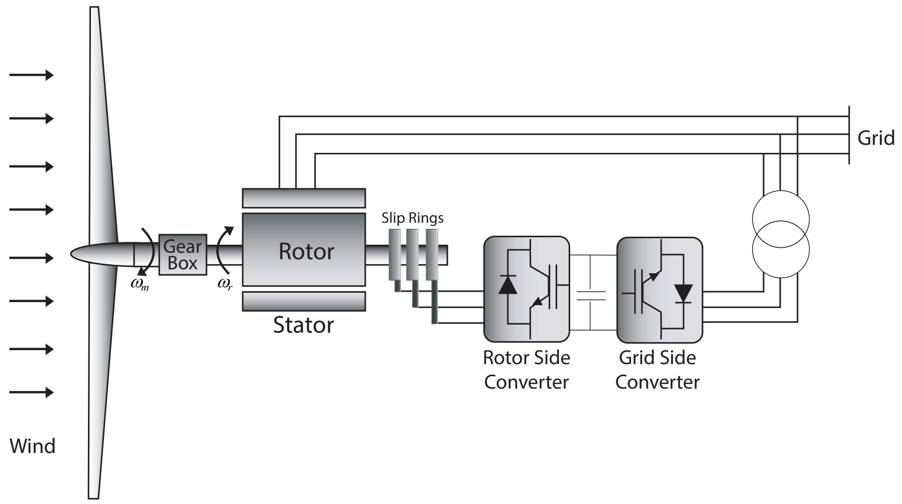

Fig. 1 Configuration of the DFIG wind turbine

B. TS Fuzzy Model

The TS fuzzy model is explained by IF-THEN rules which can be able to approximate the nonlinear system (12) - (14) by combining the linear models via nonlinear membership functions. A TS fuzzy model is examined in the i-th rule as follows:
Plan Rule i:
IF $x_{k1}(t)$ is $M_{1i}(t)$ and...and $x_{kj}(t)$ is $M_{ji}(t)$ THEN

$$\dot{x}(t) = A_i x(t) + B_i u(t) + B_w w(t) \tag{15}$$
$$z(t) = C_{1_i} x(t) \tag{16}$$
$$y(t) = C_{2_i} x(t) \qquad i = 1,\,2,\,3,...,\,r \tag{17}$$

where $M_{ji}(t)$ is the fuzzy sets, r is the number of if-then rules, $x_{k_j}(t)$ is the premise variables, $x(t) \in \Re^n$ is the state vector, $u(t) \in \Re^m$ is the input, $w(t) \in \Re^p$ is the input disturbance which belongs to $\mathcal{L}_2[0,\infty)$, $y(t) \in \Re^\ell$ is the measured output, $z(t) \in \Re^s$ is the controlled output, the matrices A_i, B_i, B_w, C_{1_i}, C_{2_i} are suitable matrices of the system. In this paper, it is assumed that $x_k(t)$ is the vector containing all the individual elements $x_{k_1}(t),...,x_{k_j}(t)$. For any specified state vector and the control input, the TS fuzzy model is inferred as follows.
Let

$$\varpi_i\left(x(t)\right) = \prod_{j=1}^{v} M_{ji}\left(x_k(t)\right)$$

and

$$\mu_i\left(x(t)\right) = \frac{\varpi_i\left(x(t)\right)}{\sum_{i=1}^{r} \varpi_i\left(x(t)\right)}$$

where $M_{ji}\left(x_k(t)\right)$ is the grade of membership of $x_k(t)$ in M_{ji}. It is assumed in this paper that

$$\varpi_i\left(x(t)\right) \geq 0, \quad i = 1,2,...,v;$$
$$\sum_{i=1}^{r} \varpi_i\left(x(t)\right) \geq 0, \quad i = 1,2,...,r;$$

where v are the number of premise variables, for all t. Therefore, for all t. For the simplicity of the notations, we use $\varpi_i = \varpi_i\left(x(t)\right)$ and $\mu_i = \mu_i\left(x(t)\right)$. Thus, we can generalize that the TS fuzzy models as the weighted average of the following forms:

$$\dot{x}(t) = \sum_{i=1}^{r} \mu_i\left(A_i x(t) + B_i u(t)\right) + B_w w(t) \tag{18}$$
$$z(t) = \sum_{i=1}^{r} \mu_i\left(C_{1_i} x(t)\right) \tag{19}$$
$$y(t) = \sum_{i=1}^{r} \mu_i\left(C_{2_i} x(t)\right) \qquad i = 1,2,3,..,r \tag{20}$$

C. $\mathcal{H}_\infty$ Fuzzy Integral Controller

This section begins with considering the problem of designing an $\mathcal{H}_\infty$ fuzzy integral controller which guarantees the $\mathcal{L}_2$ gain from the exogenous input noise to the regulated output less than or equal to some prescribed value. Here, an LMI approach will be utilized to derive a fuzzy controller which stabilizes the system (15)-(17). Suppose there exists a fuzzy integral controller of the term:
Controller Rule j:
IF $x_{k_1}(t)$ is $M_{1i}(t)$ and...and $x_{k_j}(t)$ is $M_{ji}(t)$ THEN

$$u(t) = -K_j x(t) + K_{Ij} q(t), \forall j = 1,\,2,\,3,...,\,r. \tag{21}$$

where $x(t)$ is state vector and $q(t)$ is state integral vector. K_j and K_{I_j} are the controller gain of an $\mathcal{H}_\infty$ fuzzy state feedback and state integral feedback controller, respectively. Finally, the fuzzy controller can be inferred as

$$u(t) = \sum_{j=1}^{r} \mu_j\left(-K_j x(t) + K_{Ij} q(t)\right), \forall j = 1,\,2,\,3,...,\,r. \tag{22}$$

From the system (15)-(17) with the fuzzy controller (22) can be rewritten by

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\left(\tilde{A}_{ij}\tilde{x}(t)\right) + \tilde{B}_w\tilde{w}(t) \tag{23}$$

$$\tilde{z}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\left(\tilde{C}_{1_i}\tilde{x}(t)\right) \tag{24}$$

$$\tilde{y}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r}\mu_i\mu_j\left(\tilde{C}_{2_i}\tilde{x}(t)\right) \tag{25}$$

where

$$\tilde{A}_{ij} = \begin{bmatrix} A_i - B_iK_j & B_iK_{I_j} \\ C_{2_i} & 0 \end{bmatrix}, \tilde{B}_w = \begin{bmatrix} B_w & 0 \end{bmatrix},$$

$$\tilde{C}_{1_i} = \begin{bmatrix} C_1 & 0 \\ 0 & 0 \end{bmatrix}, \tilde{C}_{2_i} = \begin{bmatrix} C_2 & 0 \end{bmatrix},$$

$$\tilde{x}(t) = \begin{bmatrix} x(t) \\ q(t) \end{bmatrix}, \tilde{w}(t) = \begin{bmatrix} w(t) \\ 0 \end{bmatrix}.$$

An LMI approach will be applied to derive a fuzzy controller which stabilizes the system (23)-(25) and guarantees the disturbance rejection of level $\gamma > 0$, immediately. Firstly to design fuzzy integral controller, the following requirement are satisfied

(a) The closed loop system is asymptotically stable when $\tilde{w}(t) = 0$.

(b) Under zero initial condition, the system (24) satisfies $\|\tilde{z}\|_2 \le \gamma\|\tilde{w}\|_2$ for any non-zero $\tilde{w}(t) \in \mathcal{L}_2[0, +\infty)$, where $\gamma > 0$ is a prescribed constant.

Next, let us recall the following definition.

Definition 1. Suppose γ is a given positive real number: A system of the form (23) and (24) is said to $\mathcal{L}_2$-gain less than or equal to γ if

$$\int_0^{T_f} \tilde{z}^T(t)\tilde{z}(t)\,dt \le \gamma^2\left[\int_0^{T_f} \tilde{w}^T(t)\tilde{w}(t)\right]dt. \tag{26}$$

for all $T_f \ge 0$ and $\tilde{w}(t) \in \mathcal{L}_2[0, T_f]$.

Note that for the symmetric block matrices, we use (*) as an ellipsis for terms that are induced by symmetry.

So the following results deal with the system (23)-(25).

Theorem 1. *Consider the system (23)-(25). Given a prescribed $\mathcal{H}_\infty$ performance $\gamma > 0$ and the inequality (26) holds if there exist a matrix $P_1 = P_1{}^T, P_2 = P_2{}^T$ and matrices $Y_j, Y_{Ij}, j = 1, 2, ..., r$, satisfying the following linear matrix inequalities:*

$$P = \begin{pmatrix} P_1 & P_2 \\ P_2 & P_1 \end{pmatrix} > 0 \tag{27}$$

$$\begin{pmatrix} \Psi_{ij}^{11} & (*)^T & (*)^T & (*)^T \\ \Psi_{ij}^{21} & \Psi_{ij}^{22} & (*)^T & (*)^T \\ B_w{}^T & 0 & -\gamma^2 I & (*)^T \\ C_{1_i}P_1 & C_{1_i}P_2 & 0 & -I \end{pmatrix} < 0, \tag{28}$$

where

$$\Psi_{ij}^{11} = A_iP_1 + P_1A_i{}^T - Y_j{}^TB^T - BY_j + BY_{Ij} + Y_{Ij}^TB^T,$$
$$\Psi_{ij}^{21} = P_2A_i{}^T - Y_j{}^TB^T + Y_{Ij}^TB^T - C_{2i}P_1,$$
$$\Psi_{ij}^{22} = -C_{2i}P_2 - P_2C_{2i}^T.$$

Furthermore, the suitable choice of the fuzzy controller is

$$u(t) = \sum_{j=1}^{r}\mu_j\left(-K_jx(t) + K_{Ij}q(t)\right) \tag{29}$$

where $K_j = Y_jP_1{}^{-1}$ and $K_{Ij} = Y_{Ij}P_2{}^{-1}$.

Proof: The detail of the proof is omitted for brevity.

IV. Simulation Results

The system from (12)-(14) can be described by the following state equations:

$$\dot{x}_1(t) = -\frac{R_s}{L_s}x_1(t) + \omega_sx_2(t) + L_m\frac{R_s}{L_s}x_3(t) \tag{30}$$

$$\dot{x}_2(t) = -\omega_sx_1(t) + -\frac{R_s}{L_s}x_2(t) + L_m\frac{R_s}{L_s}x_4(t) \tag{31}$$

$$\dot{x}_3(t) = -\frac{R_r}{\sigma L_r}x_3(t) - (\omega_s + Px_5(t))x_4(t) \tag{32}$$

$$\begin{aligned}\dot{x}_4(t) =& (\omega_s - Px_5(t))\frac{L_m}{L_s}x_1(t) \\ &+ (\omega_s - Px_5(t))x_3(t) - \frac{R_r}{\sigma L_r}x_4(t)\end{aligned} \tag{33}$$

$$\dot{x}_5(t) = -\frac{1}{J_t + GJ_r}\frac{L_m}{L_s}x_1(t)x_4(t) - \frac{f}{J_t + J_r}x_5(t) \tag{34}$$

$$\begin{aligned}z_1(t) =& \frac{1}{L_sL_m}\left(\frac{\omega_sx_1(t)}{L_m} - \frac{R_sx_4(t)}{L_s}\right)x_1(t) \\ &- \frac{1}{\omega_sL_s}\left(\frac{\omega_sx_1(t)}{L_m} - \frac{R_sx_4(t)}{L_s}\right)x_3(t) \\ &- \frac{1}{\omega_sL_s}\left(\frac{\omega_sx_1(t)}{L_m} - \frac{R_sx_4(t)}{L_s}\right)x_4(t)\end{aligned} \tag{35}$$

$$z_2(t) = \frac{L_m}{L_s}\left(\frac{\omega_sx_1(t)}{L_m} - \frac{R_sx_4(t)}{L_s}\right)x_4(t) \tag{36}$$

$$z_3(t) = x_5(t) \tag{37}$$

where
$x_1(t) = \varphi_{ds},\ x_2(t) = \varphi_{qs},\ x_3(t) = i_{dr},\ x_4(t) = i_{qr},\ x_5(t) = \omega_r$ and $z_1(t) = Q_s, z_2(t) = P_s, z_3(t) = \omega_r$. It is found that the flux magnetic, the currents and the speed in dynamic model of DFIG from (30) and (37) are highly nonlinear. Simultaneously, it is also possible in changing the wind speed. Thus, the nonlinearity including the disturbance wind have to be taken into account. The nonlinear system plant can be approximated by TS fuzzy rules. Let choose the membership functions of the fuzzy sets as shown in Fig. 2 The membership function can be written as

$$n_1(x_1(t)) = \frac{-x_1(t) + E_1}{E_2 - E_1} \text{and } N_1(x_1(t)) = \frac{-x_1(t) + E_2}{E_2 - E_1}$$

$$n_2(x_4(t)) = \frac{-x_4(t) + F_1}{F_2 - F_1} \text{and } N_2(x_4(t)) = \frac{-x_4(t) + F_2}{F_2 - F_1}$$

$$n_3(x_5(t)) = \frac{-x_5(t) + G_1}{G_2 - G_1} \text{and } N_3(x_5(t)) = \frac{-x_5(t) + G_2}{G_2 - G_1}$$

The dynamic model of the wind energy system is represented by TS fuzzy model (15)-(17), which is composed of 8 rules. Thus, the local system matrices A_i, B_i, C_{1_i} and C_{2_i} as the following below. The parameter v_{ji} corresponding with each rule is addressed in Table I. The fuzzy premise variables

x_{kj} depend not only the converter states, but also the lower and upper bound parameter (n_j, N_j) that can be obtained from specification DFIG wind energy system.

TABLE I
TS FUZZY RULES

Rules	Fuzzy-Sets			Then-Part		
i	M_{1i}	M_{2i}	M_{3i}	v_{1i}	v_{2i}	v_{3i}
1	E_1	F_1	G_1	n_1	n_2	n_3
2	E_1	F_1	G_2	n_1	n_2	N_3
3	E_1	F_2	G_1	n_1	N_2	n_3
4	E_1	F_2	G_2	n_1	N_2	N_3
5	E_2	F_1	G_1	N_1	n_2	n_3
6	E_2	F_1	G_2	N_1	n_2	N_3
7	E_2	F_2	G_1	N_1	N_2	n_3
8	E_2	F_2	G_2	N_1	N_2	N_3

The local system matrices are shown as follows:

$$A_1 = A_5 = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_s & L_m\frac{R_s}{L_s} & 0 & 0 \\ -\omega_s & -\frac{R_s}{L_s} & 0 & L_m\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_r}{\sigma L_r} & \omega_s - n_3 & 0 \\ (\omega_s - n_3)\frac{L_m}{L_s} & 0 & -\omega_s + n_3 & -\frac{R_r}{\sigma L_r} & 0 \\ -\frac{1}{J_t+GJ_r}\frac{L_m}{L_s}n_2 & 0 & 0 & 0 & -\frac{f}{J_t+J_r} \end{bmatrix},$$

$$A_2 = A_6 = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_s & L_m\frac{R_s}{L_s} & 0 & 0 \\ -\omega_s & -\frac{R_s}{L_s} & 0 & L_m\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_r}{\sigma L_r} & \omega_s - n_3 & 0 \\ (\omega_s - n_3)\frac{L_m}{L_s} & 0 & -\omega_s + n_3 & -\frac{R_r}{\sigma L_r} & 0 \\ -\frac{1}{J_t+GJ_r}\frac{L_m}{L_s}N_2 & 0 & 0 & 0 & -\frac{f}{J_t+J_r} \end{bmatrix},$$

$$A_3 = A_7 = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_s & L_m\frac{R_s}{L_s} & 0 & 0 \\ -\omega_s & -\frac{R_s}{L_s} & 0 & L_m\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_r}{\sigma L_r} & \omega_s - N_3 & 0 \\ (\omega_s - N_3)\frac{L_m}{L_s} & 0 & -\omega_s + N_3 & -\frac{R_r}{\sigma L_r} & 0 \\ -\frac{1}{J_t+GJ_r}\frac{L_m}{L_s}n_2 & 0 & 0 & 0 & -\frac{f}{J_t+J_r} \end{bmatrix},$$

$$A_4 = A_8 = \begin{bmatrix} -\frac{R_s}{L_s} & \omega_s & L_m\frac{R_s}{L_s} & 0 & 0 \\ -\omega_s & -\frac{R_s}{L_s} & 0 & L_m\frac{R_s}{L_s} & 0 \\ 0 & 0 & -\frac{R_r}{\sigma L_r} & \omega_s - N_3 & 0 \\ (\omega_s - N_3)\frac{L_m}{L_s} & 0 & -\omega_s + N_3 & -\frac{R_r}{\sigma L_r} & 0 \\ -\frac{1}{J_t+GJ_r}\frac{L_m}{L_s}N_2 & 0 & 0 & 0 & -\frac{f}{J_t+J_r} \end{bmatrix},$$

$$B_1, B_2, \ldots, B_8 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\sigma L_r} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma L_r} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{J_t+G^2J_r} \end{bmatrix},$$

$$B_w = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0.01 & 0 & 0 \\ 0.01 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$C_{1_1} = C_{12} = \begin{bmatrix} \frac{1}{L_sL_m}D_{22} & 0 & -\frac{1}{\omega_sL_s}D_{22} & -\frac{R_s}{\omega_s{L_s}^2}D_{22} & 0 \\ 0 & 0 & 0 & \frac{L_m}{L_s}D_{22} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$C_{13} = C_{14} = \begin{bmatrix} \frac{1}{L_sL_m}D_{23} & 0 & -\frac{1}{\omega_sL_s}D_{23} & -\frac{R_s}{\omega_s{L_s}^2}D_{23} & 0 \\ 0 & 0 & 0 & \frac{L_m}{L_s}D_{23} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$C_{15} = C_{16} = \begin{bmatrix} \frac{1}{L_sL_m}D_{24} & 0 & -\frac{1}{\omega_sL_s}D_{24} & -\frac{R_s}{\omega_s{L_s}^2}D_{24} & 0 \\ 0 & 0 & 0 & \frac{L_m}{L_s}D_{24} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$C_{17} = C_{18} = \begin{bmatrix} \frac{1}{L_sL_m}D_{25} & 0 & -\frac{1}{\omega_sL_s}D_{25} & -\frac{R_s}{\omega_s{L_s}^2}D_{25} & 0 \\ 0 & 0 & 0 & \frac{L_m}{L_s}D_{25} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

TABLE II
PARAMETER OF DFIG

Symbol	Value
Rated Power	1.5 Mw
Stator resistance	0.012 Ω
Rotor resistance	0.021 Ω
Pole pairs	3
Stator inductance	0.0137 H
Rotor inductance	0.0136 H
Mutual inductance	0.0135 H
Friction coefficient	0.0024 $N.M.s^{-1}$
Moment of inertia	1000 $kg.m^2$
Slip	30
Angular speed	157 rad/sec

TABLE III
PARAMETER OF TURBINE

Symbol	Value
Radius of wind	35.25 m
Gain multiplier	90
Air density	1.225 kg/m^3

with

$$D_{22} = \left(\frac{\omega_s n_1}{L_m} - \frac{R_s n_2}{L_s}\right), D_{23} = \left(\frac{\omega_s n_1}{L_m} - \frac{R_s N_2}{L_s}\right),$$

$$D_{24} = \left(\frac{\omega_s N_1}{L_m} - \frac{R_s n_2}{L_s}\right), D_{25} = \left(\frac{\omega_s N_1}{L_m} - \frac{R_s N_2}{L_s}\right),$$

$$D_{26} = \frac{1}{L_sL_m}\left(\frac{\omega_s\varphi_{ds}}{L_m} - \frac{0.1R_si_{qr}}{L_s}\right),$$

$$D_{27} = -\frac{1}{\omega_sL_s}\left(\frac{\omega_s\varphi_{ds}}{L_m} - \frac{0.1R_si_{qr}}{L_s}\right),$$

$$D_{28} = -\frac{0.1R_s}{\omega_s{L_s}^2}\left(\frac{\omega_s\varphi_{ds}}{L_m} - \frac{0.1R_si_{qr}}{L_s}\right),$$

$$D_{29} = \frac{L_m}{L_s}\left(\frac{\omega_s\varphi_{ds}}{L_m} - \frac{0.1R_si_{qr}}{L_s}\right).$$

In order to examine the performance of the proposed control strategies under different situations, the changing in the wind speeds from 5 m/s to 11 m/s as input [22] is assumed as shown in Fig. 3. Figs. 4-6 show the performance of the proposed $\mathcal{H}_\infty$ fuzzy integral controller (HFI) as compared to PID controller.

V. CONCLUSION

This paper has presented the $\mathcal{H}_\infty$ fuzzy integral controller for the DFIG wind energy system. We have developed $\mathcal{H}_\infty$ TS fuzzy control system in conjunction with a control strategy whose design procedures are satisfied the tracking of the power. Analysis performance and simulation show that the proposed controller can overcome nonlinearities and the disturbances of the dynamic behavior of wind energy system. Also, it can simultaneously achieve the steady-state behavior of the system and satisfactory power tracking, including a stability criterion which guarantees the stability of the nonlinear TS fuzzy control system. The obtained results show that the proposed controller provides a better dynamic performance and high-efficiency control system for the DFIG wind energy system.

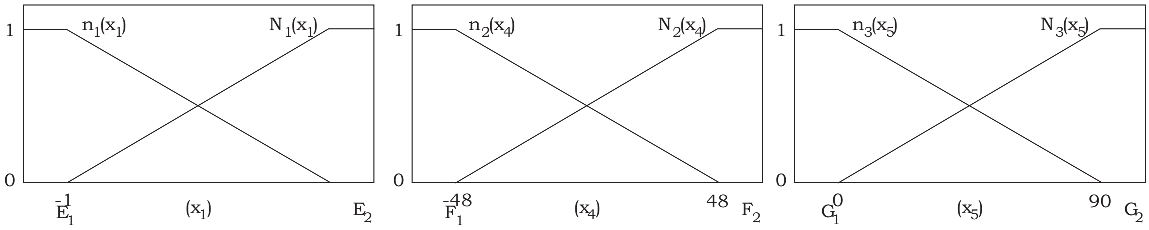

Fig. 2 Membership functions for the two fuzzy set

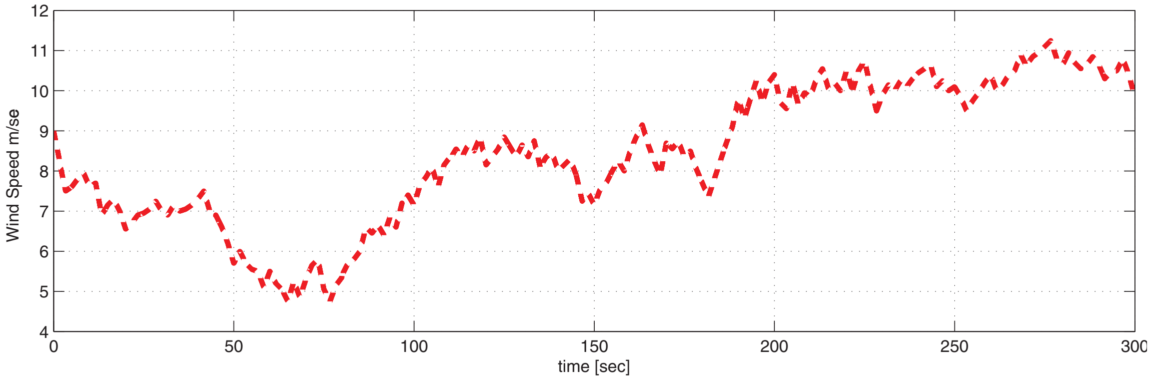

Fig. 3 Wind speed profile

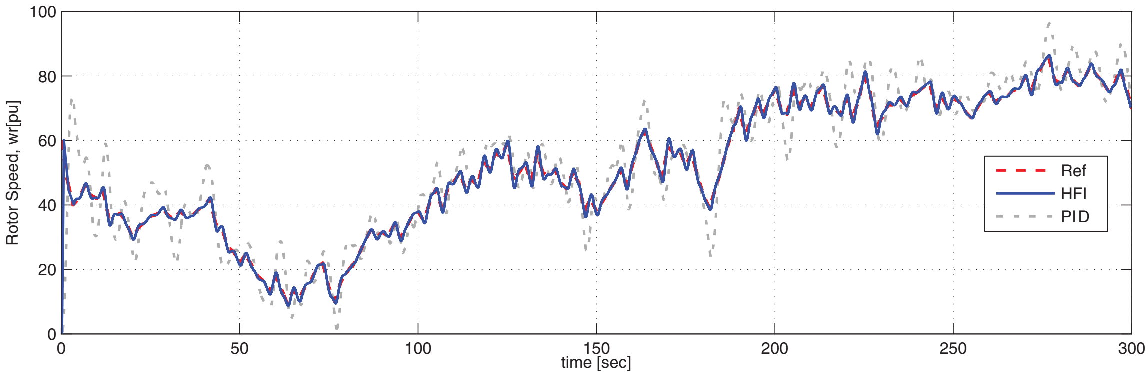

Fig. 4 Rotor speed variations

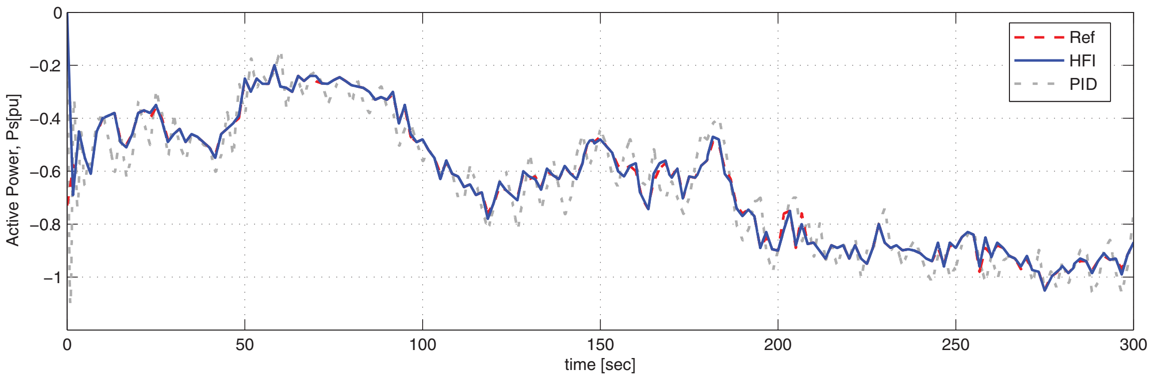

Fig. 5 Stator active power variations

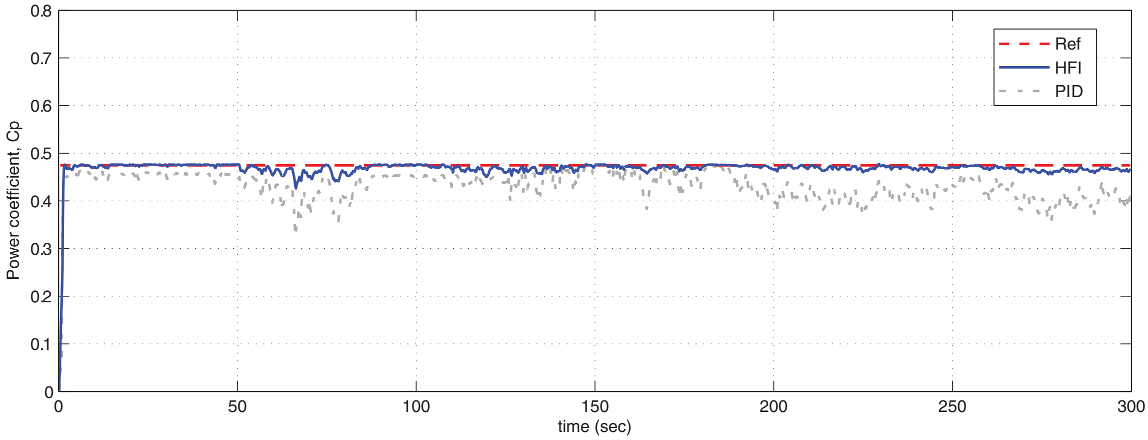

Fig. 6 Power coefficient variations

References

[1] D. Cooper, "Website of the Johnson Cornell University, Johnson′s Energy Club Competes in Renewable Energy, https://www.johnson.cornell.edu," 2012.

[2] Y. Guo, S. Hosseini, C. Tang, J. Jiang, and R. Ramakumar, "An approximate wind turbine control system model for wind farm power control," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 1, pp. 262–274, 2013.

[3] L. Mihet-Popa, F. Blaabjerg, and I. Boldea, "Network power flux control of a wind generator," *IEEE Transactions on Industry Applications*, vol. 40, no. 1, pp. 3–10, 2004.

[4] D. Aouzellag, K. Ghedamsi, and E. Berkouk, "Network power flux control of a wind generator," *Journal of Renewable Energy*, vol. 34, no. 3, pp. 615–622, 2009.

[5] J. Ben Alaya, A. Khedher, and M. Mimouni, "DTC, DPC and nonlinear vector control strategies applied to DFIG operated at variable speed," *WSEAS transaction on environment and development*, vol. 6, no. 11, pp. 744–753, 2010.

[6] M. Ma, H. Chen, X. Liu, and F. Allgöwer, "Moving horizon h_∞ control of variable speed wind turbines with actuator saturation," *Journal of IET Renewable Power Generation*, vol. 8, no. 5, pp. 498–508, 2014.

[7] S. Muller, M. Deicke, and R. D. Doncker, "Doubly fed induction generator systems for wind turbines," *IEEE Industry Applications Magazine*, vol. 8, no. 3, pp. 26–33, 2002.

[8] A. Peterson, "Analysis, modeling and control of doubly-fed induction generators for wind turbines," Ph.D. dissertation, Chalmers University of Technology, Goteborg, Sweden, 2005.

[9] A. Junyent-Ferré, O. Gomis-Bellmunt, A. Sumper, M. Sala, and M. Mata, "Modeling and control of the doubly fed induction generator wind turbine," *International Journal of Simulation Modelling Practice and Theory*, vol. 18, no. 9, pp. 1365–1381, 2010, dOI: 10.1016/j.simpat.2010.05.018.

[10] S. Kovendan and P. Sebastian, "High efficiency control for a wind energy conversion system with induction generator," *International Journal of Engineering Research & Technology (IJERT)*, vol. 3, no. 12, pp. 262–265, 2014.

[11] W. Dinghui, L. Yiyang, J. Zhicheng, and S. Yanxia, "Self-adaptive PID optimal control of wind energy conversion system," in *Proceedings of Control and Decision Conference, CCDC 2014, Changsha, China*, 2014, pp. 13–17.

[12] H. Nguyen and S. Naidu, "Advanced control strategies for wind energy systems," in *Power Systems Conference and Exposition, PSCE 2011, Phoenix, Arizona*, 2011, pp. 1–8.

[13] T. Blanchett, G. Kember, and R. Dubay, "PID gain scheduling using fuzzy logic," *ISA Transaction*, vol. 39, no. 3, pp. 317–325, 2000.

[14] V. Galdi, A. Piccolo, and P. Siano, "Designing an adaptive fuzzy controller for maximum wind energy extraction," *IEEE Transactions on Energy Conversion*, vol. 23, no. 2, pp. 559–569, 2008.

[15] W. Assawinchaichote, "Further results on robust fuzzy dynamic systems with LMI D-stability constraints," *International Journal of Applied Mathematics and Computer Science*, vol. 24, no. 4, pp. 785–794, 2014.

[16] P. Vadive, R. Sakthivel, K. Mathiyalagan, and P. Thangaraj, "Robust stabilisation of non-linear uncertain Takagi-Sugeno fuzzy system by H_∞ control," *International Journal of IET Control Theory & Applications*, vol. 6, no. 16, pp. 2556–2566, 2012.

[17] M. Aliyu, *Nonlinear H_∞-Control, Hamiltonian Systems, and Hamilton-Jacobi Equations*. Boca Raton, FL: CRC Press, 2011.

[18] W. Assawinchaichote, "A non-fragile H_∞ output feedback controller for uncertain fuzzy dynamical systems with multiple time-scales," *International Journal of Computers, Communications & Control*, vol. 78, no. 1, pp. 514–531, 2012.

[19] S. Bououden, M. Chadli, S. Filali, and A. Hajjaji, "Fuzzy model based multivariable predictive control of a variable speed wind turbine: LMI approach," *International Journal of Renewable Energy Research*, vol. 37, no. 1, pp. 434–439, 2012.

[20] M. Ragheb and A. Ragheb, "Wind turbines theory-The betz equation and optimal rotor tip speed ratio," in *Fundamental and Advanced Topics in Wind Power*, C. R., Ed. Intech, 2011.

[21] M. Cheng and Y. Zhu, "The state of the art of wind energy conversion systems and technologies: A review," *Journal of Energy Conversion and Management*, vol. 88, no. 2014, pp. 332–347, 2014.

[22] M. Hand and M. Balas, "Systematic controller design methodology for variable-speed wind turbines," National Renewable Energy Laboratory (NREL), Golden, Colorado, USA, Tech. Rep. NREL/TP-500-29415, 2002.