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MPPT Control for Wind Energy Conversion System based on a T-S Fuzzy

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ABSTRACT

In this paper, we focus on the modeling and control of a wind power system based on a Permanent Magnet Synchronous Generator (PMSG). We proposed a technique of control strategies to have the maximum power from wind turbine (WT). This study deals with the problem of Maximum Power Point Tracking (MPPT) based on Takagi Sugeno fuzzy model. The stability analysis is achieved. The gains of the designed controller are calculated by solving Linear Matrix Inequality (LMI). Finally, simulation results are provided to demonstrate the validity and the effectiveness of the proposed method.

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1. INTRODUCTION

A serious damage of the environment is caused by global warning and fossil fuel pollution and in consequence it became a problem for humanity. These reasons led researchers to present alternative sources of supply such as photovoltaic and wind energy systems. These solutions are considered as the most sustainable sources for many uses for example irrigation and electrification in isolated areas [1]. Also, Variable Speed Wind Energy Conversion Systems are the dominant technologies in the present wind power industry because they have multiples advantages, over the fixed velocity systems, as the ability to obtain Maximum Power Point Tracking (MPPT) control methodology in order to extract maximum power at different wind, higher overall efficiency, power quality and it can be controlled to reduce aerodynamic noise and mechanical stress on VS-WECS by absorbing the wind-power fluctuations. Moreover, the Wind Turbines Generators based on Permanent Magnet Synchronous Generators (PMSG) are considered popular for variable-speed generation system and the use of the PMSG in large WTG is increasing. It is connected directly to the turbine without gearbox and so it can operate at low speeds [2]. In addition, it can decrease again weight, losses, costs, demands maintenance requirements.

In order to extract the optimal accessible power given by the WECS, several studies have presented multiple control schemes [3]. The simplest techniques for searching the maximum power point are based on PI controller but this method is still classical and lack of performance, the perturb & observe method is the simplest algorithm for searching the maximum power point but the duty of the power converter perturbs rapidly and causes energy loss near the maximum power point [4]-[5], The neural network method estimates the wind speed from the measured turbine power and generator speed and thus decides the maximum power generator speed command or torque reference for the operational point tracker [6]. In addition, fuzzy logic methods have been widely adopted and they have presented better effectiveness [7]. Nevertheless, the main issues of most of these methods are lack of stability and strict theoretical analysis so that the maximum power point varies over a wide range.

In literature, the T-S fuzzy model-based control has been fully mentioned for example [8]-[9]. Thus, the control based on (T-S) model has been more popular as one of the most successful techniques for systems and control applications due to its reliability and effectiveness. The principal advantage is that the controller is systematically realized by using parallel distributed compensation (PDC) and a linear matrix inequality (LMI) technique [10]. The fuzzy model of Takagi-Sugeno allows modelling the nonlinear system by representing local dynamics by linear models. As a result, the global system model is achieved by a combination of the different linear models. Then, a linear feedback control has to be constructed for every local linear model. Accordingly, the consequent overall nonlinear controller is once more a fuzzy combination of each distinct linear controller [11].

The rest of this paper is arranged as following: in the second section, a dynamic modelling of the WECS is presented. The third section starts with presenting the control strategy. Then, fuzzy modelling of the system is presented. Finally, the control design is explained and stability conditions are given. Section 4 is reserved to present numerical simulations that illustrate the effectiveness of the proposed control topology. We finish by a conclusion.

2. MODELLING OF THE WIND TURBINE GENERATOR

3.1. Wind turbine model

A schematic overview of the WECS is shown in Figure 1. The system supplies a resistive load and consists of a wind turbine rotor, PMSG, rectifier, and a boost converter. Wind turbine converts the wind energy into mechanical energy, which then runs a generator to create electrical energy.

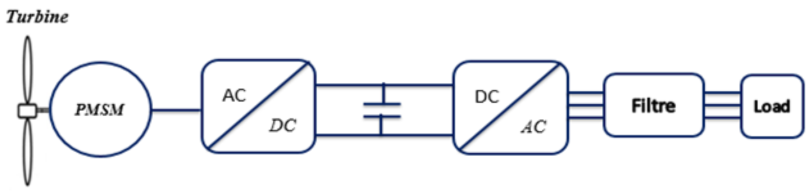

Figure 1. Structural diagram of WECS

The amount of power captured by the wind turbine is given as [12]:

$$P_m = \frac{1}{2}\rho\pi R^2 V^3 C_P(\lambda) \tag{1}$$

Where, ρ is the air density (kg/m3), R is the blade radius (m), V is the wind velocity (in m/s), and $C_p(\lambda)$ is the power coefficient usually given as a function of the tip-speed ratio λ .The tip-speed ratio λ is defined as

$$\lambda = \frac{R\omega_m}{V} \tag{2}$$

The wind turbine mechanical torque output Tm given as:

$$T_m = \frac{1}{2}\rho\pi R^5 \frac{C_P(\lambda)}{\lambda^3}\omega_m^2 \tag{3}$$

Many different versions of fitted equations for C_p have been used in previous studies. This paper defined C_p based on the following [13]:

$$C_P = -0.212\lambda^3 + 0.0856\lambda^2 + 0.2539\lambda \quad (4)$$

The maximum of C_p, that is $C_{P\max} = 0.15$, is reached for $\lambda_{opt} = 0.78$. Hence, there is one particular $\lambda = \lambda_{opt}$, optimal power coefficient, and an optimal turbine rotating velocity ω_{m_opt}, under which C_p takes a maximum value $C_{p\_\max}$. λ_{opt} is the optimal value of the tip speed ratio, which is dependent on the characteristics of the turbine system. Also, the maximum power can be captured from the wind. Accordingly, the turbine system works in maximum power point tracking (MPPT) [14], as depicted in Figure 2.

The Figure 3 presents C_p as a function of λ. According to the figure, there is only one optimal point, denoted by λ_{opt}, where C_p is maximum. Continuous operation of the wind turbine at this point guarantees that it will obtain the maximum available power from the wind at any speed, as shown in Figure 4.

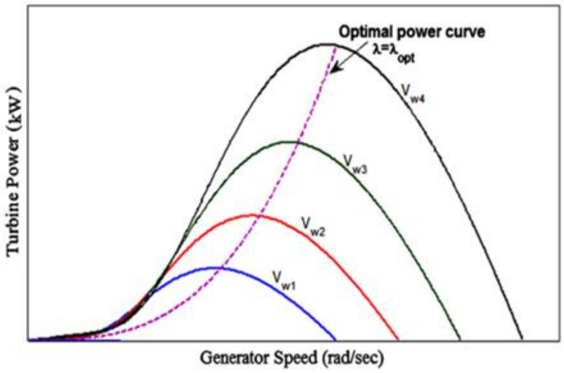

Figure 2. Characteristics of turbine power as a function of the rotor speed

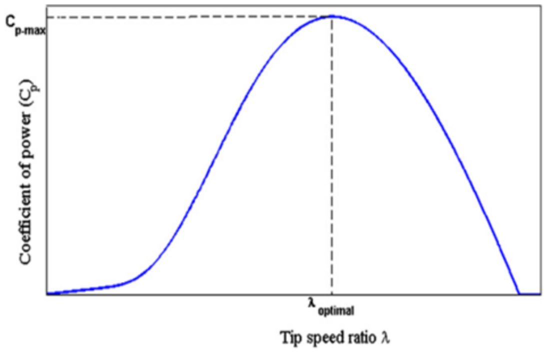

Figure 3. The characteristic of the power coefficient as a function of tip speed ratio

3.2. PMSG Model

In order to simplify the dynamic model of the electrical part of PMSG, applying a change of landmarks which rotates at the same speed as the rotor (Two bobbins dq rotate with the rotor and generating the same effect as the three fixed coils) [14]. Then the electrical model of the PMSG is defined in the rotating reference fame d-q as follows:

$$V_{sd} = R_s I_{sd} + L_d \frac{dI_{sd}}{dt} - \omega_e L_q I_{sq} \quad (5)$$

$$V_{sq} = R_s I_{sq} + L_q \frac{dI_{sq}}{dt} + \omega_e (L_d I_{sd} + \psi_m) \quad (6)$$

Where V_{sq}, V_{sd} are the direct and quadrature components of the PMSG voltages, R_s, L_d and L_q, respectively, are the resistance, the direct and the quadrature inductance of the PMSG winding, $\psi_m (wb)$ represents the magnet flux, ω_e (rad/s) is the electrical rotational speed of PMSG, I_{sd}, I_{sq} (A) are the direct and quadrature components of the PMSG currents, respectively.

The dynamic equation of the wind turbine is described by:

$$\frac{d\Omega_t}{dt} = \frac{1}{J_T} T_e + \frac{D_T}{J_T} \Omega_t - \frac{1}{J_T} T_t \quad (7)$$

The electromagnetic torque of a p-pole machine is obtained as [16]:

$$T_{em} = \frac{3}{2} n_p (\psi_m I_{sq} + (L_d - L_q) I_{sd} I_{sq}) \tag{8}$$

Where T_{em} (N m) is the electromagnetic torque, n_p is the number of pole pairs, D_T is the damping coefficient and J_T is the moment of inertia.

3. CONTROL STRATEGY

3.1 The control strategy of the MPPT

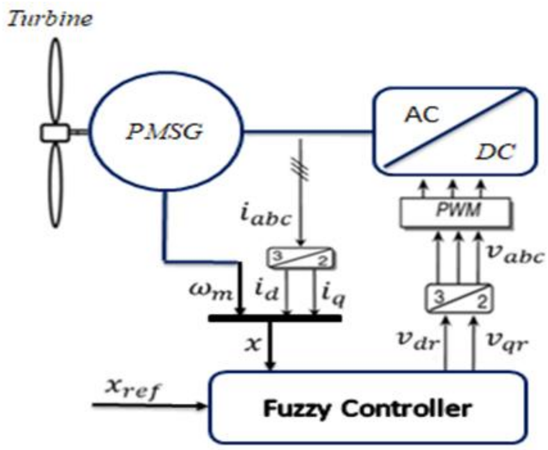

Figure 4. Fuzzy tracking control diagram

The Figure 4 present the control scheme treated in the current work in the aim to maintain generated power at its maximum value. MPPT is a process that searches the operating point which allows extracting the maximum available produced power at any wind speed level. The control algorithm requires to measure reference signals to be tracked for the rotor speed, the direct and quadrature stator current. Then, the MPPT control is realized by acting on the rectifier side by generating control signals (U_{dr} and U_{qr}) to track the peak power point. The rotor speed is measured according to the following equation,

$$\Omega_r = \frac{\lambda_{opt} V_v}{R} \tag{9}$$

In this study, the d-axis reference current is chosen as: $i_{sdr} = 0$ we can calculate the reference of the current in quadrature given, once the rotor speed reference isdetermined by:

$$i_{qref} = \frac{C_{em_{ref}}}{k_t} = Cte.\frac{\Omega_t^2}{k_t} \tag{10}$$

Where $k_t = \varphi_f \times p$ And $Cte = \frac{\rho \pi R_t^5 C_{p\max}}{2\lambda_{opt}^3}$

3.2 T-S Fuzzy model of wind energy conversion system

In the T-S fuzzy models, the nonlinear system of a SPMSM is represented by several linear sub-systems according to the model rules. Each sub-model leads to the overall behavior of the nonlinear system using a weighting function [2]. The dynamic model of the PMSG-WT can be described by the following nonlinear state space form [13]:

$$\dot{x}(t) = A(x(t))x(t) + Bu(t) + ET_m(t) \quad (11)$$

Where: $$x = \begin{pmatrix} \Omega_m & i_{sd} & i_{sq} \end{pmatrix}^T \quad (12)$$

$x(t)$ are the state variables, $u(t)$ are the control inputs, A_i, B_i et E_i are the state matrices of the sub-system.

$$A(x(t)) = \begin{pmatrix} -\frac{D_T}{J} & \frac{p\psi}{J} & 0 \\ -\frac{p\psi}{L_q} & -\frac{R_s}{Lq} & -p\omega_m \\ 0 & p\omega_m & -\frac{R_s}{L_d} \end{pmatrix}, \; B = \begin{pmatrix} 0 & 0 \\ \frac{1}{L_q} & 0 \\ 0 & \frac{1}{L_d} \end{pmatrix}$$

$$u = \begin{pmatrix} V_q & V_d \end{pmatrix}^T, \; E = \begin{pmatrix} -\frac{1}{J} & 0 & 0 \end{pmatrix}^T$$

Where V_d and V_q represent the average control signals of the inverter in d-q frame. Moreover, the nonlinear model (12) can be presented by a T-S fuzzy model with r = 2^1 fuzzy If-Then rules as follows:

Model rules i:

If $z(t)$ is F_1^1 then $\dot{x}(t) = Ax_1(t) + B_1u(t) + E_1T_m(t)$ (13)

If $z(t)$ is F_2^1 then $\dot{x}(t) = Ax_2(t) + B_2u(t) + E_2T_m(t)$ (14)

Where $z(t) = \omega_m(t)$ is the premise variable and F_i^1 is the membership functions, Let define $D = \max(\omega_m(t))$ and $d = \min(\omega_m(t))$, so $\omega_m(t) = [d, D]$.

$$F_1^1 = \frac{\omega_m(t) - d}{D - d} \quad (15)$$

$$F_2^1 = 1 - F_1^1 \quad (16)$$

Hence, the local subsystem matrices are given by:

$$A_1 = \begin{pmatrix} -\frac{D_T}{J} & \frac{p\psi}{J} & 0 \\ -\frac{p\psi}{L_q} & -\frac{R_s}{Lq} & -pM \\ 0 & pM & -\frac{R_s}{L_d} \end{pmatrix}, B_1 = B_2 = \begin{pmatrix} 0 & 0 \\ \frac{1}{L_q} & 0 \\ 0 & \frac{1}{L_d} \end{pmatrix}$$

$$A_2 = \begin{pmatrix} -\frac{D_T}{J} & \frac{p\psi}{J} & 0 \\ -\frac{p\psi}{L_q} & -\frac{R_s}{Lq} & -pm \\ 0 & pm & -\frac{R_s}{L_d} \end{pmatrix}, E_1 = E_2 = \begin{pmatrix} -\frac{1}{J} & 0 & 0 \end{pmatrix}$$

After defuzzification, the fuzzy system of a PMSM can be expressed as:

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))(A_i x(t) + B_i u(t) + E_i T_m(t)) \tag{17}$$

Where $$h_i(z(t)) = \frac{F_j^1(z(t))}{\sum_{j=1}^{r} F_j^1(z(t))} \tag{18}$$

$\forall t > 0$, $h_i(z(t)) \geq 0$ and $\sum_{i=1}^{r} h_i(z(t)) = 1$

3.3 The PDC control

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

$$x_e(t) = x(t) - x_{opt}(t) \to 0 \text{ as } t \to \infty \tag{19}$$

Where $x(t) = \omega_m(t)$, $x_{opt}(t)$ is the desired value of ω_m, and $x_e(t)$ be defined as the tracking error and its time derivative is given by:

$$\dot{x}_e(t) = \dot{x}(t) - \dot{x}_{op}(t) \tag{20}$$

Hence, the new PDC fuzzy controller is designed such as [13]:

$$\tau = -\sum_{i=1}^{2} h_i(z(t)) K_i x_e(t) \tag{21}$$

and $$\tau = \left[\tau_q, \tau_d\right]^T \tag{22}$$

Where τ_q, τ_d are new controller to be designed via LMIs approach, K_i denotes the control gain corresponding to each linear sub-model and $x_e(t)$ is the augmented state vector. Therefore, by replacing τ by its expression, the closed loop model is described by [15]:

$$\dot{x}_e(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t)) h_j(z(t))(A_i - B_i K_j) x_e(t) \tag{23}$$

With: $G_{ij} = (A_i - B_i K_j)$

The x_e can be written as: $$\dot{x}_e(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t)) h_j(z(t)) G_{ij} x_e(t) \tag{24}$$

4. RESULTS AND DISCUSSION

In this section, a numerical simulation was carried out by using MATLAB/Simulink, the system described in Figure 4. First, we have simulated the system without controllers. The wind speed is given as a sum of several harmonics [16]:

$$V_{vent} = V_0 + \sum_{i=1}^{n} V_i . \sin(\omega_i . t) \text{ , (Figure 5).} \tag{25}$$

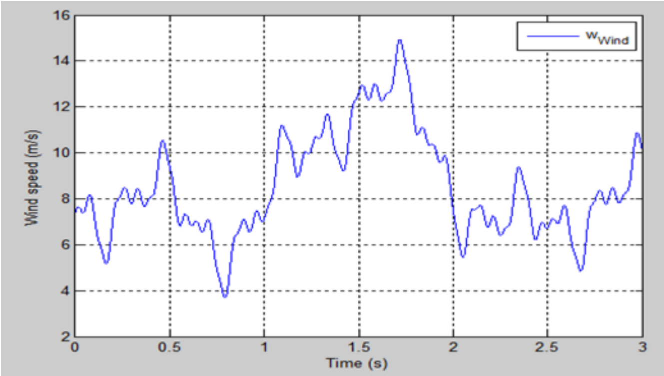

Figure 5. Wind speed variation

The proposed fuzzy controller results in the MPPT responses shown in Figure 6, where the trajectory of the speed of the PMSM is tracking its reference signal and the Power coefficient is quickly achieved. Next, to carry out comparisons with the traditional control method, we apply proportional-integral (PI) control to track the Rotor speed and the Power coefficient Cp

After applying the proposed fuzzy controller, the responses of the Rotor speed and the Power coefficient are shown in Figure 7, Figure 8.the control result is also compared with the PI based MPPT, where the comparison of the tracking error demonstrate that the system with the synthesized T-S fuzzy controller has a good behavior. Indeed, the rotor speed and the power coefficient track well the reference trajectory with good reliability over the whole speed range.

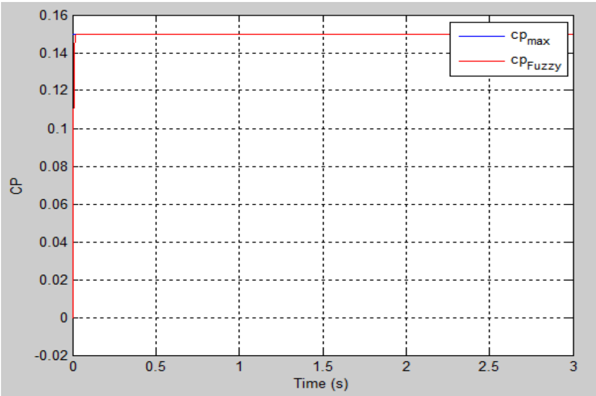

Figure 6a. Power coefficient Cp

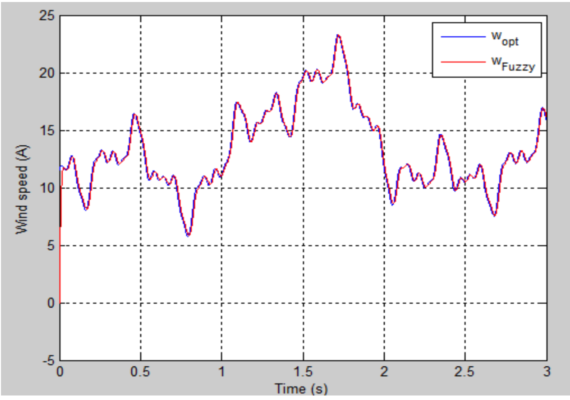

Figure 6b. Rotor speed tracking

Figure 6. Nonlinear T-S Fuzzy control method

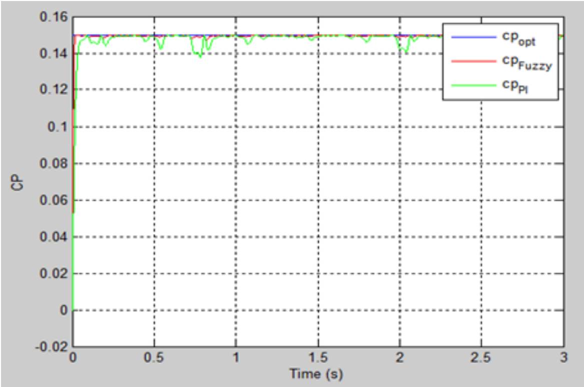

Figure 7a. Power coefficient Cp of PI and TS methods

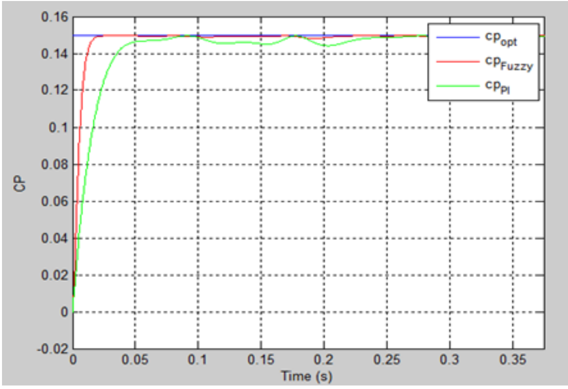

Figure 7b. Zoom of coefficient Cp

Figure 7. Response of Power coefficient Cp

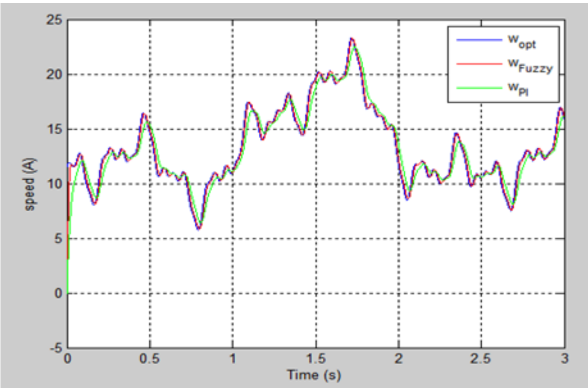

Figure 8a. Rotor speed tracking of PI and TS methods

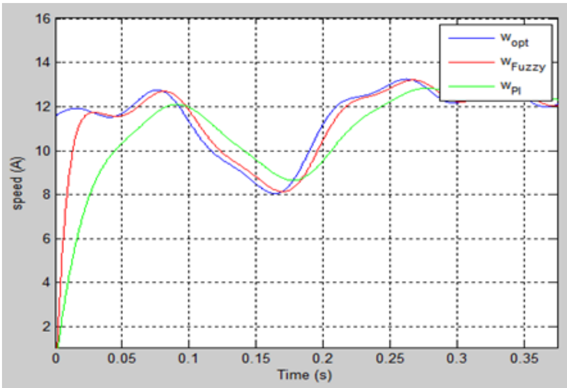

Figure 8b. Zoom of rotor speed tracking

Figure 8. Response of rotor speed tracking

5. CONCLUSION

This work has been devoted to modeling, simulation and analysis of a wind conversion system with the main objective to ensure maximum peak power tracking (MPPT). We have proposed a fuzzy tracking control for a PMSG-WT, the proposed controller has been compared with the PI controller. Simulation results show that the proposed wind system gives best performance and were found the faster than the PI controller.

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