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Fuzzy Model Reference Adaptive Pitch Control of a Variable Speed Wind Turbine in the Full-load Region

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ABSTRACT: This research studies the model reference adaptive control strategy based on the fuzzy theory to control a wind turbine with a doubly-fed induction generator (DFIG). The model reference adaptive control method, incorporating Takagi-Sugeno (T-S) fuzzy logic, is proposed to control the turbine rotor speed using a pitch angle control. The proposed control system aims to address the shortcomings of traditional wind turbine controllers, such as unknown dynamics and system nonlinearities. The proposed hybrid adaptive-fuzzy structure provides an effective tool for controlling the wind turbine system, which exhibits complex nonlinear dynamics. The superiority of the proposed method over the traditional model reference adaptive control lies in modeling the nonlinear system with multiple fuzzy linear models instead of a single linear model. Additionally, the use of the fuzzy method enhances the adaptability of this control method, resulting in more accurate outcomes. Stability analysis of the closed-loop system with the proposed fuzzy model reference adaptive control (FMRAC) is conducted using the Lyapunov method. The proposed FMRAC method is simulated for a 0.2 Mw variable speed wind Turbine and compared with the traditional model reference adaptive control. The simulation results of the proposed method demonstrate higher performance and an accurate response despite the unknown dynamics and nonlinearities of the model.

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1- Introduction

Due to the popularity of renewable energy sources, their low environmental pollution, safety, and affordability, they have attracted significant attention, leading to extensive research on their utilization [1-3]. Among these energy sources, wind energy is particularly noteworthy as a clean and accessible option that is geographically wide, scattered, and decentralized in the world [4-6].

One of the important issues in wind turbines is that, despite the uncontrollable nature of the wind [7], the rotational speed of the turbine rotor should be set within the permissible range. During strong winds, the rotational speed of the rotor can exceed its nominal speed, causing damage to the wind turbine and increasing the output power beyond the required level.

To adjust the rotational speed in large wind turbines, which have a blade angle adjustment system, the pitch angle control of the wind turbine blade is used [8]. Therefore, the application of different control algorithms on wind turbine models has attracted a great deal of attention [9-16]. The traditional pitch angle control strategy is a Proportional Integral (PI) regulator with a gain scheduling [10-12]. Linear Quadratic Gaussian (LQG) and Linear Quadratic Regulator (LQR) optimal control strategies for the wind turbines were also studied in [13-15]. To achieve the desired performance, the method of the model reference control has been used in [17, 18]. In this method, a reference model is defined and the control effort is to make the closed-loop system similar to the reference model with a desired performance. However, this method is applied to a linear model provided by the linearization approximation of nonlinear dynamics. Therefore, an exact model of the dynamics is required and the method works in a limited region of the work point that the linear model is valid. On the other hand, achieving a specific aerodynamic model of wind turbines is difficult [19]. In addition, a significant problem is the difficulty in accurately measuring the wind speed. Without knowing the exact wind speed, it is challenging to formulate the mechanical characteristics of a wind turbine. To deal with the nonlinear and unknowing dynamical model of wind turbines, fuzzy logic control methods were proposed in [20-22]. Despite the advantages of fuzzy control methods, their problem is that the controller in this method does not have a specific structure and there is usually no guarantee of stability for the closed-loop system. Also, the performance of the closed-loop system is highly dependent on the complex design of the fuzzy rules.

In this paper, to avoid the problems and limitations of the mentioned methods and also to take advantage of the two

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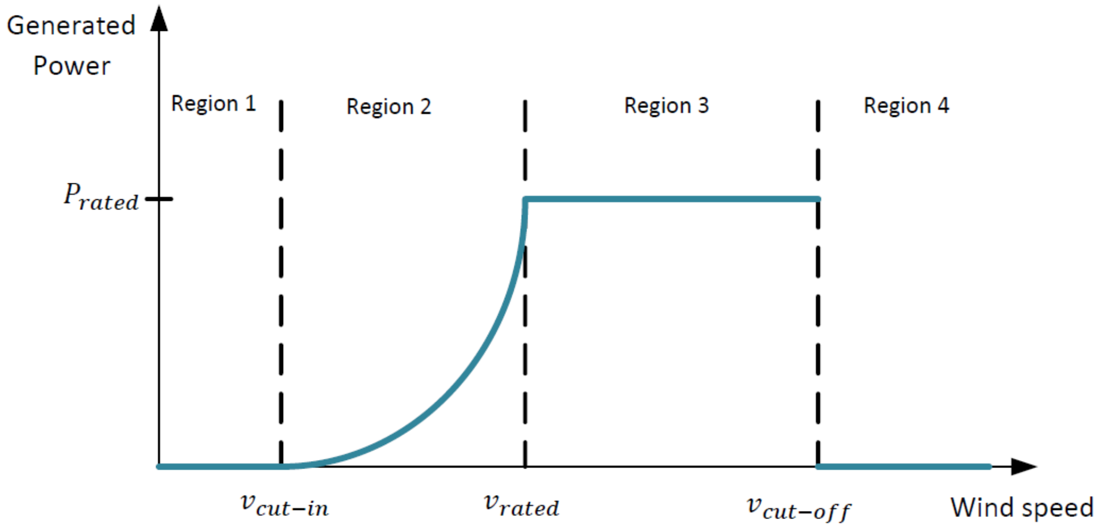

Fig. 1. The different operational regions of the variable speed wind turbine

methods; the model reference control and the fuzzy method, we propose a new control method which is a combination of them, called the Fuzzy Model Reference Adaptive Control. In this method, to control the nonlinear system more accurately, instead of using one linear model, the nonlinear system is approximated to a combination of fuzzy multiple linear models, which is a more accurate approximation of the nonlinear dynamics. In addition, using fuzzy functions in the models helps to deal with unknown dynamics. Therefore, we design a new reference model appropriate to the dynamics of fuzzy multiple linear models of the system. Then, the traditional reference model adaptive control method is extended to the FMRAC that fits the new modeling. The stability of the closed-loop system with the proposed control method is guaranteed by using the Lyapunov method. In addition, by Lyapunov analysis, the new adaptive laws are derived.

The structure of this paper is as follows: A dynamical model of the wind turbine is introduced in Section 2. Section 3 presents the proposed controller design and analyzes its stability and convergence. In Section 4, the simulation results are shown, and finally, Section 6 concludes the paper.

2- Mathematical Model

Wind turbines exhibit nonlinear dynamics due to their complex subsystems. In this paper, we investigate a wind turbine operating exclusively in the full load region and subsequently design the blade pitch angle control.

Based on the wind speed, the variable speed wind turbines operate within four distinct regions, as illustrated in Fig. 1. In Region 1, where the wind speed falls below the cut-in threshold v_{cut-in}, the turbine remains stationary. Region 2, known as the partial load region, features wind speeds insufficient to achieve the rated power generation. In this region, the objective is to maximize power capture from the wind. At an optimal turbine speed, the power extraction is maximized with a pitch angle of zero. Region 3, or the full load region, occurs when the wind speeds exceed the necessary threshold for the rated power generation v_{rated}. Here, the goal is to sustain the power at its rated value using the pitch control system. The turbine power is regulated by dynamically adjusting the rotor blade angle. A control system employs an independent hydraulic actuator to rotate each blade individually between 0 and 90 degrees. In Region 4, the wind speeds surpass the cut-off threshold $v_{cut-off}$, necessitating the turbine's shutdown to prevent damage. The closed-loop structure of the blade pitch angle control is illustrated in Fig. 2.

According to aerodynamic principles, when the wind moves the blade, the produced torque is derived from:[23]

$$T_m = 0.5 C_P(\lambda, \beta) \frac{\rho}{\omega_r} V_{wind}^3 \cos(\phi), \tag{1}$$

where V_{wind} is the wind speed, ρ is the air density, C_P is the power coefficient, β is the pitch blade angle, λ is the blade tip speed, and ϕ is the yaw inclination angle. Also, the mechanical power is as follows:

$$P_m = 0.5 C_P(\lambda, \beta) \rho A V_{wind}^3 \cos(\phi). \tag{2}$$

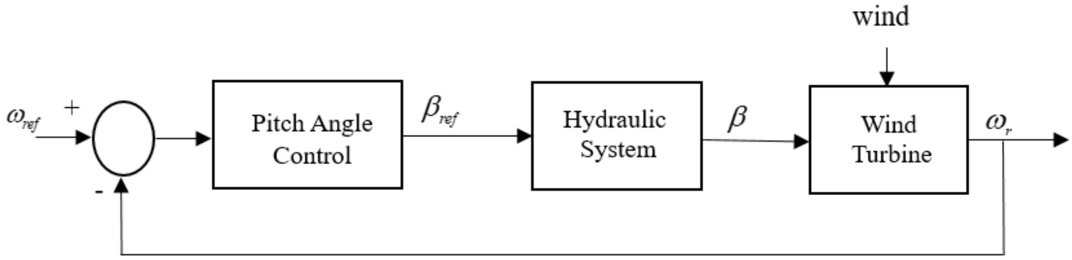

Fig. 2. The closed control loop structure of the blade pitch angle control

A is the swept area by the rotor. The power coefficient is related to the pitch angle and the nominal tip speed of the blade as follows:

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\Gamma} - 0.4\beta - 5\right)exp\left(-\frac{12.5}{\Gamma}\right), \tag{3}$$

and the parameter Γ is defined as:

$$\frac{1}{\Gamma} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1}.$$

Moreover, the blade system has a dynamic model as:

$$\dot{\beta} = \frac{1}{T_\beta}(\beta_{ref} - \beta), \tag{4}$$

where T_β is the time constant of the blade system and β_{ref} is the reference input of the pitch system. In addition, the transmission mechanical system of a turbine is modeled as:

$$T_m - nT_e = J\dot{\omega}_r, \tag{5}$$

where ω_r is the rotor speed, J is the rotor inertia, n is the gearbox ratio, and T_e is the electrical torque of the generator. In this study, an asynchronous generator is considered and it is assumed to be an ideal generator ignoring magnetic saturation, hysteresis, and swirl of stator and rotor. Furthermore, three phase windings of the stator are symmetrical and each phase generates sinusoidal magnetic flux. According to [24] model of the asynchronous generator is as follows:

$$T_e = \frac{gm_1U_1^2r_2}{(g\omega_g - \omega_1)[(r_1 - \frac{C_1r_1\omega_1}{g\omega_g - \omega_1})^2 + (x_1 + C_1x_2)^2]}, \tag{6}$$

where g is the number of poles, m_1 is the phase number, U_1 is the input voltage, r_1 and x_1 are the reactance and the resistance of the rotor, C_1 is a correction factor, ω_g is the generator speed, and ω_1 is the synchronous speed of the generator. Note that the presented model is independent of the network.

From (1), (5), and (6), the overall rotor speed has a dynamical model as:

$$\dot{\omega}_r = \frac{1}{J}\left(\begin{array}{l} 0.5C_P(\lambda,\beta)\frac{\rho}{\omega_r}V_{wind}^3 cos(\phi) \\ -n\dfrac{gm_1U_1^2r_2}{(g\omega_g - \omega_1)[(r_1 - \frac{C_1r_1\omega_1}{g\omega_g - \omega_1})^2 + (x_1 + C_1x_2)^2]} \end{array}\right). \tag{7}$$

Since the yaw angle, ϕ is assumed to be constant, the variation in the angular speed of the turbine is a nonlinear function of ω_r and β:

$$\dot{\omega}_r = f(\omega_r, \beta). \tag{8}$$

The linearized dynamical model is represented by:

$$\dot{\omega}_r = \delta\omega_r + \gamma\beta, \tag{9}$$

where the constants δ and γ are calculated by:

$$\delta = \left.\frac{\partial\dot{\omega}_r}{\partial\omega_r}\right|_{op}, \gamma = \left.\frac{\partial\dot{\omega}_r}{\partial\beta}\right|_{op}. \tag{10}$$

Therefore, the overall state space is presented as:

$$\dot{x}=\begin{bmatrix}\delta & \gamma \\ 0 & -\dfrac{1}{T_\beta}\end{bmatrix}\begin{bmatrix}\omega_r \\ \beta\end{bmatrix}+\begin{bmatrix}0 \\ \dfrac{1}{T_\beta}\end{bmatrix}\beta_{ref}, \tag{11}$$

$$y=\begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}\omega_r \\ \beta\end{bmatrix}, \tag{12}$$

where the state variables are ω_r and β. The control signal is β_{ref}, and the output signal is the rotor speed, ω_r.

3- Proposed Method

From (11) and (12), it is concluded that the dynamic behavior of the wind turbine can be described by second-order differential equations as follows:

$$\ddot{y}(t)=-a\dot{y}(t)-by(t)+cu(t). \tag{13}$$

Therefore, to have multiple linear models from the nonlinear dynamics of the wind turbines, the T-S fuzzy model can be used as follows:

$$\begin{aligned} R^i: & \textit{if} \quad y \quad \textit{is} \quad A_{i_a} \quad \textit{and} \quad \dot{y} \quad \textit{is} \quad B_{i_b} \\ & \textit{then} \quad \ddot{y}(t)=-a_i\dot{y}(t)-b_i y(t)+c_i u(t), \\ & i=1,2,3,\ldots,k. \end{aligned} \tag{14}$$

A_{i_a} and B_{i_b} are the membership functions of the fuzzy model and

$$i_a=1,2,\ldots,n_a, \text{ and } i_b=1,2,\ldots,n_b, \tag{15}$$

where n_a and n_b are the number of membership functions for the first and the second input variables; y and $\dot{y}$. $k=n_a\times n_b$ is the total number of fuzzy rules. The output of the T-S model is derived as:

$$\ddot{y}(t)=\frac{\sum_{i=1}^{k} w_i^*\left(\varphi(k)\right)\left(-a_i\dot{y}(t)-b_i y(t)+c_i u(t)\right)}{\sum_{i=1}^{k} w_i^*\left(\varphi(k)\right)}, \tag{16}$$

where $\varphi(k)$ represents the regressor signals. In order to obtain the degree of fulfillment, the T-norm relation is applied:

$$w_i^*(\varphi(k))=\mu_{A_i}(y)\mu_{B_i}(\dot{y}), \tag{17}$$

where $\mu_{A_i}(y)$ and $\mu_{B_i}(\dot{y})$ are degrees of fulfillment. By defining the vector $\boldsymbol{w}^*\triangleq\left[w_1^*,w_2^*,\ldots,w_k^*\right]^T$ and normalizing as $\boldsymbol{w}=\dfrac{\boldsymbol{w}^*}{\sum_{i=1}^{k}w_i^*}$ that means $\|\boldsymbol{w}\|=1$, the model (16) is rewritten as follows:

$$\ddot{y}(t)=-\boldsymbol{w}^T\boldsymbol{a}\dot{y}(t)-\boldsymbol{w}^T\boldsymbol{b}y(t)+\boldsymbol{w}^T\boldsymbol{c}u(t), \tag{18}$$

where $\boldsymbol{a}=\begin{bmatrix}a_1 & a_2 & \ldots & a_k\end{bmatrix}^T$, $\boldsymbol{b}=\begin{bmatrix}b_1 & b_2 & \ldots & b_k\end{bmatrix}^T$, and $\boldsymbol{c}=\begin{bmatrix}c_1 & c_2 & \ldots & c_k\end{bmatrix}^T$.

It is assumed that the signs of all c_is; $i=1,2,\ldots,k$ are known and the same; $\text{sign}(c_1)=\text{sign}(c_2)=\ldots=\text{sign}(c_k)=\text{sign}(c^*)$.

The fuzzy form of the reference model is written as:

$$\ddot{y}_m(t)=-\boldsymbol{w}^T\boldsymbol{a_m}\dot{y}_m(t)-\boldsymbol{w}^T\boldsymbol{b_m}y_m(t)+\boldsymbol{w}^T\boldsymbol{c_m}u_c(t), \tag{19}$$

where $\boldsymbol{a_m}$, $\boldsymbol{b_m}$, and $\boldsymbol{c_m}$ are defined as $\boldsymbol{a}_m=\begin{bmatrix}a_m & a_m & \ldots & a_m\end{bmatrix}_{k\times 1}^T$, $\boldsymbol{b}_m=\begin{bmatrix}b_m & b_m & \ldots & b_m\end{bmatrix}_{k\times 1}^T$, and $\boldsymbol{c}_m=\begin{bmatrix}c_m & c_m & \ldots & c_m\end{bmatrix}_{k\times 1}^T$, respectively. Since the reference model is stable, $a_m>0$, and $b_m>0$. In addition, we define the output error as:

$$e(t)\triangleq y(t)-y_m(t). \tag{20}$$

The adaptive fuzzy model reference control law is proposed as:

$$u=\boldsymbol{w}^T\boldsymbol{k}_1u_c+\boldsymbol{w}^T\boldsymbol{k}_2y+\boldsymbol{w}^T\boldsymbol{k}_3\dot{y}, \tag{21}$$

where the parameters $\boldsymbol{k}_1$, $\boldsymbol{k}_2$, and $\boldsymbol{k}_3$ are calculated by the following adaptation laws:

$$\begin{aligned} \dot{\boldsymbol{k}}_1&=-\lambda_1\boldsymbol{w}u_c\,\dot{e}\,sign(c^*), \\ \dot{\boldsymbol{k}}_2&=-\lambda_2\boldsymbol{w}\,y\,\dot{e}\,sign(c^*), \\ \dot{\boldsymbol{k}}_3&=-\lambda_3\boldsymbol{w}\,\dot{y}\,\dot{e}\,sign(c^*), \end{aligned} \tag{22}$$

where λ_1, λ_2, and λ_3 are the learning rate constants. The block diagram of the proposed method is shown in Fig. 3.

Theorem. For the turbine dynamics given by (8), using the proposed fuzzy model adaptive reference control law (21) and the adaptation laws (22), the closed loop system is stable and the control parameters are all bounded.

Proof. First, we consider the following control input:

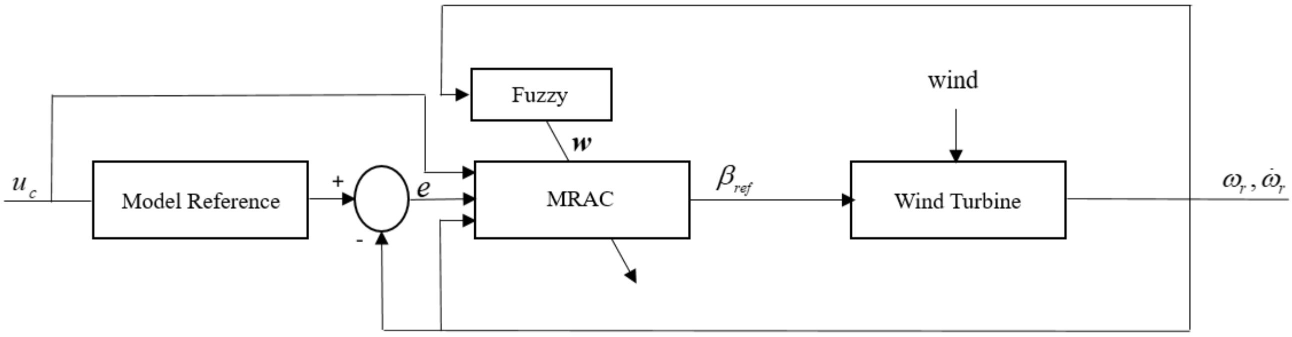

Fig. 3. The block diagram of the wind turbine controlled by the proposed FMRAC method

$$u = \frac{1}{\boldsymbol{w}^T\boldsymbol{c}}\left(\boldsymbol{w}^T\boldsymbol{k}_1^* u_c + \boldsymbol{w}^T\boldsymbol{k}_2^* y + \boldsymbol{w}^T\boldsymbol{k}_3^*\dot{y}\right). \quad (23)$$

By replacing (23) with (18), the closed loop system is:

$$\begin{aligned}\ddot{y}(t) &= \left(-\boldsymbol{w}^T\boldsymbol{a} + \boldsymbol{w}^T\boldsymbol{k}_3^*\right)\dot{y}(t) \\ &+ \left(-\boldsymbol{w}^T\boldsymbol{b} + \boldsymbol{w}^T\boldsymbol{k}_2^*\right)y(t) + \boldsymbol{w}^T\boldsymbol{k}_1^* u_c(t).\end{aligned} \quad (24)$$

Using the output error definition in (20) and by substituting (19) and (24) in $\ddot{e}(t)$ equation, we have:

$$\begin{aligned}\ddot{e}(t) &= -\boldsymbol{w}^T\boldsymbol{a}_m\dot{e} - \boldsymbol{w}^T\boldsymbol{b}_m e + \dot{y}(t)\left(\boldsymbol{w}^T\boldsymbol{k}_3^* - \boldsymbol{w}^T\boldsymbol{a} + \boldsymbol{w}^T\boldsymbol{a}_m\right) \\ &+ y(t)\left(\boldsymbol{w}^T\boldsymbol{k}_2^* - \boldsymbol{w}^T\boldsymbol{b} + \boldsymbol{w}^T\boldsymbol{b}_m\right) + u_c\left(\boldsymbol{w}^T\boldsymbol{k}_1^* - \boldsymbol{w}^T\boldsymbol{c}_m\right).\end{aligned} \quad (25)$$

We consider the following Lyapunov function:

$$\begin{aligned}&V(e, y, f_i^*, q_i^*) = \\ &\frac{1}{2}\left(\boldsymbol{w}^T\boldsymbol{b}_m e^2 + \dot{e}^2 + \gamma_3^{-1}\tilde{\boldsymbol{a}}^T\tilde{\boldsymbol{a}} + \gamma_2^{-1}\tilde{\boldsymbol{b}}^T\tilde{\boldsymbol{b}} + \gamma_1^{-1}\tilde{\boldsymbol{c}}^T\tilde{\boldsymbol{c}}\right),\end{aligned} \quad (26)$$

where γ_1, γ_2, and γ_3 are positive constants, and $\tilde{\boldsymbol{a}}$, $\tilde{\boldsymbol{b}}$, and $\tilde{\boldsymbol{c}}$ are defined as follows:

$$\begin{aligned}\tilde{\boldsymbol{a}} &\triangleq \boldsymbol{a}_m - \boldsymbol{a} + \boldsymbol{k}_3^*, \\ \tilde{\boldsymbol{b}} &\triangleq \boldsymbol{b}_m - \boldsymbol{b} + \boldsymbol{k}_2^*, \\ \tilde{\boldsymbol{c}} &\triangleq -\boldsymbol{c}_m + \boldsymbol{k}_1^*.\end{aligned} \quad (27)$$

The time derivatives of the Lyapunov function is:

$$\dot{V} = \boldsymbol{w}^T\boldsymbol{b}_m e\dot{e} + \dot{e}\ddot{e} + \gamma_3^{-1}\tilde{\boldsymbol{a}}^T\dot{\tilde{\boldsymbol{a}}} + \gamma_2^{-1}\tilde{\boldsymbol{b}}^T\dot{\tilde{\boldsymbol{b}}} + \gamma_1^{-1}\tilde{\boldsymbol{c}}^T\dot{\tilde{\boldsymbol{c}}}. \quad (28)$$

By replacing $\ddot{e}$ from (25), we have:

$$\begin{aligned}\dot{V} &= \boldsymbol{w}^T\boldsymbol{b}_m e\dot{e} - \boldsymbol{w}^T\boldsymbol{a}_m\dot{e}^2 - \boldsymbol{w}^T\boldsymbol{b}_m e\dot{e} \\ &+ \left(\dot{e}\dot{y}\boldsymbol{w}^T + \gamma_3^{-1}\dot{\tilde{\boldsymbol{a}}}^T\right)\tilde{\boldsymbol{a}} + \left(\dot{e}y\boldsymbol{w}^T + \gamma_2^{-1}\dot{\tilde{\boldsymbol{b}}}^T\right)\tilde{\boldsymbol{b}} \\ &+ \left(\dot{e}u_c\boldsymbol{w}^T + \gamma_1^{-1}\dot{\tilde{\boldsymbol{c}}}^T\right)\tilde{\boldsymbol{c}}.\end{aligned} \quad (29)$$

Therefore, by choosing:

$$\begin{aligned}\dot{\tilde{\boldsymbol{a}}}^T &= -\gamma_3\dot{e}\,\dot{y}\,\boldsymbol{w}^T, \\ \dot{\tilde{\boldsymbol{b}}}^T &= -\gamma_2\dot{e}\,y\,\boldsymbol{w}^T, \\ \dot{\tilde{\boldsymbol{c}}}^T &= -\gamma_1\dot{e}\,u_c\boldsymbol{w}^T,\end{aligned} \quad (30)$$

we have:

$$\dot{V} = -\boldsymbol{w}^T\boldsymbol{a}_m\dot{e}^2, \quad (31)$$

which is negative definite. This completes the proof. On the other hand, since the reference u_c, x_m and $\dot{x}_m$ are bounded, $\dot{x}$ should also be bounded. In addition, from the boundedness of $\ddot{V}$, by using Barbalat's lemma, it can be also concluded that $\lim_{t\to\infty}\dot{e}(t) = 0$.

Using the definitions (27) in (30), the adaptation laws are derived as:

$$\begin{aligned}\dot{\boldsymbol{k}}_1^* &= -\gamma_1\boldsymbol{w}u_c\,\dot{e}, \\ \dot{\boldsymbol{k}}_2^* &= -\gamma_2\boldsymbol{w}\,y\dot{e}, \\ \dot{\boldsymbol{k}}_3^* &= -\gamma_3\boldsymbol{w}\,\dot{y}\dot{e}.\end{aligned} \quad (32)$$

Now, by defining $\boldsymbol{k}_i \triangleq \frac{\boldsymbol{k}_i^*}{\boldsymbol{w}^T\boldsymbol{c}}$, and $\lambda_i \triangleq \frac{\gamma_i}{\boldsymbol{w}^T\boldsymbol{c}} sign(c^*)$; $i = 1,2,3$, and substituting in control law (24) as well as in the adaptation laws (32), the equations (21) and (22) are derived as the control and the adaptation laws, respectively.

4- Simulation Results

In this section, we simulate a 0.2 MW wind turbine using the parameters provided in Table 1. The nonlinear dynamics model is described by equations (4) and (7). We apply a wind model with an average speed of 12 m/s to the system, as shown in Fig. 4. The angular velocity is controlled by pitch angle using the FMRAC method, and the results are compared with those obtained using the traditional MRAC.

The controller is designed as described in (21) with the adaptation laws given in (22). For each of the two variables $y(t)$, and $\dot{y}(t)$, three Gaussian membership functions with the formula $f_k = e^{-(\frac{y-m_k}{v_k})^2}$; $k = 1,2,3$ are applied, where m_k and v_k are the k^{th} center and the k^{th} deviation of the function, respectively. The deviations related to the variable $y(t)$ are 2 and the centers are chosen as 0.1, 0.65, and 3. For the variable $\dot{y}(t)$, the deviations vector is $[15000 \quad 150000 \quad 15000]$ and the center's vector is $[-100 \quad 0 \quad 100]$. Fig. 5 compares the regulation of the rotor angular speed at the reference angular

Table 1. The simulated turbine parameters

Parameters	Values
n	40.96
D	47 m
ρ	1.25 kg/m^3
T_β	0.01 s
ω_1	188.4 rad/s
J	0.578
m_1	3
U_1	690 v
r_1	0.046 Ω
x_1	0.425 Ω
r_2	0.046 Ω
x_2	0.353 Ω

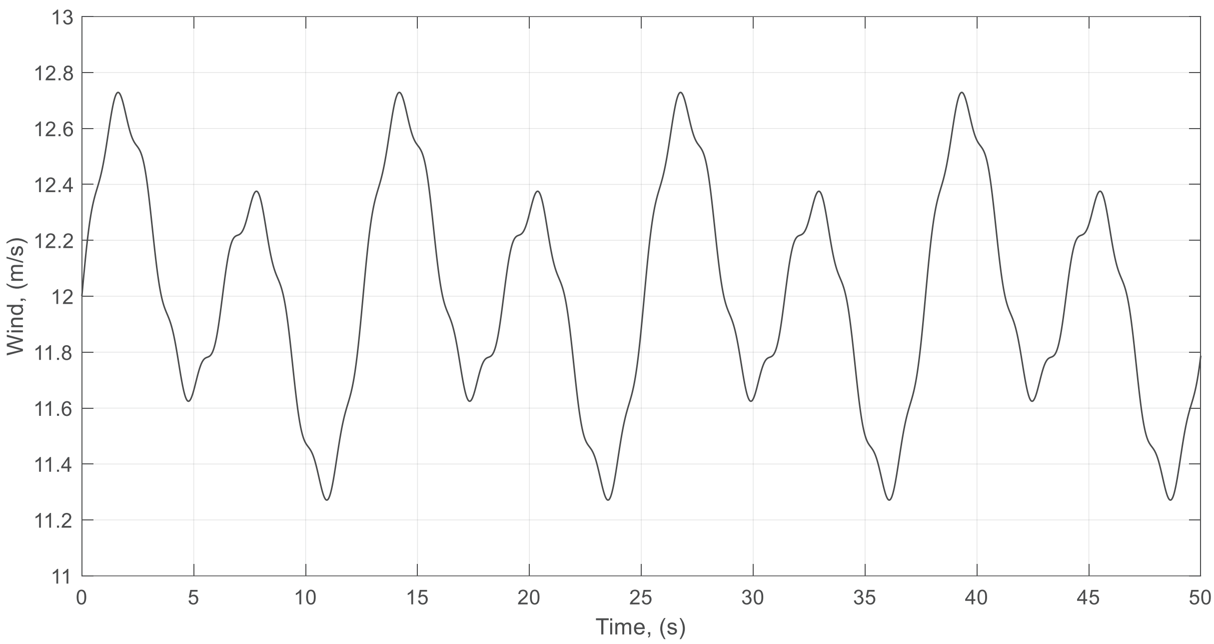

Fig. 4. The wind speed profile with an average of 12 m/s.

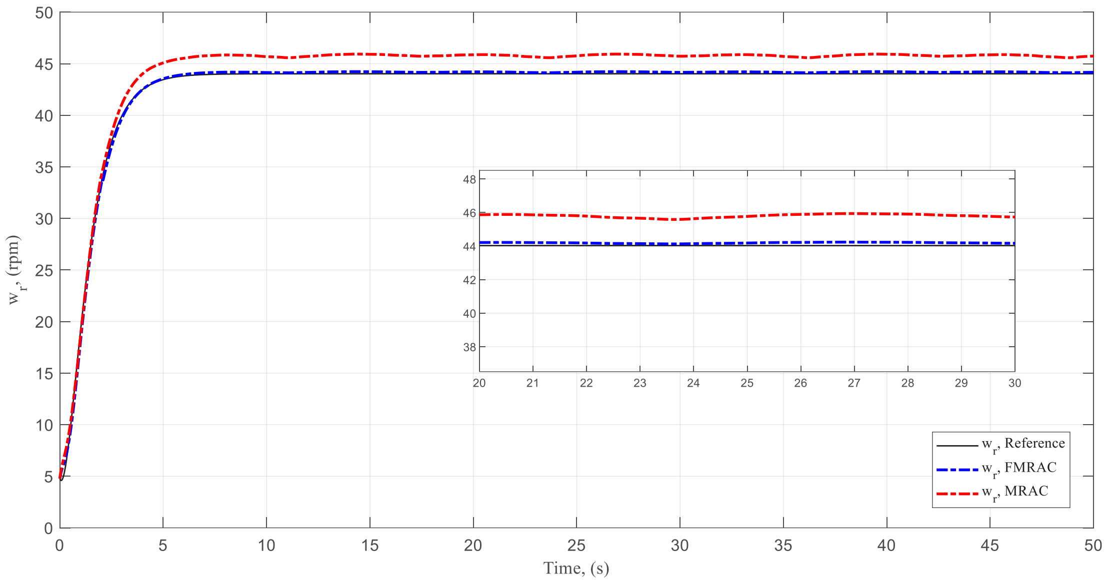

Fig. 5. The angular speed of the rotor is controlled with two methods, FMRAC and MRAC.

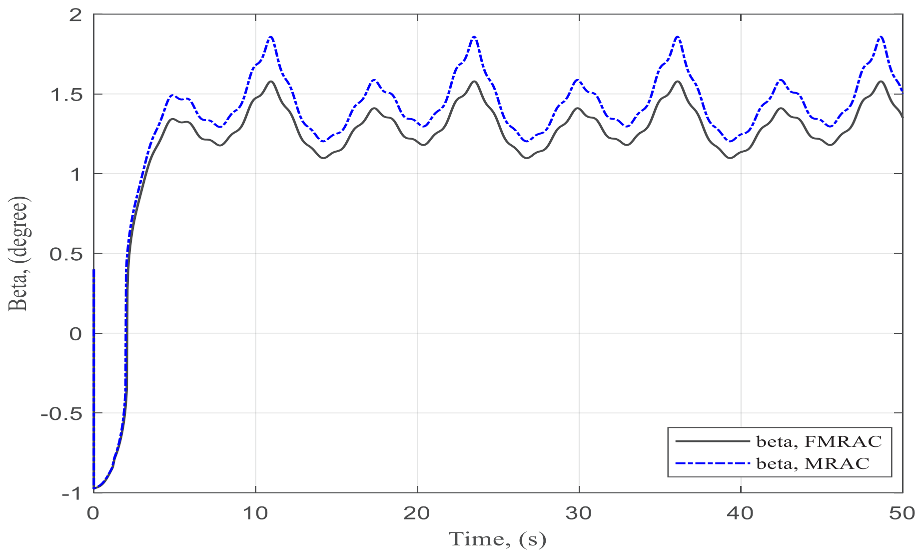

Fig. 6. The pitch angle changes.

speed of 44.04 *rpm*, with both control methods; *FMRAC*, and *MRAC*. For better comparison, the figure is zoomed in on the time interval of 20-30 seconds. As seen, the *FMRAC* method has higher efficiency than the *MRAC* method. This is due to its higher adaptability and the use of several adaptive linear models of the system instead of a single linear model. Fig. 6 also shows the changes in the pitch angle. Fig. 7 shows the electrical power. As expected, it is negative for the stator speed less than the synchronous speed, ω_1. For higher speeds, the turbine produces 0.2 MW of electrical power.

5- Conclusion

In this study, the proposed FMRAC controller has been applied to a DFIG wind turbine for pitch angle control to regulate the rotor angular speed. The stability of the proposed method, as well as the boundedness of the controller parameters have been proven by Lyapunov analysis. The proposed method has been applied to a 0.2 MW wind turbine with unknown nonlinear dynamics. The results showed that the rotor angular speed is controlled with high performance despite the nonlinearities and uncertainties in the dynamics.

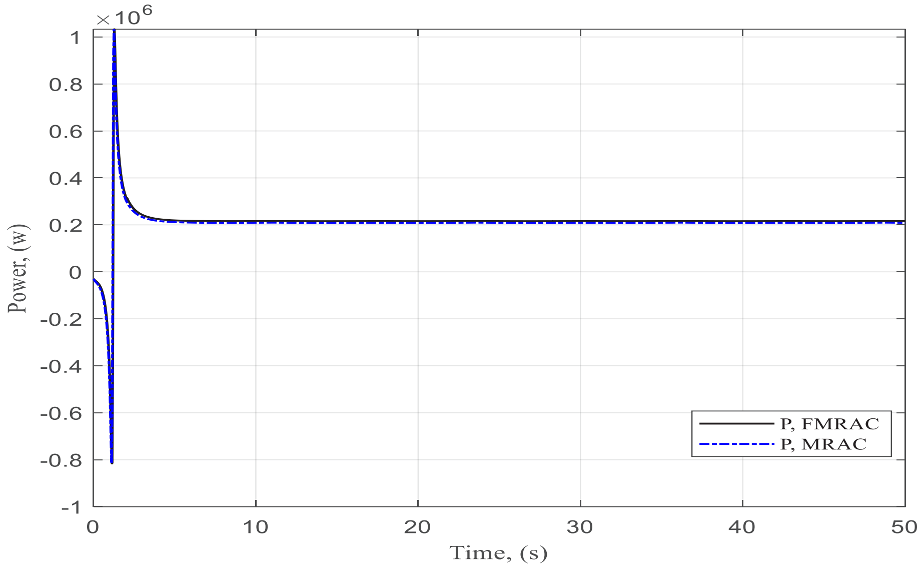

Fig. 7. The electrical power generated by the 0.2 MW turbine.

Additionally, the proposed controller, utilizing a fuzzy logic approach, shows better performance compared to the traditional MRAC due to its higher adaptability and the use of several adaptive linear models of the system instead of a single linear model. The reliability and performance of the proposed method could make it a suitable option for replacing the existing wind turbine control systems to meet the power supply requirements.

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