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MPPT control of a Wind Energy Conversion System using T-S Fuzzy Model

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***Abstract*—A wind generation system composed of a wind turbine and a Permanent Magnet Synchronous Generator (PMSG) associated to an AC-DC converter is treated in this paper. As to maintain a maximum power produced by the turbine, a fuzzy controller based on Takagi-Sugeno (T-S) model is designed in the objective of Maximum Power Point Tracking (MPPT). First, The Wind Energy Conversion System (WECS) is modeled using TS fuzzy approach. Then, the design of the controller is carried out in means of Linear Matrix Inequalities (LMI) techniques and by applying Lyapunov stability approach. Finally, Simulation results are presented to validate the performance of the proposed strategy.**

***Index Terms* —WECS, MPPT, T-S fuzzy controller, LMI.**

I. INTRODUCTION

Many factors have led to the increase of renewable energy popularity such as the low cost of installation, the lack of the fossil fuels reserves, and especially it is considered as a suitable solution for rural areas which are isolated. Since wind energy conversion systems (WECS) can provide a reliable electricity supply and allow continuous power generation, so they represent a cost-competitive solution dedicated to rural electrification. Therefore wind energy applications are widely spread in the world.

The primary energy source of the generators in wind turbine systems is the wind which is unpredictable and changes frequently [1]. For this reason, a power electronic interface is needed to establish the connection between the wind generator and the grid in the objective of extracting the optimum of produced power although different wind speed changes.

Many structures of wind systems are treated in literature like in [2], [3], [4], [13] and [16]. In this study, we consider the system shown in Fig.1, which is composed of a fixed pitch angle wind turbine that drives a permanent magnet synchronous generator (PMSG). An AC/DC power electronic converter is mounted with the synchronous generator and followed by a continuous DC bus. So, the wind turbine power is transmitted to the DC link and finally supplied to the load.

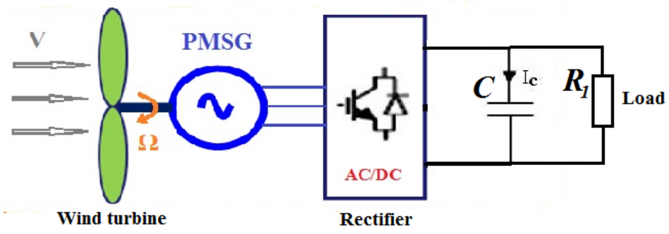

Fig. 1. Block diagram of the wind generation system

The aim in this work is to control the considered wind system in order to track the maximum power point and to provide a reliable energy supply. Numerous researches have focused on this topic and different MPPT algorithms have been investigated such as in [5], [6], [7] and [15].

The most known classical MPPT schemes for wind systems are PI regulator and vector control like in [8], [9], [12] and [14].

In the current study, we propose an intelligent control strategy to guarantee the maximum wind power tracking using fuzzy logic. Due to the high non linearity that is characterizing the system, the designed controller is based mainly on T-S fuzzy modeling which permits to describe non-linear system by the decomposition of the model into linear local sub-models. . Next, a combination of those sub-models is realized in the means of control design [10]. For the stability analysis of the treated system, the control gains are calculated by using Linear Matrix Inequality (LMI) techniques and Lyapunov approach.

The paper is organized as following: in section II the different components of the wind energy studied system are modeled. Then, the third section describes the design of the T-S fuzzy controller. First, the MPPT strategy principle is presented. Then, the system is described by a T-S fuzzy model and stability analysis of the controller is studied in terms of H infinity performance. In the next section, simulation results for the proposed fuzzy controller are presented in order to check the effectiveness of the control scheme. Finally, the manuscript ends with some conclusions in section V.

II. MODELING OF THE WIND ENERGY CONVERSION SYSTEM:

As illustrated in Fig.1, The WECS treated in this study includes a fixed-pitch angle wind turbine coupled with a PMSG and a power electronic converter. The power generated by the turbine is given by [11]:

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$$P_t = 0.5C_p(\lambda,\beta)\rho A v^3 \qquad (1)$$

Where A denotes the turbine swept area (m^2), ρ presents the air density $(Kg.m^{-3})$, v is the wind velocity $(m.s^{-1})$, and $C_p(\lambda)$ is the power coefficient.

The tip-speed ratio λ is such that $\lambda = (R.\Omega/v)$ (2)

where R is the blade length and Ω is the rotational speed.

The maximum power generated by the turbine satisfies

$$P_{t(\max)} = 0.5C_{p(\max)}(\lambda_{opt})\rho\pi R^5\Omega_r^3 / \lambda_{opt}^3 \qquad (3)$$

Where $C_{p(max)}$ and λ_{opt} are respectively the optimal values of the tip speed ratio and the power coefficient.

The expression of the optimum mechanical torque is the following:

$T_{m(ref)} = K_o\,\Omega_r$ (4)

where $K_o = 0.5C_{p(max)}\,\rho\pi R^5/\lambda_{opt}^3$

By defining i_{sd} and i_{sq} the stator current (d,q) components, the electromagnetic torque in d-q reference frame is described as $T_{em} = p\Psi_f i_{sq}$ (5)

Where p represents the pole pairs number and ψ_f being the magnetic flux.

Also, the mechanical speed behavior of the PMSG is described by

$$J\frac{d\Omega}{dt} = T_m - T_{em} - f\Omega \qquad (6)$$

where J is defining the PMSG moment of inertia and f is the friction coefficient.

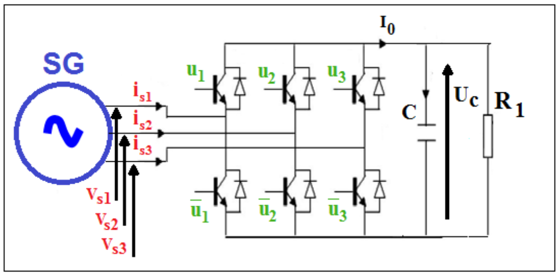

Fig.2. PMSG associated to the rectifier

In Fig.2 , a description of the synchronous generator coupling with the rectifier is presented. The input three phases voltages V_{si} (i=1,2,3) and the output current I_0 are described using β_i which denotes the average value of the switching function u_i over the PWM period, the output DC side voltage U_c and the input currents i_{si}. The dynamic of the stator voltage expressions in d − q reference frame are given by :

$$\begin{cases} v_{sd} = -R_s i_{sd} - L_s\dfrac{di_{sd}}{dt} + p\Omega L_s i_{sq} = \dfrac{U_c}{2}\beta_d \\ v_{sq} = -R_s i_{sq} - L_s\dfrac{di_{sq}}{dt} - p\Omega L_s i_{sd} + p\Omega\Psi_f = \dfrac{U_c}{2}\beta_q \end{cases} \qquad (7)$$

where R_s and L_s denote respectively the synchronous resistance and inductance.

The stator current, the stator voltage and the output current are expressed in d-q reference frame as following :

$$\begin{bmatrix} \dfrac{d}{dt}i_{sd} \\ \dfrac{d}{dt}i_{sq} \end{bmatrix} = \begin{bmatrix} -\dfrac{R_S}{L_S} & w \\ -w & -\dfrac{R_S}{L_S} \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L_S} & 0 \\ 0 & \dfrac{1}{L_S} \end{bmatrix}\begin{bmatrix} E_d \\ E_q \end{bmatrix} - \frac{1}{2L_S}\begin{bmatrix} \beta_d \\ \beta_q \end{bmatrix}U_c \qquad (8)$$

with w=pΩ is the electrical angular speed, E_d and E_q are the electromotive force (d,q) components given by $E_d = 0$ and $E_q = p\psi_f\Omega$

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} \beta_d \\ \beta_q \end{bmatrix}U_c \qquad (9)$$

$$I_0 = \frac{3}{4}\begin{bmatrix} \beta_d & \beta_q \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} \qquad (10)$$

The voltage at the rectifier output satisfies:

$$\frac{dU_c}{dt} = \frac{3}{4C}\begin{bmatrix} \beta_d & \beta_q \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} - \frac{U_C}{R_1 C} \qquad (11)$$

III. T-S FUZZY CONTROLLER

A. *The principle of MPPT control*

The aim of the MPPT algorithm is to keep the generated power at its maximum by maintaining the tip speed ratio at $\lambda_{opt,}$. So, the reference of the rotor speed is given by the following expression $\Omega_r = (\lambda_{opt}.v_v)/R$.

The principle of the control strategy is to keep the controlled parameters at their references, once the optimum value of λ is known, it is easy to calculate the reference of the q-axis stator currant as following:

$$i_{sqr} = -\frac{K_o}{p\psi_f}\Omega_r^2 \qquad (12)$$

The reference signal of the d-axis stator current is supposed equal to zero $i_{sdr} = 0$, therefore, we can calculate the reference of the voltage as follows

$$U_{cr} = \frac{2}{\beta_q}(p\psi_f\Omega_r) \qquad (13)$$

B. *T-S Fuzzy Modeling*

In this section we will focus on the T-S fuzzy modeling of the WECS. So we introduce the state vector as: $x(t) = [i_{sd} \quad i_{sq} \quad U_c \quad \Omega]^T$

and the control signal as

$u(t) = [\beta_d \quad \beta_q]^T$

So that, the fuzzy model of the WECS can be described by :

$$\dot{x}(t) = A(x,u)x(t) + B(x)u(t) \qquad (14)$$
$$y(t) = Cx(t)$$

Where

$$A(x,u) = \begin{bmatrix} \frac{-R_s}{L_s} & p\Omega & 0 & 0 \\ -p\Omega & \frac{-R_s}{L_s} & 0 & \frac{p\psi_f}{L_s} \\ \frac{3}{4C}\beta_d & \frac{3}{4C}\beta_q & -\frac{1}{R_1 C} & 0 \\ 0 & -\frac{p\psi_f}{J} & 0 & \frac{K_o\Omega - f}{J} \end{bmatrix}$$

$$B(x) = \begin{bmatrix} \frac{-U_c}{2L_s} & 0 \\ 0 & \frac{-U_c}{2L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

and $C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

The fuzzy premise variables are noted z_j (t) and given by :

$$z_1(t) = \Omega; z_2(t) = \beta_d; z_3(t) = \beta_q; z_4(t) = U_c$$

Hence, the wind generation system is then described by T-S fuzzy rules which are written in ‘if-then’ form as following:

If $z_1(t)$ is S_{1i} and …and $z_4(t)$ is S_{4i}, then

$$\dot{x}(t) = A_i x(t) + B_i u(t) \qquad (15)$$
$$y(t) = Cx(t)$$

Where S_{ji} denotes the fuzzy sets, r is the fuzzy rules number and A_i and B_i are the local subsystem matrices given by:

$$A_i = \begin{bmatrix} \frac{-R_s}{L_s} & pz_{1i} & 0 & 0 \\ -pz_{1i} & \frac{-R_s}{L_s} & 0 & \frac{p\psi_f}{L_s} \\ \frac{3}{4C}z_{2i} & \frac{3}{4C}z_{3i} & -\frac{1}{R_1 C} & 0 \\ 0 & -\frac{p\psi_f}{J} & 0 & \frac{K_o z_{1i} - f}{J} \end{bmatrix} \quad B_i = \begin{bmatrix} \frac{-z_{4i}}{2L_s} & 0 \\ 0 & \frac{-z_{4i}}{2L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

Let define the premises variable vector as: $z(t) = \begin{bmatrix} z_1(t) & z_2(t) & z_3(t) & z_4(t) \end{bmatrix}^T$

The WECS can be described by the following equations:

$$\begin{cases} \dot{x}(t) = \sum\limits_{i=1}^{r} H_i(z(t))\{A_i x(t) + B_i u(t)\} \\ y(t) = Cx(t) \end{cases} \qquad (16)$$

The degree of activation for rule “i” is normalized as:

$$H_i(z(t)) = \frac{v_i(z(t))}{\sum\limits_{i=1}^{r} v_i(z(t))} \text{ with } v_i(z(t)) = \prod_{j=1}^{4} S_{ji}(z(t))$$

Defining M_j and m_j as the maximum and the minimum bounds of the variable $z_j(t)$ for j=1,2,3,4 , the membership functions are chosen as

$$f_j = \frac{z_j(t) - m_j}{M_j - m_j} \;,\; \bar{f}_j = 1 - f_j \qquad (17)$$

The reference state vector to track is defined as $x_r(t) = [i_{sdr} \quad i_{sqr} \quad U_{cr} \quad \Omega_r]^T$, so we introduce $e(t) = x(t) - x_r(t)$ as a state tracking errors, therefore the new PDC fuzzy controller is given by :

$$u(t) = -\sum_{i=1}^{r} H_i(z(t))K_i e(t) \qquad (18)$$

and the the resulting dynamic error model is designed as :

$$\dot{e}(t) = \sum_{i=1}^{r} H_i(z(t))(A_i(t) + B_i u(t) + A_i x_r) \qquad (19)$$

By introducing another state variable $e_I = \int e$ in order to avoid steady state errors, then the control law is expressed by

$$u(t) = -\sum_{i=1}^{r} H_i(z(t))\bar{K}_i \bar{e}(t)$$

where $\bar{K}_i = \begin{bmatrix} K_i & F_i \end{bmatrix}$ and $\bar{e}(t) = \begin{bmatrix} e(t) & e_I(t) \end{bmatrix}^T$.

So that the augmented form of T-S model is described by:

$$\dot{e}(t) = \sum_{i=1}^{r} H_i(z(t))[\bar{G}_i \bar{e}(t) + \bar{D}_i \bar{h}] \qquad (20)$$

With $\bar{G}_i = \bar{A}_i - \bar{B}_i \bar{K}_i \qquad \bar{A}_i = \begin{bmatrix} A_i & 0 \\ I & 0 \end{bmatrix} \qquad \bar{B}_i = \begin{bmatrix} B_i \\ 0 \end{bmatrix}$

$$\bar{D}_i = \begin{bmatrix} A_i & 0 \\ 0 & 0 \end{bmatrix} \qquad \bar{h} = \begin{bmatrix} x_r \\ 0 \end{bmatrix}$$

C. *Stability analysis*

In order to study the stability of the system, the H_∞ tracking performance is adopted for ensuring smooth reference tracking under the influence of perturbation, denoting by γ a defined value :

$$\int_0^\infty \overline{e}^T(t)\overline{e}(t)dt < \gamma^2 \int_0^\infty \overline{h}^T \overline{h} dt \qquad (21)$$

$V(\overline{e}) = \overline{e}^T P \overline{e}$ is the Lyapunov function candidate where $P = P^T > 0$ is the common definite positive matrix.

The Lyaunov function time derivative has to satisfy:

$$\dot{V}(\overline{e}(t)) = \dot{\overline{e}}^T P \overline{e} + \overline{e}^T P \dot{\overline{e}} < 0 \qquad (22)$$

In the aim to accomplish the H-infinity performance associated to the tracking error, the condition is:

$$\dot{V}(\overline{e}(t)) + \overline{e}^T(t)\overline{e}(t) - \gamma^2 \overline{h}^T \overline{h} < 0 \qquad (23)$$

By remplacing (19) and (21) in (22) we get:

$$\sum_{i=1}^{r} H_i(z(t)) \left\{ \begin{array}{l} \overline{e}^T(t)[\overline{G}_i^T P + P_i \overline{G}_i^T]\overline{e}(t) \\ +\overline{h}^T[\overline{D}_i^T P]\overline{e}(t) \\ +\overline{e}^T(t)[P\overline{D}_i]\overline{h} \end{array} \right\} - \gamma^2 \overline{h}^T \overline{h} < 0 \qquad (24)$$

$$\begin{bmatrix} \overline{e}^T(t) & \overline{h}^T \end{bmatrix} \times \begin{bmatrix} \sum\limits_{i=1}^{r} H_i(z(t))[\overline{G}_i^T P + P_i \overline{G}_i^T] + I & P \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i \\ \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i^T P & -\gamma^2 I \end{bmatrix} \times \qquad (25)$$

$$\begin{bmatrix} \overline{e}(t) \\ \overline{h} \end{bmatrix} < 0$$

To check this inequality, it suffices to check that:

$$\begin{bmatrix} \sum\limits_{i=1}^{r} H_i(z(t))[\overline{G}_i^T P + P_i \overline{G}_i^T] + I & P \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i \\ \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i^T P & -\gamma^2 I \end{bmatrix} < 0 \qquad (26)$$

That means :

$$\begin{bmatrix} \sum\limits_{i=1}^{r} H_i(z(t))[\overline{G}_i^T P + P_i \overline{G}_i^T] & P \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i \\ \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i^T P & -\gamma^2 I \end{bmatrix} + \qquad (27)$$

$$\begin{bmatrix} I & 0 \\ 0 & 0 \end{bmatrix} < 0$$

By using the Shur lemma we obtain:

$$\begin{bmatrix} \sum\limits_{i=1}^{r} H_i(z(t))[\overline{G}_i^T P + P_i \overline{G}_i^T] & P \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i & I \\ \sum\limits_{i=1}^{r} H_i(z(t))\overline{D}_i^T P & -\gamma^2 I & 0 \\ I & 0 & -I \end{bmatrix} < 0 \qquad (28)$$

Which allows writing :

$$\begin{bmatrix} [\overline{G}_i^T P + P_i \overline{G}_i^T] & P\overline{D}_i & I \\ \overline{D}_i^T P & -\gamma^2 I & 0 \\ I & 0 & -I \end{bmatrix} < 0 \qquad (29)$$

By multiplying by $\begin{bmatrix} P^{-1} & 0 & 0 \\ 0 & I & 0 \\ 0 & 0 & I \end{bmatrix}$, we obtain :

$$\begin{bmatrix} P^{-1}[\overline{G}_i^T P + P_i \overline{G}_i^T]P^{-1} & P^{-1}P\overline{D}_i & P^{-1} \\ \overline{D}_i^T P P^{-1} & -\gamma^2 I & 0 \\ P^{-1} & 0 & -I \end{bmatrix} < 0 \qquad (30)$$

Let $X = P^{-1}$ and $M_i = \overline{K}_i P^{-1}$, by using the T-S fuzzy control law, the MPPT of the WECS is realised if the control gains are prescribed as $\overline{K}_i = M_i X^{-1}$ with the matrices X and M_i satisfying the following LMI:

$$\begin{bmatrix} \overline{A}_i^T X + X\overline{A}_i^T - \overline{B}_i M_i - M_i^T \overline{B}_i^T & \overline{D}_i & X \\ \overline{D}_i^T & -\gamma^2 I & 0 \\ X & 0 & -I \end{bmatrix} < 0 \qquad (31)$$

IV. SIMULATION RESULTS

In order to check the performance of the proposed controller for the optimum extracted power from the WECS, the wind speed profile is chosen as illustrated in Fig 3.

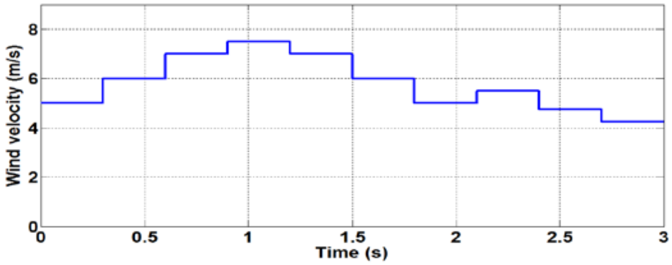

Fig.3. The wind profile

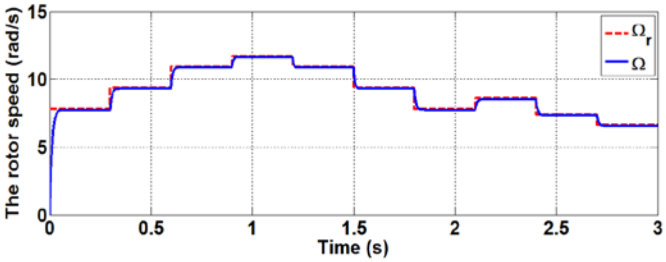

Fig.4. The rotor speed with its reference

The above figure is presenting the speed rotor tracking. It is clear that the curve follws its reference for the different wind speed variations.

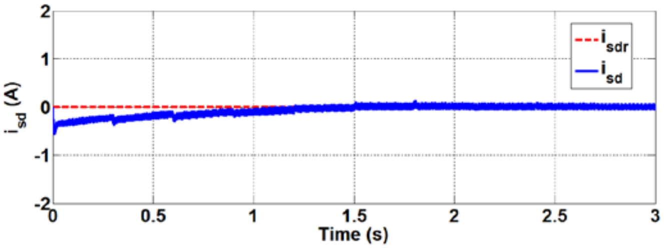

Fig.5. d-axis stator current with its reference

As it is shown in Fig.5, the direct stator current is still somewhat precisely close to zero which represents the reference of d-axis stator current.

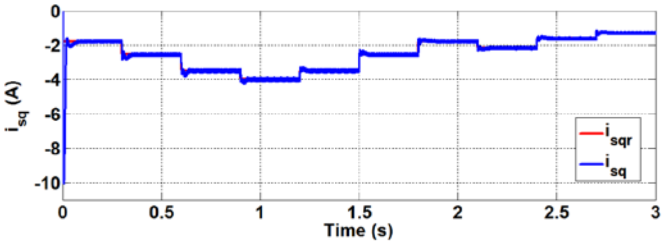

Fig.6. q-axis stator current with its reference

Moreover, the trajectory of the q-axis stator current which is given by Fig.6 is following the reference signal. Therefore, a good tracking performance is obtained through the proposed controller.

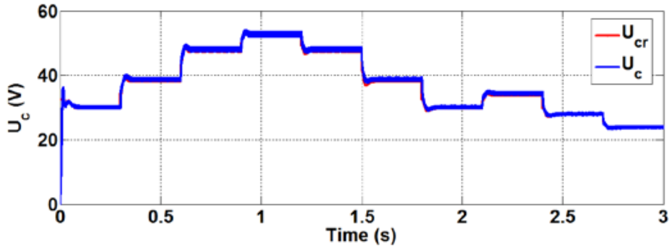

Fig.7. The bus voltage trajectory with its reference

The bus voltage curve which is shown in Fig.7 is tracking the signal of reference.

From simulations, it can be seen that the states follow their references signals which illustrates the effectiveness of the control scheme.

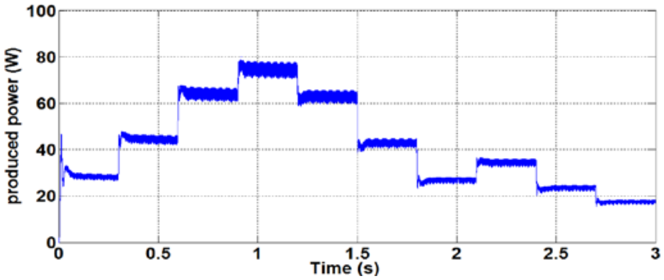

Fig.8 .WECS produced power respone

With reference to Fig.8, we can notice that for different wind speed values, the power generated by the WECS is kept maximized in spite of rapid wind speed variations. Thus, we can deduce that the designed T-S fuzzy controller ensures a good tracking performance and can to guarantee the MPPT.

V. CONCLUSION

In this study, a T-S fuzzy control scheme is designed for a wind system turbine. The different components of the WECS were modeled by means of T-S fuzzy approach. After that, the control strategy was described and the fuzzy controller design was presented. As to finish, the simulation process validates the efficiency of the MPPT algorithm in the aim to achieve the maximum power generated by the system although the wind speed variation.

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