A new fuzzy design for switching gain adaptation of sliding mode controller for a wind energy conversion system using a doubly fed induction generator

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Abstract: The paper proposes a new robust fuzzy gain adaptation of the sliding mode (SMC) power control strategy for the wind energy conversion system (WECS), based on a doubly fed induction generator (DFIG), to maximize the power extracted from the wind turbine (WT). The sliding mode controller can deal with any wind speed, ingrained nonlinearities in the system, external disturbances and model uncertainties, yet the chattering phenomenon that characterizes classical SMC can be destructive. This problem is suitably lessened by adopting adaptive fuzzy-SMC. For this proposed approach, the adaptive switching gains are adjusted by a supervisory fuzzy logic system, so the chattering impact is avoided. Moreover, the vector control of the DFIG as well as the presented one have been used to achieve the control of reactive and active power of the WECS to make the wind turbine adaptable to diverse constraints. Several numerical simulations are performed to assess the performance.

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of the proposed control scheme. The results show robustness against parameter variations, excellent response characteristics with a reduced chattering phenomenon as compared with classical SMC.

Key words: chattering phenomenon, doubly fed induction generator, fuzzy logic gain adaptation, sliding mode control, vector control, wind energy conversion systems

1. Introduction

The electrical energy has become increasingly important to humanity. In fact, getting electrical energy is ensuring great living conditions and it is a basic factor for economic and industrial development. Faced with the ever-increasing demand for electricity, and distancing from the exploitation of polluting fossil fuels, many nations turned to renewable or green energies. The wind energy represents a rather large potential to replace existing power sources and to compensate the depreciation of the increasingly power demand. A WECS based on a DFIG is an interesting solution. This generator allows electricity production with variable speed, which gives better exploitation of wind resources [1].

Several control strategies appeared; among them the vector control. The principle is to make the control of the DFIG similar to DC machine control with separate excitation [2]. This control uses conventional controllers (proportional and integral actions), which do not allow in all cases to handle switching of operation modes and also parametric variations of the machine [3].

However, there are modern control techniques, especially the non-linear SMC strategy used due to its good dynamic performances, simple structure and ability to handle a wide range of operating conditions [4]. The higher switching gain value in the switching law of the SMC generates chattering, which diminishes the performances and may damage the system. With a view to obtaining high performances and robust control of the reactive and active powers generated by the DFIG, and to overcome the shortcomings of SMC, a new approach is proposed to reduce particularly the chattering effect.

This technique consists in adjusting the switching gains of SMC by fuzzy logic rules to relieve the effect of the chattering phenomenon in classical SMC. The objective is to show that the proposed strategy can improve the performance of a WECS based on a DFIG in terms of robustness against machine parameter variations, sensibility to disturbances and reference tracking.

2. Modelling of wind turbine

2.1. Mechanical power of the turbine

The power of wind kinetic energy can be determined by [5,6]:

\[ P_{\text{wind}} = 0.5 \rho \pi R^2 V^3, \]  

(1)

where: \( P_{\text{wind}} \) is the wind power, \( \rho \) is the air density, \( V \) is the wind speed and \( R \) is the blade radius.
The expression between wind speed and aerodynamic power extracted from the wind can be described as follows:

\[ P_{\text{aer}} = 0.5 C_p(\lambda, \beta) \rho R^2 V^3, \quad (2) \]

where \( P_{\text{aer}} \) is the aerodynamic power.

The power coefficient \( C_p \) of the wind turbine is a function of \( \lambda \) for both the tip-speed ratio (TSR) and \( \beta \) blade pitch angle given by this mathematical approximation [7]:

\[ C_p(\lambda, \beta) = C_1 - C_2 (\beta - C_3) \sin(A) - C_4 (\lambda - C_5) (\beta - C_3) \quad (3) \]

with

\[ C_1 = 0.5, \quad C_2 = 0.0167, \quad C_3 = 3, \quad C_4 = 0.00184, \quad C_5 = 3, \]

\[ A = \frac{\pi (\lambda + 0.1)}{14.8 - 0.3(\beta - 2)}. \]

The tip-speed ratio \( \lambda \) is given by the following equation:

\[ \lambda = \frac{\Omega_{\text{turb}} R}{V}, \quad (4) \]

where \( \Omega_{\text{turb}} \) is the turbine rotational speed on the low-speed side of the gearbox.

Figure 1 represents the function of the power coefficient \( C_p \) with respect to the TSR \( \lambda \) for different pitch angles \( \beta \).

![Fig. 1. Power coefficient versus tip-speed ratio for different values of the pitch angle](image)

From this curve, we can notice that the maximum value of the power coefficient \( C_p^{\text{max}} = 0.5 \) for a pitch angle \( \beta = 2^\circ \) and an optimal value of TSR \( \lambda_{\text{opt}} = 9.12 \). In these conditions, we can apply maximum power point tracking (MPPT) control.

The optimal turbine rotational speed from the wind \( \Omega_{\text{turb}}^{\text{opt}} \) is given by:

\[ \Omega_{\text{turb}}^{\text{opt}} = \frac{\lambda_{\text{opt}} R}{V}. \quad (5) \]
The aerodynamic torque $T_{\text{aer}}$ can be expressed as follows:

$$T_{\text{aer}} = \frac{P_{\text{aer}}}{\Omega_{\text{turb}}} = \frac{C_p(\lambda, \beta) \rho R^2 V^3}{2 \Omega_{\text{turb}}} .$$  \hspace{1cm} (6)

2.2. Model of gearbox

A gearbox whose gear ratio $G$ transforms the mechanical speed of the wind turbine $\Omega_{\text{turb}}$ into the speed of the generator shaft $\Omega_g$ and the aerodynamic torque $T_{\text{aer}}$ into the torque generator $T_g$ according to the following mathematical formulas:

$$
\begin{align*}
G &= \frac{\Omega_g}{\Omega_{\text{turb}}} , \\
G &= \frac{T_{\text{aer}}}{T_g} .
\end{align*}
$$  \hspace{1cm} (7)

2.3. Dynamic model of shaft

The fundamental equation of the dynamics makes it possible to determine the evolution of the mechanical speed from the mechanical torque exerted on the shaft of the wind turbine rotor $T_g$ and the electromagnetic torque $T_{\text{em}}$ [8, 9]:

$$J \frac{d\Omega_g}{dt} = T_g - T_{\text{em}} - f \Omega_g ,$$  \hspace{1cm} (8)

where: $J$ is the total moment of inertia, $f$ is the viscous friction coefficient, respectively.

The total inertia $J$ consisting of the inertia of the generator $J_g$ and the turbine inertia $J_{\text{turb}}$:

$$J = \frac{J_{\text{turb}}}{G^2} + J_g .$$  \hspace{1cm} (9)

3. Wind speed modeling

The definition of the wind model requires climatic and geographical data of the site concerned. The deterministic effects and stochastic fluctuations are superimposed to form the following wind model [10]:

$$V(t) = A + \sum_{i=1}^{\infty} a_i \sin (\omega_i t + \varphi_i) ,$$  \hspace{1cm} (10)

where: $\varphi_i$ is the initial phase of each turbulence, $\omega_i$ is the pulsation, $A$ is the mean component and $a_i$ is the magnitude.

In this paper, we are interested in the turbulent wind model, this model is clearly described in [11].

The proposed profile of the wind speed model is given in Fig. 2 with 12% of the turbulence intensity and 7.5 m-s$^{-1}$ of a mean wind speed.
4. MPPT with rotor speed control loop

The MPPT control strategy consists in adjusting the torque appearing on the turbine shaft, so as to fix it at its reference speed. To achieve this, a rotor speed control loop is used. This control consists in determining the speed of the turbine, which makes it possible to obtain the maximum power generated [12]:

4.1. Application of conventional sliding mode control

With Eq. (8) of the turbine shaft given, we use the SMC algorithm to develop the control allowing the system to follow the desired trajectory, so the sliding surface is defined by [13]:

\[ S_\Omega = \Omega^*_g - \Omega_g, \]  

where \( \Omega^*_g \) is the reference speed.

We consider the following Lyapunov candidate function [14]:

\[ V = \frac{1}{2} S^2_\Omega. \]  

Its time derivative is given by:

\[ \dot{V} = S_\Omega \cdot \dot{S}_\Omega \]  

with

\[ \dot{S}_\Omega = \dot{\Omega}^*_g - \dot{\Omega}_g. \]  

By replacing (8) in the last equation, (14), we obtain:

\[ \dot{S}_\Omega = \dot{\Omega}^*_g + \frac{1}{J} (T_{em} + f\Omega - T_{\theta}). \]  

Replacing \( T_{em} \) by the term \( (T_{em}^q + T_{em}^n) \) in the previous equation according to the sliding mode theory:

\[ S_\Omega = \dot{\Omega}^*_g + \frac{1}{J} ((T_{em}^q + T_{em}^n) + f\Omega - T_{\theta}). \]
During the sliding mode and in permanent regime, we have: \( S_\Omega = 0 \), \( \dot{S}_\Omega = 0 \) and \( T_{em}^n = 0 \), from which we extract the equivalent control expression [15]:

\[
T_{eq}^{em} = -J\dot{\Omega}^* - f\Omega + T_g .
\]  

By replacing Expression (17) in (16) we obtain:

\[
\dot{S}_\Omega = \frac{1}{J} (T_{em}^n) .
\]  

To ensure the convergence of the Lyapunov function, we must set:

\[
T_{em}^n = -K_\Omega \cdot \text{sign}(S_\Omega) .
\]

where \( K_\Omega \) is a constant positive.

The control algorithm is defined by the relation:

\[
T_{em} = T_{eq}^{em} + T_{em}^n .
\]

4.2. Application of adaptive fuzzy sliding mode control

To minimize the chattering phenomenon and improve the efficiency of SMC, we propose to add the Mamdani fuzzy logic law to SMC, with the purpose of adjusting the commutation gains and attenuating its chattering [16].

When the value of the sliding surface \( S_\Omega \) is important, and once the system state trajectory is distant from the sliding surface; the switching gain \( K_\Omega \) must be raised to force the trajectory back. On the other hand, when the value of \( S_\Omega \) is relatively small, the gain must be also minimized. However, the fuzzy-logic rules could be applied to adapt the \( K_\Omega \) switching gain based on the \( S_\Omega \) sliding surface values.

The fuzzy rules for both the powers and the speed controllers are presented in Table 1. The membership-functions (MFs) of the input \( S_\Omega \) and the output \( u_\Omega_e \) signals are given in Fig. 4.
A new fuzzy design for switching gain adaptation of sliding mode controller

Table 1. Fuzzy logic controller rules

<table>
<thead>
<tr>
<th>$S_{\Omega}$</th>
<th>P-B</th>
<th>P-M</th>
<th>P-S</th>
<th>Z-E</th>
<th>N-S</th>
<th>N-M</th>
<th>N-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{\Omega e}$</td>
<td>P-B</td>
<td>P-M</td>
<td>P-S</td>
<td>Z-E</td>
<td>P-S</td>
<td>P-M</td>
<td>P-B</td>
</tr>
</tbody>
</table>

P-B: Positive-Big, P-M: Positive-Medium, P-S: Positive-Small, Z-E: Zero, N-S: Negative-Small, N-M: Negative-Medium, N-B: Negative-Big

Fig. 4. The proposed membership-functions of the fuzzy logic controller inputs and outputs

Rule 1: if $S_{\Omega}$ is P-B, consequently $u_{\Omega e}$ is P-B.

If $S_{\Omega}$ is P-B, consequently the calculated speed is significantly lower than the reference. It must be quickly increased to make it return to the reference speed, i.e., for a significant raising in the control variable $u_{\Omega e}$ is needed. Other inference rules are similarly synthetized:

Rule 2: if $S_{\Omega}$ is P-M consequently $u_{\Omega e}$ is P-M.

Rule 3: if $S_{\Omega}$ is P-S consequently $u_{\Omega e}$ is P-S.

Rule 4: if $S_{\Omega}$ is Z-E consequently $u_{\Omega e}$ is Z-E.

Rule 5: if $S_{\Omega}$ is N-S consequently $u_{\Omega e}$ is P-S.

Rule 6: if $S_{\Omega}$ is N-M consequently $u_{\Omega e}$ is P-M.

Rule 7: if $S_{\Omega}$ is N-B consequently $u_{\Omega e}$ is P-B.

To obtain the switching gains of the control, the fuzzy outputs are defuzzified by using the center of the area process and multiplied by the scaling gain $K_{\Omega}$. The actual gains of the controller are as follows:

$$K'_{\Omega} = K_{\Omega} \times u_{\Omega e}.$$  \hspace{1cm} (21)
The fuzzy-sliding-mode-controller is presented in Fig. 5.

![Fig. 5. Schematic-diagram of the proposed fuzzy sliding mode controller (FSMC)](image)

4.3. Simulation results

Several simulation tests of the wind turbine system were conducted to demonstrate the feasibility of the proposed FSMC. The parameters of a wind turbine are presented in Table 6.

A random wind profile is used, corresponding to the sub-synchronous mode. The mechanical speed extracted from the MPPT controller presented in Fig. 6, varies in the same shape as the wind speed.

This MPPT technique, keeps the power-coefficient $C_p$ at its higher value, which corresponds to 0.515 and the relative-speed stills around its optimal value $\lambda_{opt} = 9.12$.

From the mechanical speed tracking error which is almost equal to zero, the FSMC shows clearly the benefit of this algorithm in terms of chattering reduction, which is considered as one of the main disadvantages of conventional SMC.

The performance-index is a quantitative measure of the system performance. When the system achieves the lowest values, we have an optimal regulation. The performances of the wind turbine system under a random wind profile are evaluated by the various indexes for the proposed algorithms, including the IAE, ISE and ITSE in Table 2. The mathematical expressions of these indicators are [17, 18]:

Integral of absolute value of the error (IAE): This index refers to the IAE equation, (22). The total error is presented in the IAE, i.e., it shows how much the answer was with respect to the reference used.

\[
AE = \int_0^\infty |e(t)| \, dt. \tag{22}
\]

Integral of the square error (ISE): This index is defined as the square error integral equation, (23). It is related to the energy error, offering less importance to minor errors and higher importance to larger errors.

\[
ISE = \int_0^\infty [e(t)]^2 \, dt. \tag{23}
\]
Fig. 6. Wind turbine system responses to conventional SMC and FSMC

Integral of time multiplied by the squared error (ITSE): This index is equivalent to the ISE index, but it is evaluated in time Eq. (24). The ITSE index gives very little attention to initial errors.

\[
\text{ITSE} = \int_{0}^{\infty} t \cdot [e(t)]^2 \, dt, \tag{24}
\]

where \(e(t)\) is the system response error.
As shown in Table 2, it can be stated that the FSMC algorithm achieves the smallest values of the three indices.

Table 2. Quantitative performance comparison of WT controlled by SMC and FSMC strategies

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>IAE</th>
<th>ISE</th>
<th>ITSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ωg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMC</td>
<td>47.875</td>
<td>107.374</td>
<td>1463.797</td>
</tr>
<tr>
<td>FSMC</td>
<td>1.177</td>
<td>2.494</td>
<td>0.940</td>
</tr>
<tr>
<td>C_p</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMC</td>
<td>0.018</td>
<td>5.696e-6</td>
<td>8.627e-5</td>
</tr>
<tr>
<td>FSMC</td>
<td>0.011</td>
<td>4.767e-6</td>
<td>7.062e-5</td>
</tr>
<tr>
<td>λ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMC</td>
<td>3.583</td>
<td>0.611</td>
<td>9.426</td>
</tr>
<tr>
<td>FSMC</td>
<td>0.087</td>
<td>0.013</td>
<td>0.006</td>
</tr>
</tbody>
</table>

5. Modelling of DFIG

The mathematical-model of the DFIG in the $(d - q)$ frame is presented in the following equations. The stator and the rotor voltages are given by the following equations [19–21]:

\[
\begin{align*}
V_{sd} &= R_s i_{sd} + \frac{d(\phi_{sd})}{dt} - \omega_s \phi_{sq} \\
V_{sq} &= R_s i_{sq} + \frac{d(\phi_{sq})}{dt} - \omega_s \phi_{sd} \\
V_{rd} &= R_r i_{rd} + \frac{d(\phi_{rd})}{dt} - \omega_r \phi_{rq} \\
V_{rq} &= R_r i_{rq} + \frac{d(\phi_{rq})}{dt} - \omega_r \phi_{rd}
\end{align*}
\] (25)

with

\[
\omega_r = \omega_s p \Omega_g,
\] (26)

where: $V_s$ is the stator voltage, $V_r$ is the rotor voltage, $R_s$ is the stator resistance, $R_r$ is the rotor resistance, $i_s$ is the stator current, $i_r$ is the rotor current, $\phi_s$ is the stator flux, $\phi_r$ is the rotor flux, $\omega_s$ is the stator pulsation and $\omega_r$ is the rotor pulsation.

Equations (27) present the stator and rotor flux expressions [22]:

\[
\begin{align*}
\phi_{sd} &= L_s i_{sd} + M i_{rd} \\
\phi_{sq} &= L_s i_{sq} + M i_{rq} \\
\phi_{rd} &= L_r i_{rd} + M i_{sd} \\
\phi_{rq} &= L_r i_{rq} + M i_{sq}
\end{align*}
\] (27)

where: $L_s$ is the stator inductance, $L_r$ is the rotor inductance and $M$ is the mutual inductance.
And the instant active and reactive stator powers are [23]:

\[
\begin{align*}
P_s &= V_{sd}i_{sd} + V_{sq}i_{sq} \\
Q_s &= V_{sq}i_{sd} - V_{sd}i_{sq},
\end{align*}
\]  
(28)

where \( P_s \) is the instant active power and \( Q_s \) is the instant reactive power.

The DFIG electromagnetic torque \( T_{eme} \) is defined as [24]:

\[
T_{eme} = \frac{pM}{L_s} (\phi_{sq}i_{rd} - \phi_{sd}i_{rq}),
\]  
(29)

where \( p \) is the number of pole pairs.

5.1. Conventional SMC for the DFIG

After presenting the SMC theory for the MPPT control strategy in part one, the objective of this part is to control the reactive and active stator power in the DFIG, by acting on the rotor voltages. For this purpose, the control surface is determined by the following equations [25]:

\[
\begin{align*}
S_P &= P^*_s - P_s \\
S_Q &= Q^*_s - Q_s,
\end{align*}
\]  
(30)

We define the derivative of the Lyapunov function by [26]:

\[
\begin{align*}
V(S_P) &= 0.5 (S_P)^2 \\
V(S_Q) &= 0.5 (S_Q)^2
\end{align*}
\]  
(31)

with

\[
\begin{align*}
\dot{S}_P &= \dot{P}^*_s - \dot{P}_s = \dot{P}^*_s + \frac{L_sL_r\sigma}{V_sM}i_{rq} \\
\dot{S}_Q &= \dot{Q}^*_s - \dot{Q}_s = \dot{Q}^*_s + \frac{L_sL_r\sigma}{V_sM}i_{rd}
\end{align*}
\]  
(32)

Taking the derivative of the previous equation and replacing the reactive and active power respectively:

\[
\begin{align*}
\dot{S}_P &= +V_s \frac{M}{L_sL_r\sigma} \left( V_{rq} - R_i i_{rq} - \sigma L_r \omega_r i_{rd} + g \frac{MV_r}{\omega_s L_s} \right) \\
\dot{S}_Q &= +V_s \frac{M}{L_sL_r\sigma} \left( V_{rd} - R_i i_{rd} + \sigma L_r \omega_r i_{rq} \right)
\end{align*}
\]  
(33)

where \( g = \frac{\omega_s}{\omega_r} \).

Replacing \( i_{rq} \) and \( i_{rd} \) by their expressions, than \( V_{rq} \) and \( V_{rd} \) by \( V_{rq}^{eq} + V_{rq}^m \) and \( V_{rd}^{eq} + V_{rd}^m \), respectively, in the previous equation, the time surface derivative is given by:

\[
\begin{align*}
\dot{S}_P &= \dot{P}^*_s + V_s \frac{M}{L_sL_r\sigma} \left( (V_{rq}^{eq} + V_{rq}^m) - R_i i_{rq} - \sigma \omega_r L_r i_{rd} + g \frac{MV_r}{\omega_s L_s} \right) \\
\dot{S}_Q &= \dot{Q}^*_s + V_s \frac{M}{L_sL_r\sigma} \left( (V_{rd}^{eq} + V_{rd}^m) - R_i i_{rd} + \sigma \omega_r L_r i_{rq} \right)
\end{align*}
\]  
(34)
During a steady state and for the sliding-mode, we have [27]:

\[
\begin{align*}
S_P &= 0, \quad \dot{S}_P = 0, \quad V^n_{r_q} = 0, \\
S_Q &= 0, \quad \dot{S}_Q = 0, \quad V^n_{r_d} = 0.
\end{align*}
\] (35)

Therefore, the equivalent control terms are given by:

\[
\begin{align*}
V^e_{r_q} &= -\sigma L_s L_r \frac{P^*_s}{V_s M} + R_r i_{rq} + \sigma \omega_s L_r i_{rd} - g \frac{MV_s}{\omega_s L_s}, \\
V^e_{r_d} &= -\sigma L_s L_r \frac{Q^*_s}{V_s M} + R_r i_{rd} - \sigma \omega_s L_r i_{rq}.
\end{align*}
\] (36)

The switching terms are written as:

\[
\begin{align*}
V^n_{r_q} &= -K_P \text{sign} (S_P) \\
V^n_{r_d} &= -K_Q \text{sign} (S_Q).
\end{align*}
\] (37)

To verify the stability-condition of the system, the two coefficients \(K_P\) and \(K_Q\) must be positive.

5.2. Adaptive fuzzy sliding mode control for the DFIG

To achieve a robust power control, the SMC controllers are replaced by adaptive FSMC as mentioned in the previous part, where the Mamdani fuzzy logic method is added to the sign function to adjust the commutation gains in order to attenuate the chattering on the active and reactive power variables.

Hence, fuzzy logic rules can be used to adjust the switching gains \(K_P\) and \(K_Q\) according to the value of \(S_P\) and \(S_Q\), respectively. The fuzzy rules for the power controllers are shown in Table 3:

<table>
<thead>
<tr>
<th>(S_{P,Q})</th>
<th>P-B</th>
<th>P-M</th>
<th>P-S</th>
<th>Z-E</th>
<th>N-S</th>
<th>N-M</th>
<th>N-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>(u_{P,Q})</td>
<td>P-B</td>
<td>P-M</td>
<td>P-S</td>
<td>Z-E</td>
<td>P-S</td>
<td>P-M</td>
<td>P-B</td>
</tr>
</tbody>
</table>

P-B: Positive-Big, P-M: Positive-Medium, P-S: Positive-Small, Z-E: Zero, N-S: Negative-Small, N-M: Negative-Medium, N-B: Negative-Big

The MFs of the input \(S_{P,Q}\) and the output \(u_{P,Q}\) signals are shown in Fig. 7.

Rule 1: if \(S_{P,Q}\) is P-B, consequently \(u_{P,Q}\) is P-B.

If \(S_{P,Q}\) is P-B, consequently the calculated speed is significantly lower than the reference. It must be quickly increased to make it return to the reference speed, i.e., for a significant raising in the control variable \(u_{P,Q}\) is needed. Other inference rules are similarly synthetized:

Rule 2: if \(S_{P,Q}\) is P-M, consequently \(u_{P,Q}\) is P-M.

Rule 3: if \(S_{P,Q}\) is P-S, consequently \(u_{P,Q}\) is P-S.

Rule 4: if \(S_{P,Q}\) is Z-E, consequently \(u_{P,Q}\) is Z-E.
Rule 5: if $S_{P,Q}$ is N-S, consequently $u_{P,Q}$ is P-S.
Rule 6: if $S_{P,Q}$ is N-M, consequently is P-M.
Rule 7: if $S_{P,Q}$ is N-B, consequently $u_{P,Q}$ is P-B.

Additionally, to obtain the switching gains of the control, the fuzzy outputs are defuzzified by using the center of the area process and multiplied by the scaling gain $K_P$ and $K_Q$. The actual gains of the controller will be:

$$\begin{cases} K'_P = K_P \times u_P \\ K'_Q = K_Q \times u_Q \end{cases}$$  \hspace{1cm} (38)

The control algorithm is defined by the relation:

$$\begin{cases} V'_{rq} = V'^{eq}_{rq} + V'^{n}_{rq} \\ V'_{rd} = V'^{eq}_{rd} + V'^{n}_{rd} \end{cases}$$  \hspace{1cm} (39)

The architecture of the proposed FSMC for the DFIG system is illustrated in Fig. 8.

5.3. Simulation results

The simulations are implemented using MATLAB/Simulink environment for a DFIG connected to the wind turbine mentioned in the previous section. In addition, a comparison analysis is carried out between the proposed FSMC and the conventional SMC, in terms of reference tracking (reactive and active power), and chattering phenomenon elimination.
In this test the stator reactive power reference value will be fixed at step zero and the active power of the stator has a negative sign generated by the turbine, signifying that the generator produces energy and transmits it to the grid.

According to these results and for variable references, the stator active and reactive powers follow their changing references, whatever the wind fluctuations are, proving well maintained and perfect decoupling between the active and the reactive powers, as shown in Fig. 9.

The simulation results show high performances for both SMC and FSMC with significantly small active and reactive power errors. However, FSMC is more effective in terms of chattering attenuation.

The total-harmonic-distortion (THD) is calculated using the fast-Fourier-transform (FFT), as shown in Fig. 10. It shows the impact of the chattering phenomenon on the DFIG stator current.

The performances of the WECS under the same reference signals are evaluated by the various indices for both FSMC and conventional SMC algorithms, including the IAE, ISE, ITSE and ITAE in Table 4.

Table 4. Quantitative performance comparison of DFIG controlled by SMC and FSMC strategies

<table>
<thead>
<tr>
<th></th>
<th>Algorithm</th>
<th>IAE</th>
<th>ISE</th>
<th>ITSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_S$</td>
<td>SMC</td>
<td>207.34</td>
<td>2527.63</td>
<td>34 022.50</td>
</tr>
<tr>
<td></td>
<td>FSMC</td>
<td>164.59</td>
<td>1 144.86</td>
<td>22 900.90</td>
</tr>
<tr>
<td>$Q_S$</td>
<td>SMC</td>
<td>201.04</td>
<td>8 505.79</td>
<td>3 091.72</td>
</tr>
<tr>
<td></td>
<td>FSMC</td>
<td>132.09</td>
<td>664.38</td>
<td>8 094.35</td>
</tr>
</tbody>
</table>
As seen in Table 4, the FSMC algorithm offers enhanced performance by giving the smallest values of the three indexes. The THD is also reduced from 17.16% to 4.04% for the FSMC (Fig. 10). This study confirms that the FSMC has better behavior and response time, as well as optimized static and dynamic performances compared to the conventional SMC.
6. Conclusion

This paper presents a new robust fuzzy gain adaptation of the sliding mode power control strategy. The primary goal is to improve the performance of the SMC method. Different simulation scenarios for the WECS are carried under a variable-speed wind.

The results show that this fuzzy SMC is robust against parameter variations, ensures excellent response characteristics and presents almost no chattering compared to conventional SMC. The proposed strategy is also more efficient in maintaining system stability and achieving the desired performance even with various system parameters. This fuzzy sliding mode controller is a promising option for wind energy conversion systems.
Appendix

Table 5. DFIG parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_N$</td>
<td>7.5 kW</td>
</tr>
<tr>
<td>$V_S$</td>
<td>230/400 V</td>
</tr>
<tr>
<td>$F$</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$R_S$</td>
<td>0.455 Ω</td>
</tr>
<tr>
<td>$R_r$</td>
<td>0.62 Ω</td>
</tr>
<tr>
<td>$L_S$</td>
<td>0.084 C</td>
</tr>
<tr>
<td>$L_r$</td>
<td>0.081 H</td>
</tr>
<tr>
<td>$M$</td>
<td>0.078 H</td>
</tr>
<tr>
<td>$J_g$</td>
<td>0.3125 kg·m²</td>
</tr>
<tr>
<td>$f_g$</td>
<td>0.00673 N·m/s</td>
</tr>
<tr>
<td>$p$</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6. Parameters of the wind turbine

<table>
<thead>
<tr>
<th>Parameters</th>
<th>values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_N$</td>
<td>10 kW</td>
</tr>
<tr>
<td>$R$</td>
<td>3 m</td>
</tr>
<tr>
<td>$G$</td>
<td>5.4</td>
</tr>
<tr>
<td>$J_{turb}$</td>
<td>0.042 kg·m²</td>
</tr>
<tr>
<td>$f$</td>
<td>0.017 N·m/s</td>
</tr>
</tbody>
</table>

Acknowledgements

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References


