Intelligent Control of Wind Conversion System based on PMSG using T-S Fuzzy Scheme

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Received: 09.06.2015 Accepted: 21.07.2015

Abstract- This paper presents a topology of control dedicated to a wind energy conversion system (WECS) using a Permanent Magnet Synchronous Generator (PMSG) and AC/DC rectifier in the objective of ensuring maximum power generation. The control aim is to track the generator reference speed according to the wind velocity variation in order to maximize the power output and enhance system performance. For this purpose, the WECS modelling is carried out on the basis of Takagi–Sugeno (T-S) fuzzy model. The control gains are calculated by solving Linear Matrix Inequalities (LMIs). Finally, simulation results have been presented to check the proposed approach efficiency.

Keywords—Wind energy conversion system, PMSG, AC/DC converter, T-S fuzzy control, linear matrix inequality (LMI).

1. Introduction

The global warming effect together with the diminishing reserves of fossil fuels has contributed to increasing attention given to renewable electrical energy. By all of different forms of renewable energy, the wind energy has been recognized as the main source in power industry. The wind power resources are massive around the world. It has been evaluated that only 10% of raw wind potential are able to satisfy all the world requirements in electricity if it could be put to use [1]. In light of this, improving the performance of wind turbines and wind energy conversion systems (WECS) is progressively increasing attention as a topic research.

Because of the increase of the turbine power range, it has been needed to establish an interface which provides connection between the wind turbine and the grid. As a solution, power electronics are already introduced to make the link, then different topologies for power conversion schemes are adopted in literature. Many generator-converter systems have been popularly used such as in [2, 3, 22, 23]. The most widespread topology in industry is the six pulse diode rectifier and pulse width modulated (PWM) inverter because of its low cost as in [25], whereas, this technology allows the power flow in only one direction contrarily to back-to-back power converter. The latter permits the bidirectional power flow which is interesting in certain applications.

Many researchers have proposed various control schemes in order to extract the optimal accessible power given by the WECS [4]. The simplest techniques for searching the maximum power point are based on PI controller and Perturb and Observe algorithm [5, 6], but these methods are still classical and lack of performance. Another known method is neural network method which estimates the wind velocity from the measured wind power and generator speed, and consequently the maximum power generator speed control or torque reference can be deduced for the operational point tracker [7,8]. Even though neural network may guarantee fast response, the performance of control fails along the system variation. Furthermore, fuzzy logic methods have been widely adopted and they have presented better effectiveness [9, 10, 26]. However, the major problems 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 order to overcome this problem, sliding mode control is applied in
several works [11, 12], but its main drawback is its complexity and the difficulty of implementation.

In comparison, Takagi-Sugeno (T-S) modelling has proved its performance in the study of nonlinear systems. In that sense, 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. Considerable researches are investigated e.g. [13, 14, 15, 21].

The principal benefit of T-S fuzzy approach is that it provides a simple way to construct the controller since it is systematically constructed based on Parallel Distributed Compensation (PDC) together with Linear Matrix Inequality (LMI) method [14]. The fuzzy model of Takagi Sugeno allows modelling the nonlinear system by representing local dynamics by linear models. Therefore, 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 [15]. The theory of Lyapunov stability is applied to realize the fuzzy controller. In other words, the stability analysis problem and the control design are reduced to LMI conditions which can be easily solved by using Matlab LMI toolbox [17].

During this paper, a description of the wind turbine modelling and control strategy is detailed. The topology of PWM rectifier-inverter that integrates PWM converters in the machine side and the grid side is investigated to offer the possibility of the bidirectional power flow.

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 conclusions in the last section.

2. Wind Energy Conversion System Modelling

During this section, the electrical and mechanical modeling of the WECS is detailed. A schematic overview of the WECS is shown in Fig. 1. The conversion chain consists of a fixed-pitch turbine that captures the wind energy coupled with a PMSG which permits the transformation of the mechanical captured power to electrical power. Power electronic converters are employed in association with PMSG in order to maintain the power at its optimum with various wind speed.

The work treated in the current paper focuses only in the mentioned wind conversion subsystem.

2.1. Wind turbine characteristics

The aerodynamic power produced by the wind turbine is described by the following equation [24]:

\[ P_t = 0.5 C_p (\lambda, \beta) \rho A v^3 \]  \hspace{1cm} (1)

Where \( A \) is the swept area of the wind turbine (\( m^2 \)), \( \rho \) is the air density (\( Kg.m^{-3} \)), \( v \) is the wind velocity (\( m.s^{-1} \)), and \( C_p (\lambda) \) is the power coefficient which is depending on the pitch angle \( \beta \) and the tip-speed ratio \( \lambda \) given by [24]:

\[ \lambda = \frac{R \Omega}{v} \]  \hspace{1cm} (2)

where \( R \) is the blade length and \( \Omega \) represents the wind turbine rotational speed.

The maximum \( C_p \) value is obtained for \( \beta = 0^\circ \) and a specific value of \( \lambda \) which corresponds to the optimal speed ratio value (\( \lambda_{opt} \)). Thus, when assuming both \( C_{p(max)} \) and \( \lambda_{opt} \) are known, the maximum power generated by the wind turbine satisfies:

\[ P_{t(max)} = 0.5 C_{p(max)} (\lambda_{opt}) \rho \pi R^2 \Omega^2 \lambda_{opt}^3 \]  \hspace{1cm} (3)

The mechanical torque given by the turbine rotor is expressed by the following relationship:

\[ T_m = P_{t(max)} / \Omega = 0.5 C_{p(max)} (\lambda_{opt}) \rho \pi R \Omega^2 \lambda_{opt}^3 \]  \hspace{1cm} (4)

The maximum wind energy conversion occurs at the maximum power coefficient \( C_{p(max)} \) by changing the rotor speed to maintain the speed ratio at its optimum \( \lambda_{opt} \). \( T_m \) is then given by:

\[ T_{m(opt)} = K_r \Omega_{r}^2 \]  \hspace{1cm} (5)

where \( K_r = 0.5 C_{p(max)} \rho \pi R^2 / \lambda_{opt}^3 \)

The expression of electromagnetic torque in the rotor in d-q reference frame is given by:

\[ T_{em} = p [ (L_{sq} - L_{sd}) i_{sd} i_{sq}^* + \Psi_f i_{sq}^* ] \]  \hspace{1cm} (6)

where \( p \) being the number of pole pairs, \( \Psi_f \) is the magnetic flux, \( i_{sd} \) and \( i_{sq} \) are the stator current (d,q) components, \( L_{sd} \) is the direct axis inductance, \( L_{sq} \) is the inductance in quadrature.
For smooth poles $L_{sd} = L_{sq} = L_s$, so that (6) becomes:

$$T_{em} = p \Psi_f i_{sq}$$

(7)

The PMSG mechanical speed evolution is determined using the following relationship:

$$J \frac{d\Omega}{dt} = T_m - T_{em} - J f \Omega$$

(8)

where $J$ and $f$ denote respectively the moment of inertia of the PMSG and the friction coefficient.

2.2. The generator and rectifier modelling

Generally, the voltage produced by the voltage source converter can be expressed by defining switching functions for each phase of the converter. These switches are complementary; their role is to establish a connection between the AC side and the DC bus.

The input three phases voltages $V_{si}$ ($i=1,2,3$) and the output current $I_0$ can be written in function of $\beta_i$ which denotes the average value of $u_i$ over the PWM period, the output DC side voltage $U_c$, and the input currents $i_{si}$:

$$\begin{bmatrix} V_{s1} \\ V_{s2} \\ V_{s3} \end{bmatrix} = \begin{bmatrix} \frac{2\beta_1}{\beta_1 - \beta_2 - \beta_3} \\ -\frac{\beta_2}{\beta_1 - \beta_2 - \beta_3} \\ -\frac{\beta_3}{\beta_1 - \beta_2 - \beta_3} \end{bmatrix} U_c$$

$$I_0 = \frac{1}{2} \begin{bmatrix} (1+\beta_3) (1+\beta_2) (1+\beta_3) \end{bmatrix} \begin{bmatrix} i_{s1} \\ i_{s2} \\ i_{s3} \end{bmatrix}$$

Since the stator three-phase currents:

$$i_{s1} + i_{s2} + i_{s3} = 0$$

we obtain:

$$v_{si} = -R_s i_{si} - L_s \frac{di_{si}}{dt} + p\Omega L_s i_{si} = \frac{U_c}{2} \beta_i$$

$$v_{sq} = -R_s i_{sq} - L_s \frac{di_{sq}}{dt} - p\Omega L_s i_{sq} + p\Omega \Psi_f = \frac{U_c}{2} \beta_q$$

(17)

The average voltage at the rectifier output verifies the following equation:

$$\frac{dU_c}{dt} = \frac{1}{2C} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} \begin{bmatrix} i_{s1} \\ i_{s2} \\ i_{s3} \end{bmatrix} - \frac{U_c}{R_C}$$

(12)

Using the d-q reference frame, the above equations can be written as:

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} \frac{1}{2} \beta_d \\ \frac{1}{2} \beta_q \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}$$

(13)

$$I_0 = \frac{3}{4} \begin{bmatrix} \beta_d \\ \beta_q \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}$$

(14)

$$\frac{dU_c}{dt} = \frac{3}{4C} \begin{bmatrix} \beta_d \\ \beta_q \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} - \frac{U_c}{R_C}$$

(15)

The stator current in d-q reference frame is given by:

$$\begin{bmatrix} \frac{d}{dt} i_{sd} \\ \frac{d}{dt} i_{sq} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & \frac{1}{L_s} \\ -w \frac{R_s}{L_s} & -\frac{1}{L_s} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} \\ 0 \end{bmatrix} - \begin{bmatrix} \frac{1}{2L_s} \beta_d \\ \frac{1}{2L_s} \beta_q \end{bmatrix} U_c$$

(16)

Where $w = \omega$ is the electrical angular speed, $R_s$ and $L_s$ denote respectively the synchronous resistance and inductance, $E_d$ and $E_q$ are the electromotive force (d,q) components given by:

$$E_d = 0 \quad E_q = p\psi_f \Omega$$

(10)

The voltage dynamic equations of the stator in the d - q reference frame can be stated as:

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = -R_s i_{sd} - L_s \frac{di_{sd}}{dt} + p\Omega L_s i_{sd} = \frac{U_c}{2} \beta_d$$

$$\begin{bmatrix} v_{sq} \\ -R_s i_{sq} - L_s \frac{di_{sq}}{dt} - p\Omega L_s i_{sq} + p\Omega \Psi_f = \frac{U_c}{2} \beta_q$$

(17)
3. Maximum Peak Power Tracking Algorithm

3.1. The control strategy principle

The following figure summarizes the control scheme treated in the current work in the aim to maintain generated power at its maximum value.

![Control strategy of the WECS](image)

Since the optimum energy conversion is obtained at \( \lambda_{\text{opt}} \), the constraint \( \lambda = \lambda_{\text{opt}} \) implies that the mechanical rotor speed have to vary in proportion with the wind velocity to be particular; \( \Omega_{\text{r}} = \frac{\lambda_{\text{opt}} V_{\text{w}}}{R} \). Thus, the turbine can be controlled to produce maximum power given by (3) as wind speed fluctuates.

Once the rotor speed reference is determined, we can calculate the reference of the current in quadrature given by:

\[
i_{qs} = -\frac{K_p}{p \Omega_{\text{r}}} \Omega_{qs}^2
\]  

(18)

For this study, we suppose that the direct current reference \( i_{sd} = 0 \).

Using the relationship between bus voltage and stator current in q-axis described in (17), the bus voltage reference can be determined by the following expression:

\[
U_{vr} = \frac{2}{\beta_q} (p \Omega_{qs} \Omega_{r})
\]

(19)

3.2. TS Fuzzy model of wind energy conversion system

Due to the nonlinearity of the WECS, T-S modeling permits to represent its behavior by the introduction of a set of linear submodels. Each sub-model leads to the overall behavior of the nonlinear system using a weighting function. Introducing the state vector:

\[
x(t) = [i_{sd} \quad i_{sq} \quad U_{vr} \quad \Omega]^T
\]

and the input signal:

\[
u(t) = [\beta_{d} \quad \beta_{q} \quad \Omega]^T
\]

the average model of the WECS can be described by the following equations:

\[
\frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \\ U_{vr} \\ \Omega \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s} & p \Omega & 0 & 0 \\ -p \Omega & -\frac{R_s}{L_s} & 0 & \frac{p \psi_f}{L_s} \\ \frac{3}{4C} \beta_d & \frac{3}{4C} \beta_q & -\frac{1}{R_C} & 0 \\ 0 & -\frac{p \psi_f}{J} & 0 & \frac{K_p \Omega - f}{J} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \\ U_{vr} \\ \Omega \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}
\]

(20)

\[
x(t) = A(x, u)x(t) + B(x)u(t)
\]

(21)

\[
y(t) = Cx(t)
\]

(22)

With \( C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \)

Considering the fuzzy premise variables \( q_j(t) \)

\[
q_1(t) = \Omega; q_2(t) = \beta_d; q_3(t) = \beta_q; q_4(t) = U_{vr}
\]

(23)

thus, system (20) is easily described by T-S fuzzy rules as follows:

If \( q_1(t) = S_{i_1} \) and \( \ldots \) and \( q_4(t) = S_{i_4} \), then

\[
x(t) = A_j x(t) + B_j u(t)
\]

(24)

\[
y(t) = C_j x(t)
\]

(25)

\( S \) denotes the fuzzy sets, \( r \) represents the fuzzy rules number \( (r=16) \) and \( A_j \) and \( B_j \) are the local subsystem matrices given by:
The response of a TS model is a weighted sum stated as follows:

\[ A_i = \begin{bmatrix} \frac{-R_i}{L_s} & p_{qi} & 0 & 0 \\ -\frac{p_{qi}}{L_s} & 0 & \frac{-p_{qf}}{L_s} \\ \frac{3}{4C} q_{2i} & \frac{3}{4C} q_{3i} & -\frac{1}{R_i} & 0 \\ 0 & -\frac{p_{qf}}{J} & 0 & \frac{K_i q_{1i} - f}{J} \end{bmatrix} \]

\[ B_i = \begin{bmatrix} \frac{-q_{4i}}{2L_s} & 0 \\ 0 & -\frac{q_{4i}}{2L_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \]

The response of a TS model is a weighted sum stated as follows:

\[
\begin{bmatrix}
\dot{x}(t) = \sum_{i=1}^{r} \mu_i(q(t)) [A_i x(t) + B_i u(t)] \\
y(t) = C x(t)
\end{bmatrix}
\tag{26}

Where the vector \( q(t) \) is defined as:

\[ q(t) = \begin{bmatrix} q_1(t) \\ q_2(t) \\ q_3(t) \\ q_4(t) \end{bmatrix} \]

The degree of activation for rule i is normalized as:

\[ \mu_i(q(t)) = \frac{w_i(q(t))}{\sum_{i=1}^{r} w_i(q(t))} \tag{27} \]

with \( w_i(q(t)) = \prod_{j=1}^{4} s_{ji}(q(t)). \) \tag{28}

These weighting functions verify the following properties:

\[
\begin{align*}
&\sum_{i=1}^{r} \mu_i(q(t)) = 1 \\
&0 \leq \mu_i(q(t)) \leq 1 \\
&\text{for all } t.
\end{align*}
\tag{29}

The membership functions are written in the general form as:

\[ f_j = \frac{q_j(t) - m_j}{M_j - m_j} \tag{30} \]

Where \( M_j \) and \( m_j \) are respectively the maximum and the minimum bounds of the variable \( q_j(t) \) for \( j=1,2,3,4 \).

The following table presents the setting of the parameters \( q_{ji} \) setting according to each rule for \( i=1..16 \).

<table>
<thead>
<tr>
<th>Rule index</th>
<th>Fuzzy Sets of rules</th>
<th>Parameters of the ( i )-th part</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>2</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>3</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>4</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>5</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>6</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>7</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>8</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>9</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>10</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>11</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>12</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>13</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>14</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>15</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
<tr>
<td>16</td>
<td>( f_1, f_2, f_3, f_4 )</td>
<td>( M_1, M_2, M_3, M_4 )</td>
</tr>
</tbody>
</table>

3.3. Error state model

In order to ensure a smooth tracking of the references, we introduce a state reference vector:

\[ x_r(t) = [i_{sd}, i_{sq}, U_{cr}, \Omega_{r}]^T. \]

Defining \( e(t) = x(t) - x_r(t) \) as the state tracking errors, hence the new PDC fuzzy controller is designed such as:

\[ u(t) = -\sum_{i=1}^{r} \mu_i(q(t)) K_i e(t) \tag{32} \]

Thus, we can describe the resulting dynamic error model as follows:

\[ \dot{e}(t) = \sum_{i=1}^{r} \mu_i(q(t))(A_i e(t) + B_i u(t) + A_i x_r) \tag{33} \]
Another state variable $e_i = \int e$ corresponding to an integral action on the tracking error is employed in the PDC fuzzy controller so as to avoid steady state errors, then the control law is written as:

$$u(t) = -\sum_{i=1}^{r} \mu_i(q(t)) [K_i \quad F_i] [e_i(t)]$$

$$= -\sum_{i=1}^{r} \mu_i(q(t)) \tilde{K}_i \tilde{e}(t)$$

(34)

Where $\tilde{K}_i = [K_i \quad F_i]$ and $\tilde{e}(t) = [e(t) \quad e_i(t)]^T$.

Therefore, we can write the T-S model in the augmented form as follows:

$$\dot{\tilde{e}}(t) = \sum_{i=1}^{r} \mu_i(q(t)) \tilde{G}_i \tilde{e}(t) + \tilde{D}_i \tilde{h}$$

(35)

With:

$$\tilde{G}_i = \bar{A}_i - \bar{B}_i \tilde{K}_i$$

$$\bar{A}_i = \begin{bmatrix} A_i & 0 \\ I & 0 \end{bmatrix}$$

$$\bar{B}_i = \begin{bmatrix} B_i \\ 0 \end{bmatrix}$$

$$\tilde{D}_i = \begin{bmatrix} A_i & 0 \\ 0 & 0 \end{bmatrix}$$

$$\tilde{h} = \begin{bmatrix} x_r \\ 0 \end{bmatrix}$$

3.4. LMI formulation for $H_\infty$ performance

In order to ensure smooth reference tracking under the influence of perturbation, the $H_\infty$ tracking performance which has been considered in several works [18], [19] and [20], is adopted.

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

(36)

Where $\gamma$ is a defined value.

In the aim of analyzing the maximum power point tracking convergence, we consider the Lyapunov function candidate $\bar{V}(\tilde{e}) = \tilde{e}^T P \tilde{e}^T$ where $P = P^T > 0$ the common definite positive matrix. The Lyapunov function time derivative along the control dynamics has to satisfy:

$$\dot{\bar{V}}(\tilde{e}(t)) = \dot{\tilde{e}}^T P \tilde{e} + \tilde{e}^T P \dot{\tilde{e}} < 0$$

(37)

The condition leading to accomplish the H-infinity performance associated to the tracking error is given as:

$$\dot{\bar{V}}(\tilde{e}(t)) + \tilde{e}^T(t) \tilde{e}(t) - \gamma^2 \tilde{h}^T \tilde{h} < 0$$

(38)

By replacing (37) and (35) in (38) we get:

$$\sum_{i=1}^{r} \mu_i(q(t)) \tilde{G}_i \tilde{e}(t) + \sum_{i=1}^{r} \mu_i(q(t)) \tilde{D}_i \tilde{h} - \gamma^2 \tilde{h}^T \tilde{h} < 0$$

(39)

$$\dot{\bar{V}}(\tilde{e}(t)) + \tilde{e}^T(t) \tilde{e}(t) - \gamma^2 \tilde{h}^T \tilde{h} < 0$$

(40)

To check this inequality, it suffices to check that:

$$\sum_{i=1}^{r} \mu_i(q(t)) \tilde{G}_i \tilde{e}(t) + \sum_{i=1}^{r} \mu_i(q(t)) \tilde{D}_i \tilde{h} - \gamma^2 I < 0$$

(41)

Where $I$ is the identity matrix.

$$\sum_{i=1}^{r} \mu_i(q(t)) \tilde{G}_i \tilde{e}(t) + \sum_{i=1}^{r} \mu_i(q(t)) \tilde{D}_i \tilde{h} - \gamma^2 I < 0$$

(42)

The use of Shur lemma allows writing:

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

(43)

$$\begin{bmatrix} \sum_{i=1}^{r} \mu_i(q(t)) \tilde{G}_i \tilde{e}(t) + \sum_{i=1}^{r} \mu_i(q(t)) \tilde{D}_i \tilde{h} & \gamma^2 I \\ 0 & I \end{bmatrix} +$$

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

(44)

That means:

$$\begin{bmatrix} \sum_{i=1}^{r} \mu_i(q(t)) \tilde{G}_i \tilde{e}(t) + \sum_{i=1}^{r} \mu_i(q(t)) \tilde{D}_i \tilde{h} & \gamma^2 I \\ 0 & I \end{bmatrix} +$$

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

(45)
\[
\begin{bmatrix}
G_i^P + pG_i^T & pD_i \\
\frac{1}{p} & 0 & -\gamma^2 I
\end{bmatrix}
\begin{bmatrix}
I \\
0 & 0 & -I
\end{bmatrix} < 0
\]  
(45)

\[
\begin{bmatrix}
G_i^P + pG_i^T & pD_i \\
\frac{1}{p} & 0 & -\gamma^2 I
\end{bmatrix}
\begin{bmatrix}
0 & 0 & 0 \\
I & 0 & -I
\end{bmatrix} < 0
\]  
(46)

\[
\begin{bmatrix}
G_i^P + pG_i^T & pD_i \\
\frac{1}{p} & 0 & -\gamma^2 I
\end{bmatrix}
\begin{bmatrix}
p^{-1} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0 \\
\end{bmatrix} < 0
\]  
(47)

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(48)

4. Numerical Simulation

Matlab/Simulink is used for the simulation of the WECS. The numerical illustration considers the wind conversion system with the parameter values given by the following table:

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<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
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<td>90V</td>
</tr>
<tr>
<td>Rated current</td>
<td>4.8 A</td>
</tr>
<tr>
<td>Rated power</td>
<td>600 W</td>
</tr>
<tr>
<td>Number of poles</td>
<td>8</td>
</tr>
<tr>
<td>Synchronous resistance</td>
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</tr>
<tr>
<td>Synchronous inductance</td>
<td>1 mH</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>0.006 N.m.s/rad</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>0.005 N.m</td>
</tr>
<tr>
<td>Blade length</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Air density</td>
<td>1.2 Kg/m²</td>
</tr>
<tr>
<td>Magnetic flux</td>
<td>0.16 wb</td>
</tr>
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Table 2. Wind conversion system parameters

The proposed strategy of control is tested for different wind velocity variations. The wind speed signal variation is presented in Fig.4.

The next figure shows the rotor speed needed to catch the maximum of accessible power produced by the wind turbine. It is easy to remark the coincidence between the blue curve which refers to the actual mechanical speed and the red curve which presents the reference rotor speed.

By choosing \( X = P^{-1} \) and \( M_i = \hat{K}_i P^{-1} \) and by using the T-S fuzzy control law, the maximum power generation of the WECS is accomplished if the controller gains are prescribed as \( \hat{K}_i = M_i X^{-1} \) with the matrices \( X \) and \( M_i \) satisfying the following LMI:

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Table 2. Wind conversion system parameters

The proposed strategy of control is tested for different wind velocity variations. The wind speed signal variation is presented in Fig.4.
The proposed fuzzy controller leads to the MPPT response presented in Fig.9. As illustrated in the figure, the main objective of our MPPT strategy is accomplished. It means that the maximum power point can be quickly achieved despite fast-varying wind velocity.

Fig. 9. Wind turbine produced power

In summary, the proposed control topology performance is clearly illustrated by the simulation results.

5. Conclusion

This paper focuses on control strategy dedicated for a wind conversion system with the main objective to ensure maximum peak power tracking (MPPT). The algorithm searches the upper accessible power using a torque reference generated by the wind turbine characteristics. By using robust control based on T-S approach, allowed to track rotational speed, stator current and voltage references which correspond to the optimum power; and therefore operate in the maximum power. So as to preserve good performances and quick response, the controller gains are designed with LMI techniques. Numerical simulations using different measurement of wind speed has validated the proposed control strategy.

As future work, we project to test this control algorithm on the complete structure of WECS as presented in Fig.1.

References


