Optimal Reference Model Based Fuzzy Tracking Control for Wind Energy Conversion System

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Abstract- This paper presents a fuzzy tracking control strategy for wind energy conversion system (WECS) using a Permanent Magnet Synchronous Generator based variable speed Wind Turbine (PMSG-WT). The main contribution is to develop a new Takagi-Sugeno (T-S) fuzzy tracking controller capable to drive the PMSG-WT system for capturing maximum wind energy over a significant wide range of weather conditions. The design procedure can be summarized in two stages: i) Construct the T-S fuzzy controller by using the PMSG-WT model and calculate its matrix gains by solving a set of Linear Matrix Inequalities (LMIs). ii) Construct the nonlinear tracking controller and the optimal reference model according to the optimal rotor speed. Simulations on PMSG-WT model and comparison with baseline Proportional Integral (PI) controller show that the wind turbine plant can be controlled effectively at different operating regions by this scheme.

Keywords Wind energy conversion system, PMSG, Takagi-Sugeno fuzzy model, fuzzy control, LMIs.

1. Introduction

Motivated by environmental concerns and the depletion of fossil fuels, an increasing attention has been paid to sustainable energy sources of which wind energy is one of the most important ones. The wind energy conversion system (WECS) using variable speed wind turbine (WT) with a permanent magnet synchronous generator (PMSG) is one of the most promising ones due to its advantages of high power, no gearbox density, high precision, except initial installation costs [1-2]. However, its control is a difficult task, due to the inherent nonlinearities. Thus, many control strategies have been proposed to overcome the various difficulties in the control and design of PMSG-WT, eg. conventional PI control [3], neural network control [4-5], predictive control [6-8], fuzzy logic PI control [9-10], adaptive control [11-12] and sliding mode control [13-14].

Recently, T-S model-based fuzzy control of machine drives has been proposed by many researchers [15-19]. The main idea behind the T-S fuzzy models is to describe the processes by an aggregation of linear models which allows constructing the controller based on Parallel Distributed Compensation (PDC) technique [20]. The PDC controller gains can be calculated based on the stability conditions of the augmented T-S fuzzy system using the theory of Lyapunov stability. These conditions can be transformed easily into LMIs which can be solved efficiently by convex programming techniques using Matlab LMI toolbox [21].

In this paper, a new fuzzy tracking control for WECS using PMSG is developed. The proposed fuzzy controller is able to drive the state of the PMSG-WT system to track its optimal trajectory. First, the nonlinear model of PMSG-WT is used to design a T-S fuzzy controller. Next, an optimal reference model is derived according to the optimal rotor speed. Finally, a nonlinear tracking controller is developed using the designed T-S fuzzy controller and the optimal reference model. The stability of the augmented system is analyzed by Lyapunov's method and described by LMIs expressions. Simulation results for PMSG-WT in various wind conditions are shown with conclusions.

2. Wind Energy Conversion Model

The conversion chain consists of a fixed-pitch turbine coupled with a PMSG which allows the transformation of the mechanical energy to electrical one. A converter is used in order to maintain the power at its optimal value with various wind speeds. In this work, we study the generator side as mentioned in the overall WECS layout shown in Fig.1.

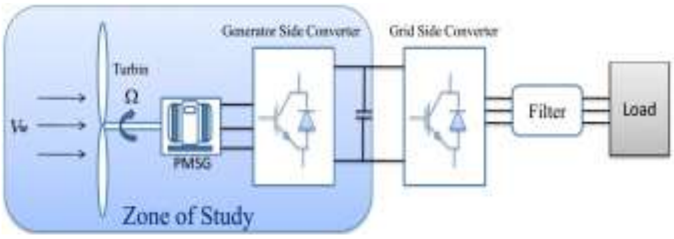

Fig. 1. Structural diagram of WECS.

2.1. Wind turbine model

The power captured from a wind turbine is given by [22-24]:

$$P = \frac{1}{2}\rho\pi R^2 V_w{}^3 C_p(\lambda) \tag{1}$$

$$\lambda = \frac{R\Omega}{V_w} \tag{2}$$

where C_p is the power coefficient, Ω is the mechanical rotation speed, λ is the tip speed ratio, V_w is the wind speed, ρ is the air density and R is the blade length.

The wind speed can be modelled as a deterministic sum of harmonics with frequency in range of $0.1-10\ Hz$, as follows [25]:

$$V_w(t) = V_0\left(1+\sum\nolimits_{n=1}^{i} A_n \sin\omega_n t\right) \tag{3}$$

where V_0 is the average wind speed, A_n is the magnitude of n[th] kind of eigenswing, ω_n is the eigenfrequency of n[th] kind of eigenswing excited in the turbine rotating.

The power coefficient is defined by the following expression [22, 23]:

$$C_p(\lambda) = -0.212\lambda^3 + 0.0856\lambda^2 + 0.2539\lambda \tag{4}$$

In order to capture a maximum power from wind, the power coefficient should be maintained at its maximum $C_{p\max}$ which is achieved by making the tip speed ratio λ equal to optimal value λ_{op} at a fixed value.

$$C_{pmax} = C_p(\lambda_{op}) \tag{5}$$

The mechanical rotation speed requires to follow its optimal reference Ω_{op} as:

$$\Omega_{op} = \frac{\lambda_{op}}{R} V_w \tag{6}$$

The optimal tip speed ratio is $\lambda_{op} = 0.78$ and $C_{p\max} = 0.1495$, as illustrated in Fig. 2.

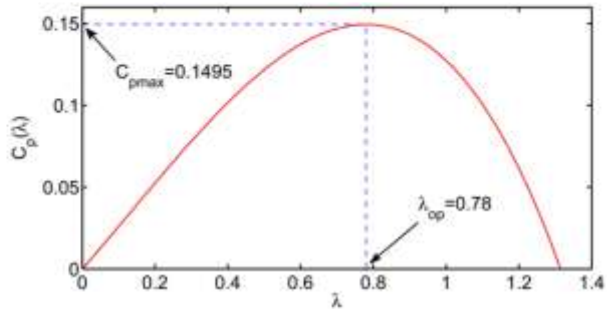

Fig. 2. Power coefficient.

2.2. PMSG Model

The voltage dynamic equations of the stator in the d-q reference frame are expressed as [26]:

$$\begin{cases} V_d = R_s i_d + L_d \dfrac{di_d}{dt} - L_q \omega i_q \\ V_q = R_s i_q + L_q \dfrac{di_q}{dt} + \omega(L_d i_d + \psi) \end{cases} \tag{7}$$

where (V_d, V_q) are the stator voltages in the d-q axis, (i_d, i_q) are the currents in the d-q axis, (L_d, L_q) are the d-q axis inductances in the d-q axis, $\omega = p\Omega$ is the electrical rotation speed, R_s is the stator resistance, ψ is the flux linkage of permanent magnets and p is the number of pole pairs. The smooth-air-gap of the synchronous machine are considered, i.e., $L_d = L_q = L$.

The electromagnetic torque in d-q reference frame is given by :

$$T_e = p\left((L_d - L_q) i_d i_q + \psi i_q\right) = p\psi i_q \tag{8}$$

The motion equation of the PMSG is expressed as :

$$J\frac{d\Omega}{dt} = T_e - T_m - f\,\Omega \tag{9}$$

where f is the viscous damping coefficient and J is the total inertia of the drive train that is equal to the summation of WT inertia constant and T_m is the mechanical torque which is given by:

$$T_m(t) = \frac{1}{2}\rho\pi R^5 \frac{C_p(\lambda)}{\lambda^3}\Omega^2(t) \tag{10}$$

The active and reactive powers in d-q frame delivered to load are provided by [3]:

$$\begin{cases} P = V_d i_d + V_q i_q \\ Q = V_q i_d - V_d i_q \end{cases} \tag{11}$$

Using Eqs. (7) and (9), the dynamic model of the PMSG-WT in d-q reference frame can be described by the following nonlinear state space form:

$$\dot{x}(t) = A(\Omega)x(t) + Bu(t) + ET_m(t) \tag{12}$$

where

$$x(t)=\begin{bmatrix}\Omega\\ i_q\\ i_d\end{bmatrix},\ A(\Omega)=\begin{bmatrix}-\frac{f}{J} & \frac{p\psi}{J} & 0\\ -\frac{p\psi}{L} & -\frac{R_s}{L} & -p\Omega\\ 0 & p\Omega & -\frac{R_s}{L}\end{bmatrix},$$

$$B=\begin{bmatrix}0 & 0\\ \frac{1}{L} & 0\\ 0 & \frac{1}{L}\end{bmatrix},\ E=\begin{bmatrix}-\frac{1}{J}\\ 0\\ 0\end{bmatrix}\ u=\begin{bmatrix}V_q\\ V_d\end{bmatrix}.$$

3. Fuzzy Control Design

The goal is to design a fuzzy tracking control scheme which is able to drive the states of the PMSG-WT system $x(t)=\begin{bmatrix}\Omega & i_q & i_d\end{bmatrix}^T$ to track their optimal trajectories $x_{op}(t)=\begin{bmatrix}\Omega_{op} & i_{qop} & i_{dop}\end{bmatrix}^T$ and capture a maximum power from wind. The first step is to develop the T-S fuzzy controller (FC) using the mathematical model of the PMSM-WT. Then, an optimal reference model (ORM) and nonlinear tracking controller (NTC) are designed according to the optimal speed Ω_{op}. Thus, a novel control scheme with FC, ORM and NTC is proposed as shown in Fig. 3, which will be presented in the next subsections.

In order to develop the T-S fuzzy controller, the mathematical model of the PMSM-WT is expressed as a T-S fuzzy model using the measurable speed as a decision variable. Then, we assume that the rotor speed is bounded as: $\underline{\Omega}\le\Omega(t)\le\bar{\Omega}$ and by using the well-known sector nonlinearity transformation [27], the nonlinear model (12) can be described by a T-S fuzzy model with $r=2^1$ fuzzy If-Then rules as follows:

Rule $i=1,...,r$: If $z(t)$ is F_{1i} Then

$$\dot{x}(t)=A_i x(t)+B_i u(t)+E_i T_m(t)$$

where $z(t)=\Omega(t)$ is the premise variable, F_{11} and F_{12} are the membership functions which can be defined as:

$$F_{11}(\Omega)=\frac{\Omega(t)-\underline{\Omega}}{\bar{\Omega}-\underline{\Omega}},\quad F_{12}(\Omega)=1-F_{11}(\Omega) \tag{13}$$

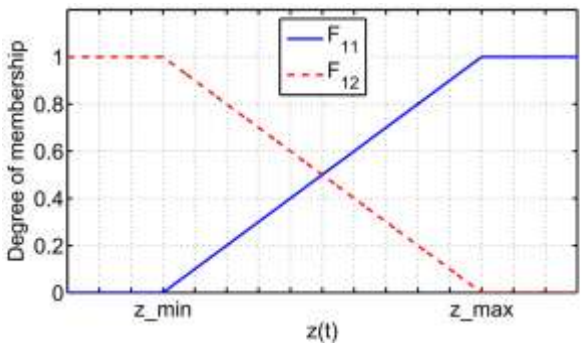

Fig. 4. Membership functions of decision variable.

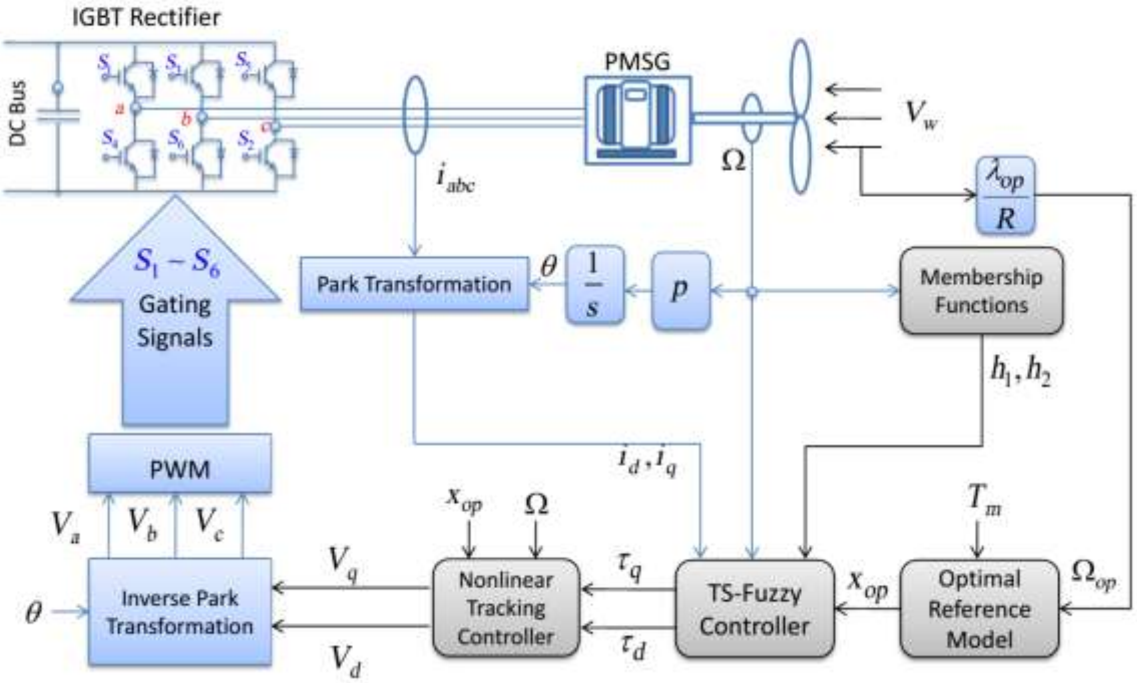

Fig. 3. Proposed fuzzy tracking control of PMSG-WT.

3.1. T-S Fuzzy controller

The sub-matrices can be defined as:

$$A_1 = \begin{bmatrix} -\dfrac{f}{J} & \dfrac{3p\psi}{2J} & 0 \\ -\dfrac{p\psi}{L} & -\dfrac{R}{L} & -p\bar{\Omega} \\ 0 & p\bar{\Omega} & -\dfrac{R}{L} \end{bmatrix}, A_2 = \begin{bmatrix} -\dfrac{f}{J} & \dfrac{3p\psi}{2J} & 0 \\ -\dfrac{p\psi}{L} & -\dfrac{R}{L} & -p\underline{\Omega} \\ 0 & p\underline{\Omega} & -\dfrac{R}{L} \end{bmatrix},$$

$$B_1 = B_2 = \begin{bmatrix} 0 & 0 \\ \dfrac{1}{L} & 0 \\ 0 & \dfrac{1}{L} \end{bmatrix}, E_1 = E_2 = \begin{bmatrix} -\dfrac{1}{J} \\ 0 \\ 0 \end{bmatrix}.$$

Using the product-inference rule, singleton fuzzifier, and the center of gravity defuzzifier, the global state is described by:

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))\left(A_i x(t) + B_i u(t) + E_i T_m(t)\right) \quad (14)$$

where $h_i(z(t)) = F_{1i} / \sum_{j=1}^{r} F_{1j}$ for all $t > 0$, $h_i(z(t)) \geq 0$ and $\sum_{i=1}^{r} h_i(z(t)) = 1$.

The goal is to drive the actual variables x of PMSM-WT system to track the optimal trajectory x_{op}, such that:

$$x(t) - x_{op}(t) \to 0 \quad as \quad t \to \infty \quad (15)$$

Let $\tilde{x} = x - x_{op}$ be defined as the tracking error and its time derivative is given by:

$$\dot{\tilde{x}}(t) = \dot{x}(t) - \dot{x}_{op}(t) \quad (16)$$

Now, replacing (14) by its value in (16) and adding the term $\sum_{i=1}^{r} h_i A_i (x_{op} - x_{op})$, Eq. (16) becomes:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} h_i(z)\left(A_i \tilde{x} + B_i u + E_i T_m + A_i x_{op}\right) - \dot{x}_{op} \quad (17)$$

Introducing new control variable $\tau(t)$ that satisfy the following relation:

$$\sum_{i=1}^{r} h_i(z) B_i \tau = \sum_{i=1}^{r} h_i(z)\left(B_i u + A_i x_{op} + E_i T_m\right) - \dot{x}_{op} \quad (18)$$

where $\tau(t)$ is the fuzzy controller law to be designed using PDC technique, as follows:

Controller $i = 1,...,r$: If $z(t)$ is F_{1i} Then $\tau(t) = -K_i \tilde{x}(t)$

where K_i are the controller gains. The final global control signal provided by the fuzzy controller is:

$$\tau(t) = -\sum_{i=1}^{r} h_i(z(t)) K_i \tilde{x}(t) \quad (19)$$

Using Eq. (18), the tracking error dynamics (17) can be given by:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} h_i(z(t))\left(A_i \tilde{x} + B_i \tau(t)\right) \quad (20)$$

Applying control law (19) to model (20), the closed-loop system becomes:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t)) h_j(z(t))\left(A_i - B_i K_j\right)\tilde{x}(t) \quad (21)$$

By letting $G_{ij} = \left(A_i - B_i K_j\right)$, Eq. (21) can be written as follows:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t)) h_j(z(t)) G_{ij} \tilde{x}(t) \quad (22)$$

In order to calculate the controller gains, the following theorem is considered [28]:

Theorem 1. *The equilibrium of the closed-loop continuous fuzzy system (22) is asymptotically stable via the PDC controller (19) if there exist a symmetric matrix* $P > 0$, *a diagonal matrix* D *and matrices* Q_{ij} *with:* $Q_{ii} = Q_{ii}^T$ *and* $Q_{ji} = Q_{ij}^T$ *for* $i \neq j$ *such that:*

$$G_{ii}^T P + P G_{ii} + Q_{ii} + DPD < 0, \quad i = 1,...,r \quad (23)$$

$$\left(\frac{G_{ij} + G_{ji}}{2}\right)^T P + P\left(\frac{G_{ij} + G_{ji}}{2}\right) + Q_{ij} \leq 0, \quad i < j \leq r \quad (24)$$

$$\begin{bmatrix} Q_{11} & \cdots & Q_{1r} \\ \vdots & \ddots & \vdots \\ Q_{1r} & \cdots & Q_{rr} \end{bmatrix} \equiv \tilde{Q} > 0 \quad (25)$$

for $i, j = 1,...,r$, *s.t. the pairs* (i, j), *such that,* $h_i(z(t)) h_j(z(t)) = 0, \forall t$.

Proof. Choose the candidate Lyapunov function as $V(\tilde{x}(t)) = \tilde{x}^T(t) P \tilde{x}(t)$. Its derivative is given by:

$$\dot{V} = \sum_{i=1}^{r} h_i^2 \left(\tilde{x}^T (G_{ii}^T P + P G_{ii})\tilde{x}\right) + 2\sum_{i<j\leq r} h_i h_j \times \tilde{x}^T \left(\left(\frac{G_{ij} + G_{ji}}{2}\right)^T P + P\left(\frac{G_{ij} + G_{ji}}{2}\right)\right)\tilde{x} \quad (26)$$

Using Eqs. (23) and (24), it follows that:

$$\dot{V} \le -\sum_{i=1}^{r} h_i^2 \tilde{x}^T \left(Q_{ii} + DPD\right)\tilde{x} - 2\sum_{i<j\le r} h_i h_j \tilde{x}^T Q_{ij} \tilde{x} \quad (27)$$

$$\dot{V} = -\tilde{x}^T H^T \tilde{Q} H \tilde{x} - \tilde{x}^T DPD\tilde{x} \sum_{i=1}^{r} h_i^2(z) \quad (28)$$

where $H = \begin{bmatrix} h_1 I & h_2 I & \dots & h_r I \end{bmatrix}^T$. If Eq. (25) holds and using the fact that $\sum_{i=1}^{r} h_i^2(z) \ge \frac{1}{r}$, it can be written:

$$\dot{V} \le -\frac{1}{r}\tilde{x}^T DPD\tilde{x} \le -\frac{\beta}{r} V \quad (29)$$

where $\beta = -\frac{\lambda_{min}(DPD)}{\lambda_{max}(P)}$ and $\lambda_{min}(DPD)$ is the minimal eigenvalue of the matrix DPD, $\lambda_{max}(P)$ is the maximal eigenvalue of the matrix P. Hence, we obtain $\dot{V} \le V(0) e^{-\frac{\beta}{r}t}$. Consequently, $\|\tilde{x}(t)\|^2 \le \frac{V(0)}{\lambda_{min}(P)} e^{-\frac{\beta}{r}t}$ is concluded.

Remark. The conditions of Theorem 1 can be transformed into an equivalent LMIs problem which corresponds to simple objective changes of variables $X = P^{-1}$, $K_i = M_i X^{-1}$. By using congruence in inequalities (23), (24) and (25), the following LMI expressions in variables X and M_i can be obtained:

$$\exists X = X^T > 0,\ \exists Y_{ii} = Y_{ii}^T,\ \exists Y_{ij} = Y_{ji}^T,\ \exists M_i:$$

$$\begin{bmatrix} XA_i^T + A_i X - B_i M_i - M_i^T B_i^T + Y_{ii} & XD^T \\ DX & -X \end{bmatrix} < 0,\ i = 1,\dots,r \quad (30)$$

$$\begin{aligned} &XA_i^T + A_i X + XA_j^T + A_j X - B_i M_j - M_j^T B_i^T \\ &-B_j M_i - M_i^T B_j^T + 2Y_{ij} \le 0, \quad i < i \le r \end{aligned} \quad (31)$$

$$\begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1r} \\ Y_{12} & Y_{22} & \dots & Y_{2r} \\ \vdots & \ddots & & \vdots \\ Y_{1r} & Y_{2r} & \dots & Y_{rr} \end{bmatrix} \equiv \tilde{Y} > 0 \quad (32)$$

3.2. Optimal Reference and Nonlinear Tracking Controller

The optimal reference model and nonlinear tracking controller can be determined using Eq. (18) which is rewritten as follows:

$$\sum_{i=1}^{r} h_i(z) B_i \tau = \sum_{i=1}^{r} h_i(z)\left(B_i u + A_i x_{op} + E_i T_m\right) - \dot{x}_{op} \quad (33)$$

Noting that:

$$A(\Omega) = \sum_{i=1}^{r} h_i A_i,\ B = \sum_{i=1}^{r} h_i B_i,\ E = \sum_{i=1}^{r} h_i E_i \quad (34)$$

Then, Eq. (33) can be rewritten in the following compact form:

$$B\left(u(t) - \tau(t)\right) = -A(\Omega)x_{op} - ET_m(t) + \dot{x}_{op}(t) \quad (35)$$

Applying Eq. (35) to the PMSG-WT model, we obtain the following matrix form:

$$\begin{bmatrix} 0 & 0 \\ \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} u_q - \tau_q \\ u_d - \tau_d \end{bmatrix} = -\begin{bmatrix} -\frac{f}{J} & \frac{p\psi}{J} & 0 \\ -\frac{p\psi}{L} & -\frac{R_s}{L} & -p\Omega \\ 0 & p\Omega & -\frac{R_s}{L} \end{bmatrix} \times \begin{bmatrix} \Omega_{op} \\ i_{q_{op}} \\ i_{d_{op}} \end{bmatrix} - \begin{bmatrix} -\frac{1}{J} \\ 0 \\ 0 \end{bmatrix} T_m + \frac{d}{dt}\begin{bmatrix} \Omega_{op} \\ i_{q_{op}} \\ i_{d_{op}} \end{bmatrix} \quad (36)$$

From the first equation of (36), we obtain:

$$i_{qop} = \frac{2J}{3p\psi}\left(\dot{\Omega}_{op} + \frac{f}{J}\Omega_{op} + \frac{1}{J}T_m\right) \quad (37)$$

According to field oriented vector control, the best choice for the optimal d-axis current is $i_{dop} = 0$ [6]. Then, the optimal reference model is given by:

$$x_{op} = \begin{bmatrix} \Omega_{op} & \frac{2J}{3p\psi}\left(\dot{\Omega}_{op} + \frac{f}{J}\Omega_{op} + \frac{1}{J}T_m\right) & 0 \end{bmatrix}^T \quad (38)$$

From the second and the third equation of (36), we obtain the following nonlinear tracking control:

$$\begin{cases} V_q = p\psi\Omega_{op} + R_s i_{qop} + L\frac{di_{qop}}{dt} + \tau_q \\ V_d = -pL\Omega i_{qop} + \tau_d \end{cases} \quad (39)$$

Using Eq. (11), the optimal active and reactive powers can be given by:

$$\begin{cases} P_{op} = i_{qop} V_q \\ Q_{op} = -i_{qop} V_d \end{cases} \quad (40)$$

4. Numerical Simulation

In order to verify the effectiveness and the validity of the proposed method, simulation tests have been carried out on PMSG-WT with the parameters being given in Table 1. The fuzzy controller gains are calculated by solving the LMIs (30), (31) and (32), as follows:

$$K_1 = \begin{bmatrix} -1.4573 & 7.6385 & -0.0216 \\ -0.0066 & -0.0126 & 7.9323 \end{bmatrix},$$

$$K_2 = \begin{bmatrix} -3.6088 & 6.2446 & 0.7547 \\ -0.0017 & 0.4436 & 9.1900 \end{bmatrix}.$$

Table 1. Wind conversion system parameters.

Parameter	Value	Unity
Blade length (R)	0.5	m
Air density (ρ)	1.225	Kg / m^3
Stator inductance (L)	2.7	mH
Friction coefficient (f)	0.06	$N.m.s / rad$
Moment of inertia (J)	16.1	$N.m$
Stator resistance (R_s)	1.137	Ω
Magnetic flux (ψ)	0.15	$V.s / rad$
Number of poles (p)	17	-

The proposed control strategy is tested for the following wind velocity:

$$V_w(t) = 7.5 + 0.2sin(0.1047t) + 2sin(0.2665t) + sin(1.2930t) + 0.2sin(3.6645t)$$

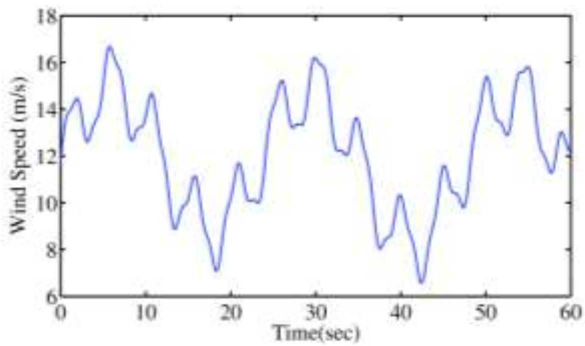

Fig. 5. Wind speed variation.

The simulation results of rotor speed, q-axis and d-axis currents are shown in Fig. 6, Fig. 7 and Fig. 8, respectively. Note that the time response of the tracking is very low. Furthermore, the less speed and current tracking errors, the better tracking performance, highlights the good tracking performances of the proposed fuzzy control method. Results demonstrate that PMSG-WT system can be successfully controlled at different operating conditions by the fuzzy controller.

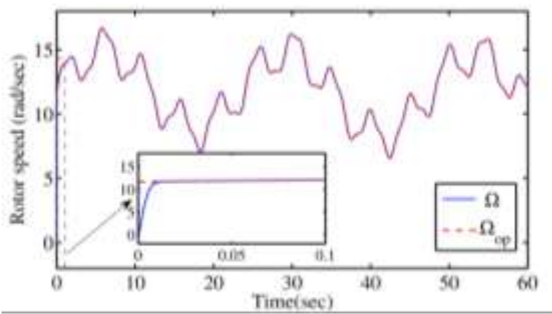

Fig. 6. Rotor speed and its optimal reference.

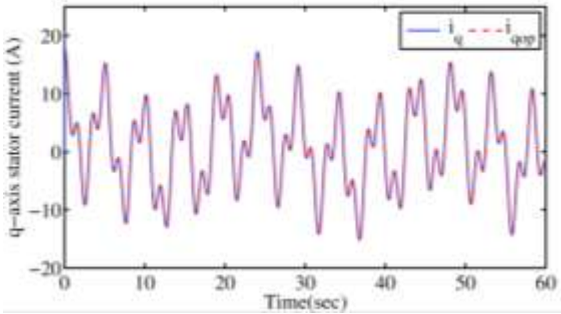

Fig. 7. q-axis current and its reference.

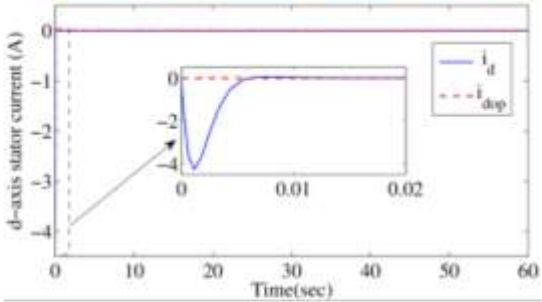

Fig. 8. d-axis current and its reference.

Fig. 9 shows the power coefficient response. It is clear that the maximum power coefficient C_{pmax} value can be almost achieved by the proposed method. It means the maximum wind power can be extracted by the proposed controller during the change of operation points.

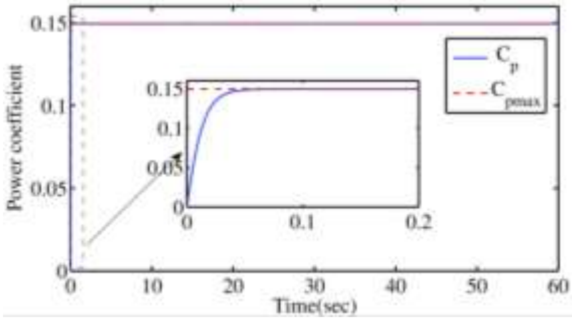

Fig. 9. Power coefficient response.

Figs. 10 and 11 show the response of active and reactive powers. It is clear that the produced power follows well its optimal reference which means that the maximum power point can be achieved despite fast-varying wind velocity.

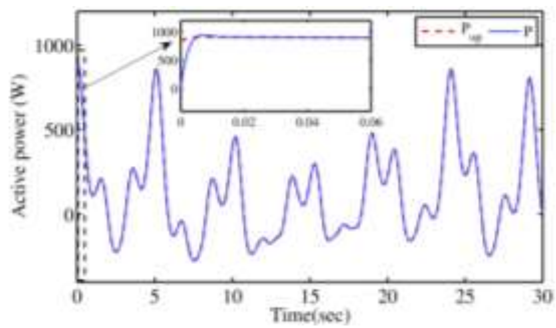

Fig. 10. Active power and its optimal reference.

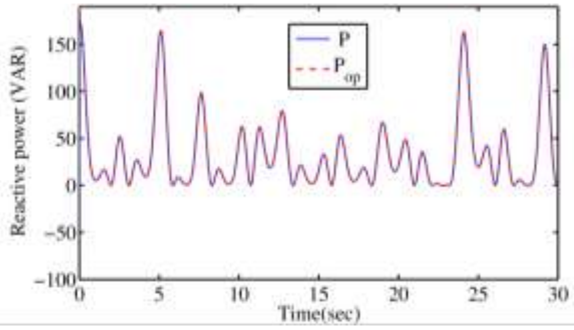

Fig. 11. Reactive power and its optimal reference.

In order to assess the controller performances, a comparative study was done with a baseline PI controller. The wind speed profile has been chosen as illustrated in Fig. 12 to show how the controllers do with the sudden changes of wind speed. The dynamic responses of rotor speed and the power coefficient are shown in Fig. 13, and Fig. 14.

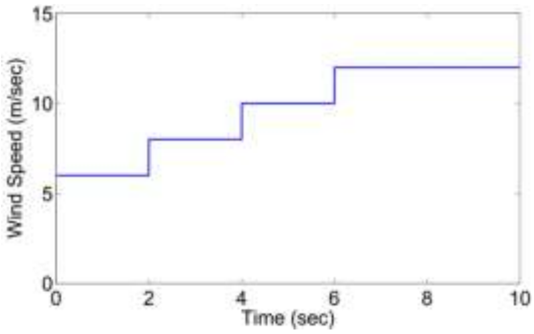

Fig. 12. Wind speed variation.

The controllers performances are shown in Table 2. From Figs. 13 and 14, it is clear that the speed and the power coefficient track well their optimal references for the two controllers. But the response time for the proposed controller is less than the conventional PI controller.

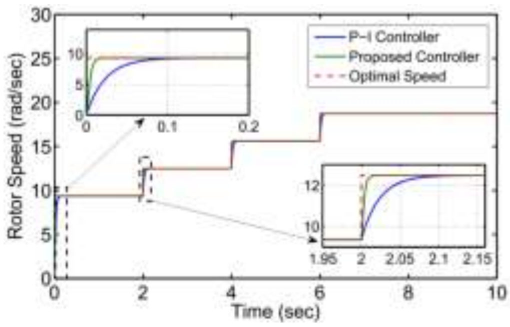

Fig. 13. Rotor speed and its optimal reference.

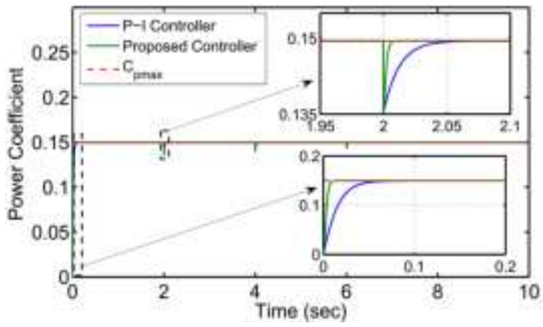

Fig. 14. Power coefficient response.

Table 2. Comparison of controllers performances.

Rotor Speed	Proposed Controller	PI Controller
Rise time (s)	0.0078	0.0506
Settling time (s)	0.0137	0.0902
Overshoot (%)	0	9.9695e-004

5. Conclusion

An efficient T-S fuzzy controller is proposed for maximum power point tracking of wind turbine equipped with PMSG. The objective is to drive the states of the considered system to track an optimal reference model and ensuring maximum power generation. The sufficient conditions are given in Linear Matrix Inequalities (LMIs) form, which can be solved using an effective optimization tools. Simulations results and comparison with baseline PI controller show that the PMSG-WT plant can be controlled effectively at different operating regions by the proposed fuzzy tracking control strategy. The robustness issue and practical implementation will be the subject of our future research work.

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