Chapter 13
Feedback T-S Fuzzy Controller in Finite Frequency for Wind Turbine

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Abstract This chapter investigates a feedback finite frequency Takagi-Sugeno (T-S) fuzzy controller synthesis for a variable speed wind turbine. The proposed control design is based on both the T-S fuzzy modeling and the finite frequency approach. The T-S fuzzy model is used to deal with a nonlinear behavior of wind turbine system, and the finite frequency approach allows the command in a specific domain of frequency. The control constraints are given in terms of a set of LMIs which can be efficiently solved using existing numerical tools. In order to illustrate the performance of the proposed control algorithm, numerical simulations are performed using Matlab software.

Keywords Finite frequency · Takagi-Sugeno fuzzy · Variable wind speed · Wind turbine

Notations

- The superscript ^{T} stands for matrix transposition.
- I denotes an identity matrix with appropriate dimension.
- "diag" stands for block diagonal matrix.
- "tr(A)" denotes the trace of matrix A.
- $A > 0$ (resp. $A < 0$) mean that matrix A is positive definite (resp. negative definite).

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13.1 Introduction

Global warming effect and fossil fuel pollution has caused great damage in the earth's environment, and has become a serious problem for people. As renewable energies sources are environment-friendly and sustainable, wind and solar energy have attracted increased attention during the last years. In light of this, improving the efficiency of wind turbine becomes an important research topic. Furthermore, control techniques have a major effect on wind energy conversion systems, and remain a key factor in maximizing the extracted energy from the wind and reducing the stresses caused by aerodynamic loads. To achieve satisfactory wind turbine performances, Takagi-Sugeno (T-S) fuzzy has received increasing attention during the past decades from many researchers. There are a lot of research results on the T-S fuzzy in the literature, such that, in Lasheen et al. (2016) the authors proposed a new algorithm of fuzzy predictive for collective pitch control of large wind turbines. A Neuro-fuzzy inertia controller has been addressed in Hafiz et al. (2016) to control parameter selection which ensures the optimal use of available Kinetic Energy reserve. Neural network is also coupled in Medjber et al. (2016) with fuzzy logic controller to monitor maximum power for wind energy conversion system. A new kind of T-S fuzzy control technique used for capturing maximum wind energy under multi-operating condition has been discussed in An et al. (2015). A data driven design methodology able to generate a Takagi-Sugeno fuzzy model for maximum energy extraction from variable speed wind turbines has been examined in Galdi et al. (2008). A sensorless wind energy conversion system maximum wind power point tracking using Takagi-Sugeno fuzzy cerebellar model articulation control to achieve maximum power transfer under various wind speeds without actual measurement of the wind velocity has been proofed in Liu et al. (2015). Note that all those control techniques and other given in this area can improve the wind turbine robustness against the random wind speed and maximize the extracted wind power. However, when the external disturbance belong to a certain frequency range which is known beforehand, it is not favorable to control the system in the full frequency domain, because this may introduce some conservatism and poor system performance. Recently, the control synthesis in a finite frequency domain has been addressed, and there have appeared many results in this domain (Berrada et al. 2017; Chen et al. 2010; El-Amrani et al. 2016; Li et al. 2015; Zhang et al. 2014).

In light of the above, we propose feedback Finite Frequency Takagi-Sugeno Fuzzy (FFTSF) to control wind turbine under various wind conditions. We first represent the wind turbine, which is a two mass model, as a highly nonlinear dynamical model. To carry out the FFTSF design, we then rewrite the wind turbine model as a T-S fuzzy representation. Next the proposed feedback control is established by the finite frequency approach to command the wind turbine system in a specific band of frequency. Based on the generalized Kalman-Yakubovich-Popov (GKYP) lemma (Iwasaki et al. 2005), the controller constraints are given in terms of linear matrix inequalities (LMIs) which can be efficiently solved numerically. The control technique acts on generator in order to apply the electromagnetic torque reference and on the pitch actuator in order to control the pitch angle of the blades according to wind speed value, calculated from the measurements of the rotational speed of the shaft at the generator side, and of the speed of the wind by an accelerometer located at the top of the tower.

The paper is organized as follows. In Sect. 13.2, we will describe the model of the wind turbine system. In the next section, we will rewrite the obtained model as a T-S Fuzzy representation, and the controller will be designed by the Finite frequency technique. In Sect. 13.4, the performances of the proposed control strategy will be shown carried out by simulation results. Finally, some conclusions are given in Sect. 13.5.

13.2 Wind Turbine Model

The wind turbine is established by combining a model of a mechanical structure represent the drive trains and nonlinear model representing the blades aerodynamic properties. The mathematics model of the wind turbine is clearly described in Bououden et al. (2012), which is represented by the following state representation:

$$\dot{x}_0 = \begin{bmatrix} 0 & 1 & -1 \\ -\frac{K_s}{J_r} & -\frac{B_s}{J_r} & \frac{B_s}{J_r} \\ -\frac{K_s}{J_g} & -\frac{B_s}{J_g} & \frac{B_s}{J_g} \end{bmatrix} x_0 + \begin{bmatrix} 0 & 0 \\ \frac{1}{J_r} & 0 \\ 0 & \frac{1}{J_g} \end{bmatrix} \begin{bmatrix} T_a \\ T_g \end{bmatrix} \tag{13.1}$$

where $x_0 = [\theta_s, \omega_r, \omega_g]^T$, θ_s, ω_r, ω_g, B_s and K_s are the torsion angle, the rotor speed, the generator speed, the damping of the transmission and the stiffness of the transmission, respectively. J_r and J_g are the inertia of the rotor and the generator, respectively. T_g is the generator torque which is a nonlinear function depends to the generator speed and the zero-torque speed ω_z.

$$T_g = B_s(\omega_g - \omega_z) \tag{13.2}$$

T_a is the aerodynamic torque which is expressed as:

$$T_a = \frac{1}{2}\pi\,\rho\,R^3\,C_q(\lambda, \beta)\,v^2 \tag{13.3}$$

with $C_q(\lambda, \beta) = \frac{1}{\lambda}C_p(\lambda, \beta)$ is the torque coefficient. $C_p(\lambda, \beta)$ is the power coefficient that is a nonlinear function of the pitch angle β and the reduced speed λ. So, T_a is a nonlinear function depends to wind speed, rotor speed and pitch angle, can be linearized by the following expression:

$$T_a = T_{av}v + T_{a\beta}\beta + T_{a\lambda}\lambda \tag{13.4}$$

where T_{av}, $T_{a\beta}$ and $T_{a\lambda}$ are individual partial derivatives of the aerodynamic torque T_{av} for rotor speed, wind speed and pitch angle at the operating point, respectively.

The actuator describes the dynamic behavior between the desired pitch β_d and the actuation of this desired pitch β is modeled as:

$$\dot{\beta} = \frac{1}{\tau}(\beta_d - \beta) \tag{13.5}$$

where τ is a time constant.

Finally, according to the Eqs. (13.1), (13.2), (13.3), (13.4), and (13.5), and replacing T_a and T_g with their approximated expressions, the dynamic model of the wind turbine can be represented as:

$$\begin{aligned} \dot{x} &= Ax + Bu + Ev \\ y &= Cx \end{aligned} \tag{13.6}$$

where $x = [\theta_s, \omega_r, \omega_g, \beta]^T$, $u = [\beta_d, \omega_z]^T$, $y = \omega_g$ and matrices A, B and E are given by:

$$A = \begin{bmatrix} 0 & 1 & -1 & 0 \\ -\frac{K_s}{J_r} & -\frac{B_s}{J_r} & \frac{B_s}{J_r} & \frac{T_{a\beta}}{J_r} \\ -\frac{K_s}{J_g} & -\frac{B_s + B_g}{J_g} & \frac{B_s}{J_g} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau} \end{bmatrix}, \; B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & \frac{B_g}{J_g} \\ \frac{1}{\tau} & 0 \end{bmatrix}, \; E = \begin{bmatrix} 0 \\ \frac{T_{av}}{J_r} \\ 0 \\ 0 \end{bmatrix} \tag{13.7}$$

Let $\xi = x - x_{ref}$ so $x = x_{ref} + \xi$ and then $\dot{x} = \dot{x}_{ref} + \dot{\xi}$.

The system dynamic model (13.6) becomes:

$$\begin{aligned} \dot{\xi} &= A\xi + Bu + Dw \\ \chi &= C\xi \end{aligned} \tag{13.8}$$

where $w = [x_{ref}, \dot{x}_{ref}, v]^T$ and $D = [A, -I, E]$ with x_{ref} is the reference signal.

13.3 Finite Frequency T-S Fuzzy Control

13.3.1 T-S Fuzzy Representation

The best possible performance from the highly nonlinear system (13.6) can be obtained using T-S fuzzy model. The wind turbine variables are assumed varying in the operating range $v_1 \leq v \leq v_2$, $\beta_1 \leq \beta \leq \beta_2$. Consequently, The T-S fuzzy model of system (13.6) is established by the following rules IF-THEN for $i = 1, \ldots, 4$ and $l, k = 1, 2$:

$$\text{If}(\beta \text{is} M_l)\text{And}(v \text{is} N_k)\text{Then} \begin{cases} \dot{\xi} = A_i \xi + B_i u + D_i w \\ \chi = C_i \xi \end{cases} \tag{13.9}$$

Membership functions are given by:

$$h_1 = M_1(\beta)N_1(v),\ h_2 = M_1(\beta)N_2(v),\ h_3 = M_2(\beta)N_1(v),\ h_4 = M_2(\beta)N_2(v)$$

with:

$$M_1(\beta) = \frac{\beta - \beta_1}{\beta_2 - \beta_1},\ M_2(\beta) = \frac{\beta_2 - \beta}{\beta_2 - \beta_1},\ N_1(v) = \frac{v - v_1}{v_2 - v_1},\ N_2(v) = \frac{v_2 - v}{v_2 - v_1}$$

The fuzzy basis functions satisfies: $h_i \geq 0$ and $\sum_{i=1}^{4} h_i = 1$.

The fuzzy system can be written as following form:

$$\begin{aligned} \dot{\xi} &= A(h)\xi + B(h)u + D(h)w \\ \chi &= C(h)\xi \end{aligned} \tag{13.10}$$

where:

$$A(h) = \sum_{i=1}^{4} h_i A_i,\ B(h) = \sum_{i=1}^{4} h_i B_i,\ D(h) = \sum_{i=1}^{4} h_i D_i,\ C(h) = \sum_{i=1}^{4} h_i C_i$$

The fuzzy state feedback controller can be designed as:

$$u = \sum_{i=1}^{4} h_i K_i \xi = K(h)\xi \tag{13.11}$$

Combining (13.10) and (13.11) together, we can get the following closed-loop fuzzy system:

$$\begin{aligned} \dot{\xi} &= A_c(h)\xi + D(h)v \\ \chi &= C(h)\xi \end{aligned} \tag{13.12}$$

where: $A_c(h) = A(h) + B(h)K(h)$.

The transfer function from the input ξ to the output χ is given by:

$$G(j\omega) = c(h)[j\omega I - A(h)]^{-1} D(h) \tag{13.13}$$

13.3.1.1 Problem Description

The objective is to design a state feedback controller in (13.11) for system (13.12) such that two conditions are satisfied:

1. Closed-loop system (13.12) is asymptotically stable.
2. The following finite frequency index holds:

$$\int_{\omega_1 \leq \omega \leq \omega_2} \chi(\omega)^T \chi(\omega) d\omega \ \leq \ \int_{\omega_1 \leq \omega \leq \omega_2} w(\omega)^T w(\omega) d\omega \tag{13.14}$$

where ω_1 and ω_2 are known scalars.

13.3.2 Finite Frequency

We start this section by introducing some basic lemmas, which we will be used in the proof of our results.

Lemma 1 *Let be a given scalar. For the system* (13.12) *is asymptotically stable, and the FF* H_∞ (13.14) *is satisfied if there exists Hermitian matrices, such* $P = P^T$ *that:*

$$\begin{bmatrix} A_c(h) & D(h) \\ I & 0 \end{bmatrix}^T \begin{bmatrix} -Q(h) & P(h) + j\omega_c Q(h) \\ I & 0 \end{bmatrix} \begin{bmatrix} P(h) - j\omega_c Q(h) & -\omega_1\omega_2 Q(h) \\ I & 0 \end{bmatrix}$$
$$+ \begin{bmatrix} C(h)^T C(h) & 0 \\ 0 & -\gamma^2 I \end{bmatrix} \ < \ 0 \tag{13.15}$$

where $\omega_c = \frac{1}{2}(\omega_1 + \omega_2)$.

Proof First, suppose (13.15) holds. Post multiplying by $[\xi^T \quad w^T]$ from the left and by its conjugate transpose from the right, we have:

$$2\dot{\xi}^T P\xi - \dot{\xi}^T P\dot{\xi} + j\omega_c\dot{\xi} Q\xi - j\omega_c\xi^T Q\dot{\xi} - \omega_1\omega_2\xi^T Q\xi + \chi^T\chi - \gamma^2 w^T w \ \leq \ 0 \tag{13.16}$$

Note that for any vectors ϕ and φ, the equality $\phi^T Q\varphi = \text{tr}(\varphi\phi^T Q)$ holds. Then (13.16) can be rewritten as

$$\frac{d}{dt}(\xi^T P\xi) + \chi^T\chi - \gamma^2 w^T w \leq \text{tr}\left[H_e\left(\omega_1\xi + j\dot{\xi}\right)\left(\omega_2\xi + j\dot{\xi}\right)^T Q\right] \tag{13.17}$$

Taking the integrating from $t = 0$ to ∞ using the stability property, we have

$$\xi(\infty)^T P\xi(\infty) + \int_0^\infty \chi^T\chi dt - \gamma^2 \int_0^\infty w^T w dt \leq \text{tr}[H_e(S)Q] \tag{13.18}$$

where:

$$S = \int_0^\infty \left(\omega_1 \xi + j\dot{\xi}\right)\left(\omega_2 \xi + j\dot{\xi}\right)^T dt \tag{13.19}$$

Note that $\xi(\infty)^T P \xi(\infty) \geq 0$ for $P > 0$, then we have:

$$\int_0^\infty \chi^T \chi dt \leq \gamma^2 \int_0^\infty w^T w dt + \mathrm{tr}[H_e(S)Q] \tag{13.20}$$

By the Parseval's theorem (Goodwin et al. 2001; Skenton et al. 1998), we have:

$$S = \frac{1}{2\pi}\int_{-\infty}^{\infty} (\omega_1 - \omega)(\omega_2 - \omega) X(\omega) X(\omega)^T dt \tag{13.21}$$

$$\int_0^\infty \chi^T \chi dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} Y(\omega)^T Y(\omega) dw \tag{13.22}$$

$$\int_0^\infty w^T w dt = \frac{1}{2\pi}\int_{-\infty}^{\infty} W(\omega)^T W(\omega) dw \tag{13.23}$$

And hence S is Hermitian and the bound on the right-hand side of (13.20) becomes, and hence (13.20) is equivalent to:

$$\int_0^\infty \chi^T \chi d\omega - \gamma^2 \int_0^\infty w^T w d\omega \leq 2\pi \ \mathrm{tr}(SQ) \tag{13.24}$$

Note that $X^T Q X \geq 0$ for $Q > 0$, and $(\omega_1 - \omega)(\omega_2 - \omega) \leq 0$ for $\omega_1 \leq \omega \leq \omega_2$. Then we have

$$\begin{aligned} 2\pi \ \mathrm{tr}(SQ) &= \int_{\omega_1 \leq \omega \leq \omega_2} (\omega_1 - \omega)(\omega_2 - \omega) \ \mathrm{tr}(X X^T Q) d\omega \\ &= \int_{\omega_1 \leq \omega \leq \omega_2} (\omega_1 - \omega)(\omega_2 - \omega) X^T Q X d\omega \ \leq 0 \end{aligned} \tag{13.25}$$

From (13.24) and (13.25), we have statement (13.14), and hence the finite frequency performance is satisfied.

Remark 1 If all the matrices in Lemma 1 are independent on h, then the fuzzy system becomes a linear system, and Lemma 1 is reduced to the generalized KYP lemma (Iwasaki et al. 2005), which proved to be an effective tool to deal with the Finite Frequency problem of linear time-invariant systems.

Lemma 2 (Projection Lemma Apkarian et al. 2001) *Given a symmetric matrix Φ and two matrices Γ, Π of column dimension m, there exists a symmetric matrix F such that the following LMI holds*

$$\Phi + \Gamma F \Pi + \Pi^T F^T \Gamma^T \ < 0 \tag{13.26}$$

If and only if the following projection inequalities with respect to F are satisfied:

$$\Gamma^{\perp}\Phi\Gamma^{\perp T} < 0 \tag{13.27}$$

$$\Pi^{\perp}\Phi\Pi^{\perp T} < 0 \tag{13.28}$$

Now, an important theorem which can guarantee the asymptotical stability and the FF H_∞ performance of the system in (13.12) is going to be proposed.

Theorem 1 *For a given constant $\gamma > 0$, consider the closed-loop system (13.12), if there exist symmetric matrices $\overline{Q}(h) > 0$, $X > 0$, $Z(h)$ and general matrix $Y(h)$ such that the following linear matrices inequality holds*

$$\Psi = \begin{bmatrix} -\overline{Q}(h) & -X + Z(h) + j\omega_c\overline{Q}(h) & 0 & 0 \\ \star & \Upsilon & D(h) & XC(h)^T \\ \star & \star & -\gamma^2 I & 0 \\ \star & \star & \star & -I \end{bmatrix} < 0 \tag{13.29}$$

$$S = A(h)X + XA(h)^T + B(h)Y(h) + Y(h)^T B(h)^T < 0 \tag{13.30}$$

with: $\Upsilon = A(h)X + XA(h)^T - B(h)Y(h) - Y(h)^T B(h)^T - \omega_1\omega_2\overline{Q}(h)$.

The controller gains K_i are given by:

$$K(h) = Y(h)X^{-1} \tag{13.31}$$

Proof Using the Lemma 1, and according to the close loop system (13.12). The inequality (13.15) can be rewritten as:

$$\begin{bmatrix} A(h) & D(h) \\ I & 0 \\ 0 & I \end{bmatrix}^T \Phi \begin{bmatrix} A(h) & D(h) \\ I & 0 \\ 0 & I \end{bmatrix} < 0 \tag{13.32}$$

where:

$$\Phi = \begin{bmatrix} -Q(h) & P(h) + j\omega_c Q(h) & 0 \\ P(h) - j\omega_c Q(h) & \omega_1\omega_2 Q(h) + C(h)^T C(h) & 0 \\ 0 & & -\gamma^2 I \end{bmatrix} \tag{13.33}$$

On the other hand, we can obtain

$$\begin{bmatrix} I & 0 \\ 0 & 0 \\ 0 & I \end{bmatrix}^T \Phi \begin{bmatrix} I & 0 \\ 0 & 0 \\ 0 & I \end{bmatrix} = \begin{bmatrix} -Q(h) & 0 \\ 0 & -\gamma^2 I \end{bmatrix} < 0 \tag{13.34}$$

According to the projection Lemma 2, with:

$$\Gamma^{\perp} = \begin{bmatrix} A(h)^T & I & 0 \\ D(h)^T & 0 & I \end{bmatrix} \tag{13.35}$$

$$\Pi^{\perp} = \begin{bmatrix} I & 0 & 0 \\ 0 & 0 & I \end{bmatrix} < 0 \tag{13.36}$$

The following inequality is a sufficient condition for (13.15).

$$\Phi + \begin{bmatrix} -I \\ A(h)^T \\ D(h)^T \end{bmatrix} F \begin{bmatrix} 0 & I & 0 \end{bmatrix} + \begin{bmatrix} 0 & I & 0 \end{bmatrix}^T F \begin{bmatrix} -I \\ A(h)^T \\ D(h)^T \end{bmatrix}^T < 0 \tag{13.37}$$

By substituting $A_c(h) = A(h) + B(h)X$, we obtain:

$$\begin{bmatrix} -Q(h) & -F + P(h) + j\omega_c Q(h) & 0 \\ \star & \Lambda & FD(h) \\ \star & \star & -\gamma^2 I \end{bmatrix} < 0 \tag{13.38}$$

with: $\Lambda = A(h)^T F + FA(h) + FB(h)K(h) + K(h)^T B(h)^T F - \omega_1\omega_2 Q(h) + C(h)^T C(h)$.

Multiplying both sides of (13.36) by the full rank matrix diag$(F^{-1}\ F^{-1}\ I)$ and its transpose from the left and right, and defining new variables $\overline{Q}(h) = F^{-1}Q(h)F^{-1}$, $Z(h) = F^{-1}P(h)F^{-1}$, $Y(h) = K(h)F^{-1}$ then (13.36) is rewritten as follows:

$$\begin{bmatrix} -\overline{Q}(h) & -X + Z(h) + j\omega_c \overline{Q}(h) & 0 \\ \star & \overline{\Lambda} & D(h) \\ \star & \star & -\gamma^2 I \end{bmatrix} < 0 \tag{13.39}$$

with: $\overline{\Lambda} = A(h)X + CA(h)^T + B(h)Y(h) + Y(h)^T B(h)^T F - \omega_1\omega_2 \overline{Q}(h) + XC(h)^T + C(h)X$.

Applying the Schur complement to inequality (13.39), we obtain exactly the inequality (13.29).

For the second sufficient condition of Theorem 1, let us construct a Lyapunov function inequality, $A(h)$ is stable if and only if there exists $F = F^T$ such that:

$$A_c(h)^T F + FA_c(h) < 0 \tag{13.40}$$

By substituting, $A_c(h) = A(h) + B(h)K(h)$, we get

$$A(h)^T F + FA(h) + FB(h)K(h) + K(h)^T B(h)^T F < 0 \tag{13.41}$$

Multiplying both sides of (13.41) by the matrix F^{-1} and its transpose from the left and right, then we can get

$$F^{-1}A(h)^T + A(h)F^{-1} + B(h)K(h)F^{-1} + F^{-1}K(h)^T B(h)^T < 0 \tag{13.42}$$

Let $X = F^{-1}$ and $Y(h) = K(h)F^{-1}$, then (13.40) became exactly the inequality (13.28).

Theorem 2 *Given a positive scalar $\gamma > 0$, there exists a T-S fuzzy control law* (13.11) *which makes the H_∞ norm of the T-S fuzzy system* (13.12) *less than γ in the frequency domain, if there exist matrices $\overline{Q}_i > 0$, $X > 0$, Z_i and general matrix Y_i, such that the following LMIs hold for all $i < j = 1, \ldots, 4$.*

$$\Psi_{ii} < 0 \tag{13.43}$$

$$\Psi_{ij} + \Psi_{ji} < 0 \tag{13.44}$$

$$S_{ii} < 0 \tag{13.45}$$

$$S_{ij} + S_{ji} < 0 \tag{13.46}$$

where:

$$\Psi_{ij} = \begin{bmatrix} -\overline{Q}_i & -X + Z_i + j\omega_c\overline{Q}_i & 0 & 0 \\ \star & A_iX + XA_i^T - B_iY_j - Y_j^T B_i^T - \omega_1\omega_2\overline{Q}_i & D_i & XC_i^T \\ \star & \star & -\gamma^2 I & 0 \\ \star & \star & \star & -I \end{bmatrix} \tag{13.47}$$

Proof Taking the following summations:

$$\sum_{i=1}^{4}\sum_{j=1}^{4} h_i h_j \Psi_{ij};\ \sum_{i=1}^{4}\sum_{j=1}^{4} h_i h_j S_{ij} \tag{13.48}$$

Using Theorem 1, the proof is completed.

13.4 Simulation Results

The wind turbine model (13.6) with the numerical values listed in Table 13.1 is considered under the variable wind speed $12 \leq v \leq 35\,\text{m/s}$. The Rotor speed is maintained around the nominal speed value in the high speed region, and the operated range of pitch angle is $-2 \leq \beta \leq 24°$. Matrices of the T-S fuzzy model are:

Table 13.1 Wind turbine parameters

Parameter	K_s	B_s	B_g	J_g	J_r	ρ	R	τ
Value	1.566×10^6	3029.5	15.993	5.9	83×10^4	1.225	30	500
Unit	N/m	Nms/rad	Nms/rad	kg m^2	kg m^2	kg/m^3	m	µs

$$A_1 = A_2 = \begin{bmatrix} 0 & 1 & -1 & 0 \\ -\frac{K_s}{J_r} & -\frac{B_s}{J_r} & \frac{B_s}{J_r} & \frac{T_{a\beta 1}}{J_r} \\ -\frac{K_s}{J_g} & -\frac{B_s + B_g}{J_g} & \frac{B_s}{J_g} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau} \end{bmatrix} \tag{13.49}$$

$$A_3 = A_4 = \begin{bmatrix} 0 & 1 & -1 & 0 \\ -\frac{K_s}{J_r} & -\frac{B_s}{J_r} & \frac{B_s}{J_r} & \frac{T_{a\beta 3}}{J_r} \\ -\frac{K_s}{J_g} & -\frac{B_s + B_g}{J_g} & \frac{B_s}{J_g} & 0 \\ 0 & 0 & 0 & -\frac{1}{\tau} \end{bmatrix} \tag{13.50}$$

$$B_1 = B_2 = B_3 = B_4 = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & \frac{B_g}{J_g} \\ \frac{1}{\tau} & 0 \end{bmatrix} \tag{13.51}$$

$$D_1 = \begin{bmatrix} 0 \\ \frac{T_{av1}}{J_r} \\ 0 \\ 0 \end{bmatrix}, \quad D_1 = \begin{bmatrix} 0 \\ \frac{T_{av2}}{J_r} \\ 0 \\ 0 \end{bmatrix} \tag{13.52}$$

where $T_{a\beta 1} = T_{a\beta}(\beta = \beta_1)$, $T_{a\beta 2} = T_{a\beta}(\beta = \beta_2)$, $T_{av1} = T_{av}(v = v_1)$ and $T_{av1} = T_{av}(v = v_2)$.

The simulation is carried out under the following operating conditions:

- Wind speed profile $17 \leq v \leq 31$ m/s (see Fig. 13.1)
- The operating frequency domain represents the rotation frequency maximum and minimum of the aerodynamics rotor (3–42 rpm) which is equivalent to

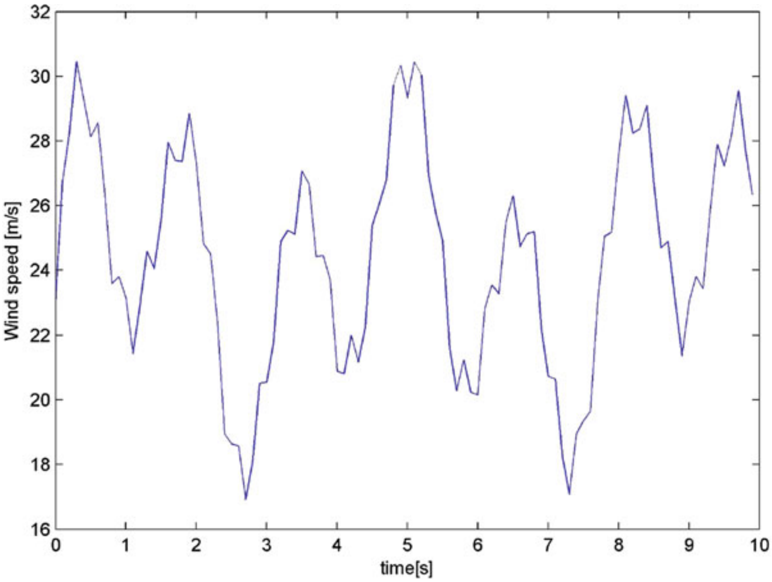

Fig. 13.1 Wind speed input profile

[0.05, 0.7] Hz, and for the generator (1500–1550 rpm) which is equivalent to [25, 25.83] Hz.

By solving the linear matrix inequalities (13.43), (13.44), (13.45), and (13.46) for $i < j = 1, \ldots, 4$ with the optimized variable $\gamma > 0$ and the ranges of frequency:

- $[\omega_1 = 0.05\,\text{Hz}, \omega_2 = 0.7\,\text{Hz}]$,
- $[\omega_1 = 25\,\text{Hz}, \omega_2 = 25.83\,\text{Hz}]$,

for the regulators of pitch angle and zero-torque speed, respectively, we can obtain the control gains:

$$K_1 = 10^3[1.049\ 3.484\ \ -0.953\ \ -0.052\ \ -97.814\ 0.160\ \ -4.743\ \ -0.005]$$

$$K_2 = 10^3[1.064\ 3.531\ \ -1.042\ \ -0.053\ \ -97.874\ \ -0.040\ \ -2.363\ \ -0.002]$$

$$K_3 = 10^3[0.585\ 2.029\ \ -0.731\ \ -0.030\ \ -97.877\ \ -0.050\ \ -2.089\ \ -0.002]$$

$$K_4 = 10^3[0.621\ 2.139\ \ -0.595\ \ -0.032\ \ -98.022\ \ -0.527\ \ -2.721\ 0.005]$$

The performance of the proposed Feedback T-S fuzzy controller in finite frequency (FFTSF) is illustrated using a comparison with the predictive controller (MPC) strategy [16] carried out by Bououden et al. (2012).

From the simulation results, Fig. 13.2 represents the time response of the generator speed equipped with controller FFTSF and controller MPC in dashed and

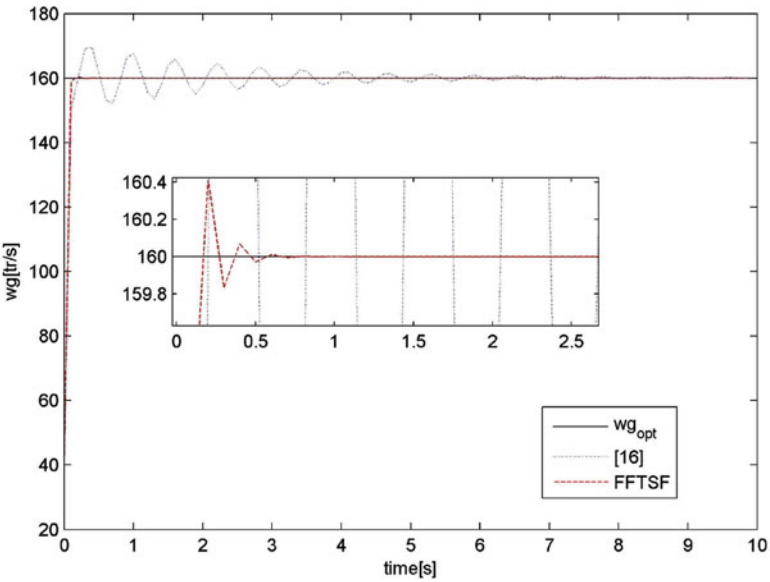

Fig. 13.2 Response time of the generator speed

dotted lines respectively, the solid line represents the optimal signal of the generator speed. The time response of controller laws: Pitch angle β_d and Zero-torque speed Ω are shown in Figs. 13.3 and 13.4, respectively. Figure 13.5 represents the variation of the membership functions.

According to these results, the generator speed with the proposed control strategy converges faster without any oscillatory behavior to its optimal value (Fig. 13.2) compared to this of the MPC controller which has some oscillators at the beginning of convergence. We can also observe that the proposed control laws, the pitch angle β_d (Fig. 13.3) and the Zero-torque Ω (Fig. 13.4), yields the best performance in terms of stability and convergence. Moreover, the applied effort at the regime transient is too small despite the presence of strong variations in wind speed.

13.5 Conclusions

This chapter proposes a Feedback T-S fuzzy controller in finite frequency synthesis for a variable speed wind turbine, which is designed using GKYP lemma extended to T-S fuzzy model. The T-S fuzzy is used to deal with the highly nonlinear term of aerodynamics torque, and the finite frequency in order to design the feedback control. The main objective of the developed control strategy is to improve the robustness of the system in a certain finite frequency range where the system operates or the external disturbance has existed. The effectiveness of the control

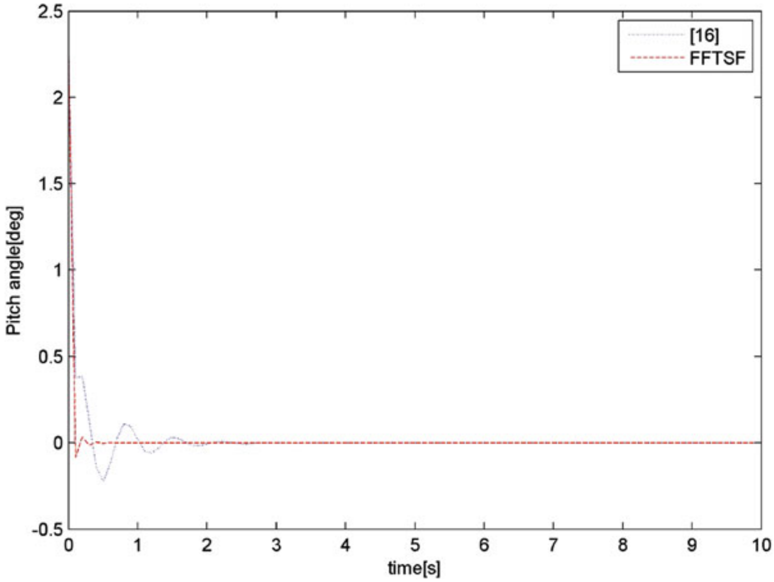

Fig. 13.3 Desired pitch angle control

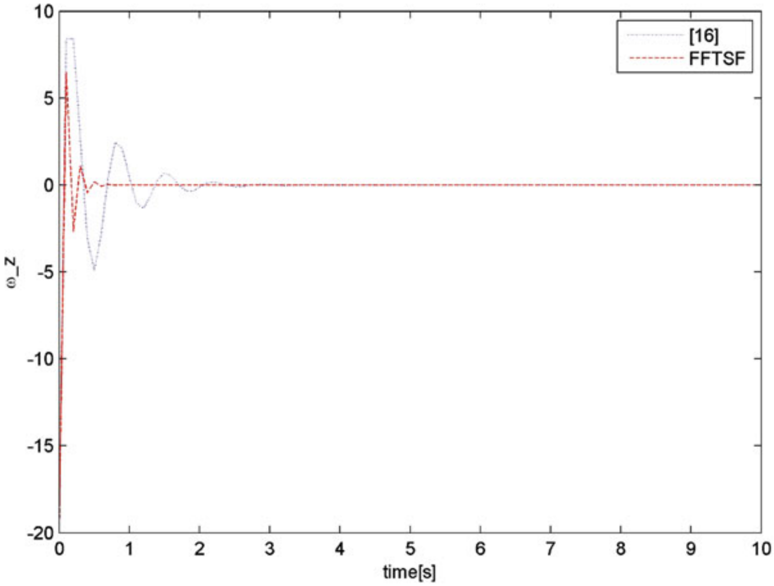

Fig. 13.4 Zero-torque speed control

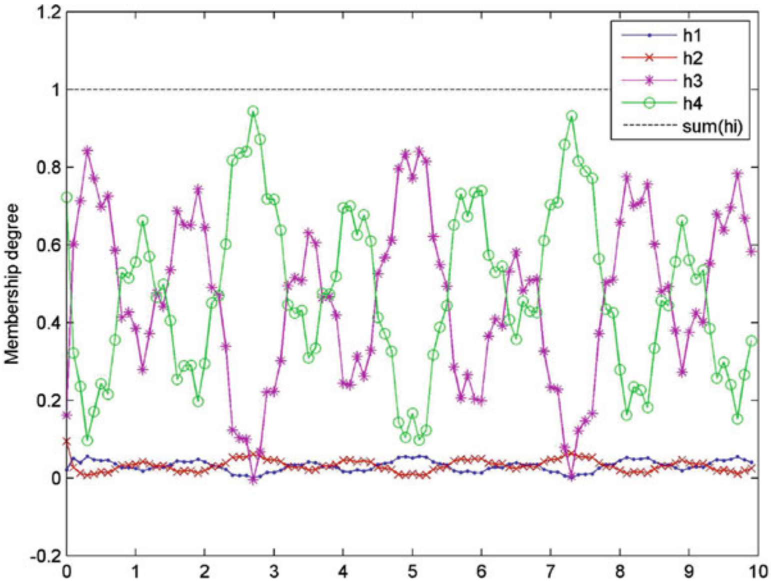

Fig. 13.5 Membership functions

strategy compared with a predictive controller has been realized, and simulation results have shown an interesting performance of the proposed control strategy in terms of stability and convergence speed, allowing a better regulation of the power generated by the wind turbine.

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