Hybrid Fuzzy Reference Signal Tracking Control of a Doubly Fed Induction Generator

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1. INTRODUCTION

In the last decades, wind energy has presented an economically viable alternative for renewable energy production similar to other renewable energy sources such as solar, hydropower, geothermal, biomass, etc. Technological progress and environmental issues have persuaded many recalcitrant opponents. A majority of installed wind turbines are of the fixed speed type, yet the number of variable speed wind turbines continues to grow [1].

The wind energy conversion system based on a doubly fed induction generator (DFIG) is the most used in large wind farms which have many advantages: variable speed operation, the decoupled control of active and reactive powers, improves the power quality and the system efficiency when a power converter of not more than 25% of the rated power is used, produce less acoustic noise and...
its mechanical losses are smaller than other types of generators [2,3].

Vector control, based on the classic PI controller is traditionally used for the control of the active and reactive powers of the DFIG [4-7]. However, it is not always easy to obtain good performance on the process controlled by PI, especially if this process has a significant pure delay. Its dynamic characteristics vary during operation. The RST regulator is a polynomial controller based on the theory of pole placement, it has the advantage of solving the problems encountered with the PI command [8-10].

Known for its robustness and simplicity of implementation, the Sliding Mode Control (SMC) has been widely used to control a large class of nonlinear systems [11-13]. This control law represents a drawback resided in the use of the sign function in the control law to ensure the transition from the phased approach to that of sliding.

Artificial intelligence methods have been combined with sliding mode control to control non-linear systems with uncertainties and at least to eliminate the chattering phenomenon. Fuzzy logic control [14,17] is often used in complex systems to overcome the limitations of conventional mathematical tools.

The fuzzy sliding mode controller (FSMC) [18-19] was designed to control the powers of a DFIG. The main drawback of FSMC is the lack of systematic methods for designing fuzzy and functional rules, Lyapunov methods [20].

To overcome these drawbacks, the current trend is to integrate these tools into hybrid controllers [21-22]. The use of a fuzzy neural network offers the possibility of modeling a priori knowledge and linguistic decision rules obtained by experts in the field. Various studies show that the ANFIS neuro-fuzzy system [23], known as adaptive networks based on fuzzy inference, can quickly learn the behavior of a system with precision and this even better than the other methods. Adaptive fuzzy controller [24]. To achieve acceptable performance and effective control of active and reactive powers of DFIG, and to overcome the drawbacks of the two controllers RST and FLC, a combination between them is proposed in this article (F-RST).

The paper is organized as follows: the modeling of the DFIG and its vector control are presented. PI, Polynomial RST, fuzzy logic controllers and the possibility to obtain their hybridization are illustrated. Different tests on tracking and robustness are taken into consideration. A comparison between the results obtained by three different methods is shown. A conclusion will finish the paper.

2. MODELING OF DFIG

The Park model of DFIG is given by the equations below [8]:

\[
\begin{align*}
V_{sd} &= R_s I_{sd} + \frac{d \phi_{sd}}{dt} - \alpha_s \phi_{sq} \\
V_{sq} &= R_s I_{sq} + \frac{d \phi_{sq}}{dt} + \alpha_s \phi_{sd} \\
V_{rd} &= R_r I_{rd} + \frac{d \phi_{rd}}{dt} - \alpha_r \phi_{rq} \\
V_{rq} &= R_r I_{rq} + \frac{d \phi_{rq}}{dt} + \alpha_r \phi_{rd}
\end{align*}
\]

(1)

The stator and rotor flux can be expressed as:

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

(2)

The stator powers of the DFIG are defined as:

\[
\begin{align*}
P_s &= V_{sd} I_{sd} + V_{sq} I_{sq} \\
Q_s &= V_{sq} I_{sd} - V_{sd} I_{sq}
\end{align*}
\]

(3)

The electromagnetic torque is done as:

\[
T_{em} = \frac{P}{L_s} \left( I_{rq} \phi_{sd} - I_{rd} \phi_{sq} \right)
\]

(4)

3. VECTOR CONTROL OF DFIG

By choosing a two-phase reference frame (d-q) linked to the stator rotating field and aligning the stator flux vector with the d axis we have \( \varphi_{sd} = \varphi_s \) and \( \varphi_{sq} = 0 \) [5,6].

The electromagnetic torque Equation (4) is then rewritten as:

\[
T_{em} = \frac{P}{L_s} \left( I_{rq} \phi_s \right)
\]

(5)

For medium and high power machines, the stator resistance \( R_s \) can be neglected, the stator voltages and fluxes can be rewritten as follows [7]:

\[
\begin{align*}
V_{sd} &= 0 \\
V_{sq} &= V_i = \omega_s \phi_i \\
\phi_{sd} &= L_s I_{sd} + M I_{rd} \\
0 &= L_s I_{sq} + M I_{rq}
\end{align*}
\]

(6)

The stator active and reactive power and voltage are given by:

\[
\begin{align*}
P_i &= -V_i \frac{M}{L_s} I_{rq} \\
Q_i &= \frac{V_i^2}{\omega_s L_s} - V_i \frac{M}{L_s} I_{rd}
\end{align*}
\]

(7)
\[ \begin{align*}
V_{rd} &= R_r I_{rd} - g \omega_b L_r \sigma I_{rq} \\
V_{rq} &= R_r I_{rq} + g \omega_x L_r \sigma I_{rd} + g \frac{MV_s}{L_s}
\end{align*} \]

(8)

where:
\[
g = \frac{\omega_x - \omega}{\omega_x} = \frac{\omega_x}{\omega_x} \cdot \sigma = 1 - \frac{M^2}{L_s L_r}
\]

Knowing relations (7) and (8), it is possible to synthesize the regulators and establish the global block-diagram of the controlled system presented in Figure 1.

Overall system control will be implemented via a power control loop with an independent controller while compensating for the perturbation terms that are present in the block diagram of Figure 1. Direct power control between the stator and the grid, shown in Figure 2.

The blocks \( R_a \) and \( R_q \) represent the controllers of the active and reactive powers.

4. CONTROLLERS SYNTHESIS

4.1. Synthesis of PI Controller

The structure of PI controller system is represented in Figure 3:

\[
Y_{ref}(P_{ref}, Q_{ref}) \quad k_p + \frac{k_i}{p} \quad B \quad A
\]

With:
\[
A = L_s R_r + p L_s L_q \sigma, \quad B = MV_s
\]

The open-loop transfer function \( G(p) \) is given by:
\[
G(p) = \frac{p + k_i}{p + \frac{k_p}{k_p} L_s L_q \sigma} \frac{MV_s}{p + \frac{R_r}{L_s \sigma}}
\]

(9)

We use the method of poles compensation for the synthesis of the controller to eliminate the zero present on the transfer function, which results in the following equality [7]:
\[
\frac{k_i}{k_p} = \frac{R_r}{L_s \sigma}
\]

(10)

Thus the closed-loop transfer function \( G(p) \) can be expressed by:
\[
G(p) = \frac{1}{1 + \tau p}
\]

(11)

With:
\[
\tau = \frac{L_s L_q \sigma}{k_p MV_s}, \quad k_i = \frac{L_s R_r}{\tau MV_s}
\]

(12)

4.2. Synthesis of RST Controller

The block diagram of the RST controller system is represented in Figure 4:

In this case, the terms \( A \) and \( B \) are expressed by:
\[
A = L_s R_r + p L_s L_q \sigma, \quad B = MV_s
\]

\[
U \quad T \quad S \quad \frac{B}{A}
\]

\[
Y_{ref}(P_{ref}, Q_{ref}) \quad Y(P_r, Q_r)
\]
The principle of pole placement is to specify an arbitrary stable polynomial $D(p)$ (corresponding to the denominator of the transfer functions in tracking and regulation) and to calculate $S(p)$ and $R(p)$ so that one obtains in accordance to the Bézout equation [8,10]:

$$D = AS + BR$$

(13)

With $\text{deg}(D) = \text{deg}(A) + \text{deg}(S)$

For the proposed model, we obtain:

$$A = a_0 p + a_1, B = b_0, D = d_0 p^3 + d_1 p^2 + d_2 p + d_3,$$

$$R = r_0 p + r_1, S = s_0 p^2 + s_1 p + s_2$$

(14)

Knowing that:

$$a_0 = L_1 L_1 \sigma, a_1 = L_3 R_1, b_0 = MV_1$$

According to the robust pole placement strategy, the polynomial is written as:

$$D(p) = (p - p_c)(p - p_f)^2$$

(15)

$P_c = 1/T_c$ is the pole of polynomial C and $P_f = 1/T_f$ is the double pole of the polynomial filter $F$.

The control pole is chosen arbitrarily 5 times greater than the pole of the polynomial $A$ where:

$$p_c = 5 p_s = -\frac{R}{L_1}, T_c = \frac{L_1 \sigma}{5 R}, T_f = \frac{1}{3} T_c = -15 \frac{R}{L_1 \sigma}$$

(16)

The Bezout equation leads to four equations with four unknown terms where the coefficients of $D$ are related to the coefficients of polynomials $R$ and $S$ by the Sylvester Matrix [10]:

$$\begin{bmatrix} d_3 \\ d_2 \\ d_1 \\ a_0 \end{bmatrix} = \begin{bmatrix} a_4 & 0 & 0 & 0 \\ 0 & a_4 & 0 & 0 \\ 0 & a_0 & b_0 & 0 \\ 0 & 0 & 0 & b_0 \end{bmatrix} \begin{bmatrix} s_2 \\ s_1 \\ s_1 \\ r_0 \end{bmatrix}$$

(17)

According to Equations (14), (15) and (17), we deduce the RST controller’s parameters as:

$$a_0 s_0 = 1, a_1 s_0 + a_2 s_1 = -2 p_f - p_c,$$

$$a_3 s_1 + b_0 s_0 = p_f^2 + 2 p_c p_f, b_1 s_1 = -p_c p_f^2$$

(18)

4. 3. Synthesis of F-RST Controller: We propose to use the combination of the two controllers previously defined, the RST during the transient regime, and that based on fuzzy logic during the steady-state.

The RST control rule is given by:

$$R(p)U(p) = T(p)[Y_{ref}(p) - S(p)] + S(p)[Y_{ref}(p) - Y(p)]$$

(19)

Noting that:

$$T(p)Y (p) - T(p)Y(p) = 0$$

(20)

By inserting (19) in (20) and arranging the expression to update the error ($E$) we find:

$$E(p) = Y_{ref} (p) - Y (p)$$

(22)

Using Equation (21), we get Figure 5.

The RST controller uses directly the input and the output to form the command law and the fuzzy logic one wants the error and its variation as inputs.

The control applied to the system has three components:

$$U = U_1 + U_2 + U_3$$

(23)

$U_1$: is to improve accuracy.

$U_2$ has an important role in the pursuit of the instructions.

$U_3$: fuzzy regulator ensuring robustness.

The FLC inputs are calculated at the instant $k$ as follows:

$$E(k) = Y_{ref}(k) - Y(k)$$

$$\Delta E(k) = E(k) - E(k - 1)$$

(24)

The control signal $U_3$ is obtained after integrating the output of the FLC:

$$U_3 = U_3(k - 1) + \Delta U_3$$

(25)

4. 3.1 Fuzzification The selected membership functions have the trapezoidal shape at the ends and triangular shown in Figure 7:
**4.3.2 Fuzzy Inference System** For the membership functions, they are defined by Table 1.

The linguistic variables are defined as (NB, NS, Z, PS, PB) meaning negative big, negative small, zero, positive small and positive big [15].

The fuzzy inference system is used the Mamdani type and the Max-Min method to deduce the fuzzy output. This method enabled preparing strictly linguistic rules [16].

**4.3.3. Defuzzification** For defuzzification, we use the method of the center of gravity [17], we get:

\[ U_j = \frac{\sum_{i=1}^{m} \mu(U_i)U_i}{\sum_{i=1}^{m} \mu(U_i)} \]  

(26)

**5. STABILITY ANALYSIS**

In this section, we present sufficient quadratic stability conditions using the Lyapunov approach [22,23].

The most commonly used Lyapunov candidate function is defined by:

\[ V(p) = p^T S(p) \]  

(27)

For the dynamic system, the derivatives of \( V(p) \) with respect to time expressed in terms of Equation (28):

\[ \frac{dV(p)}{dt} = p^T S(p) + S(p)^T p = (f(p) + b(p)u(p))^T S(p) + p^T S f(p) + b(p)u(p) \]  

(28)

\[ = F(p) + E(p)u(p) \]

where:

\[ F(p) = f(p)^T S(p) + p^T S f(p), B(p) = b(p)^T S(p) + p^T S b(p) \]

\[ B(p) = L_s L_s \sigma , F(p) = MV_s \]

Therefore,

\[ \sum_{i=1}^{m} \mu(p) F(p) = -L_s L_s \sigma MV_s \]

(29)

\[ \forall p \in P, \ V(p) \leq 0 \]

It has been proved that if the Lyapunov function candidate is negatively semi-defined the closed-loop system will be globally asymptotically stable in the Lyapunov sense.

**6. RESULTS AND DISCUSSION**

Different methods have been studied and realized using Matlab/ Simulink. The parameters of the DFIG are reported in Table 2. The performance comparisons of the three algorithms are performed under the same operating conditions.

The active powers produced by the DFIG controlled with PI, RST, and F-RST are presented in Figures 8 and 9. In this figure, it can be noticed that the ripple is not the same for the three techniques. The F-RST is more efficient and has a very fast response time and has no overshoot over PI and RST controllers.

The stator reactive powers illustrated in Figures 10, 11 tracks the irreverence values very well; it can be seen that the hybrid algorithm shows improved performance.

**6.1. Sensitivity to the Rotor Speed Variation** To verify that the measured powers remain at their set values when the speed of the DFIG varies suddenly, the mechanical speed is imposed variable at the instant \( t = 1s \),

**Figure 8. Active power response under PI, RST and (F-RST)**

**Table 1. Rules base for fuzzy controller**

| E / ΔE | NB | NS | Z | PS | PB |
|--------|----|----|---|----|----|
| NB     | NB | NB | NS| NS | Z  |
| NS     | NB | NS | Z | PS | PS |
| Z      | NS | NS | Z | PS | PS |
| PS     | NS | Z  | PS| PS | PB |
| PB     | Z  | PS | PS| PB | PB |
from 170 rad/sec to 150 rad/sec. The effect of this speed variation on the active and reactive powers of the DFIG is shown in Figures 11, 12 and 13. From these results, we can say that the (F-RST) gave good dynamic and static performances for active and reactive powers compared with those of PI and RST regulators.

Parameters of the DFIG are given in Table 2.

6.2. Robustness TEST with Parameter Uncertainty

To test the robustness against parameter uncertainty on the performances of the suggested f-rst controller, the sensitivity is tested for the three schemes for +25% variation at time t=0.6s of the rotor and stator inductances the powers are shown in Figures 14, 15, 16, 17, it can be observed from these figures, the parameter variations increase the response time of the pi and rst regulators and decrease the amplitude of the transient oscillations in the case of the f-rst.

| Parameters                  | Rated value | Unity |
|-----------------------------|-------------|-------|
| Nominal power               | 1.5         | MW    |
| Stator voltage              | 398         | V     |
| Stator frequency            | 50          | Hz    |
| Number of pairs poles       | 2           |       |
| Stator resistance           | 0.012       | Ω     |
| Rotor resistance            | 0.021       | Ω     |
| Stator inductance           | 0.0137      | H     |
| Rotor inductance            | 0.0136      | H     |
| Mutual inductance           | 0.0135      | H     |
| Inertia                     | 1000        | kg m  |
| Viscous friction            | 0.0024      | Nm/s  |
7. CONCLUSION

In this paper, a hybrid scheme for the control of the powers using the F-RST controller for DFIG has been presented. The suggested control has been compared to the VC and RST controller. Simulation results proved that the power ripples are lower in (F-RST) compared with other controls. The efficiency of the proposed algorithm has been validated by simulation tests carried out with a 1.5 MW DFIG system. Moreover, to validate the influence of parameter uncertainty on the performances of the proposed (F-RST) algorithm, it has been shown that the suggested algorithm is robust and capable to reject the influences of uncertainty in system parameters.

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Persian Abstract

چکیده

این مقاله یک سیستم ترکیبی برای کنترل توافه فعال (اکتیو) و واکنشی (ریاکتیو) با استفاده از دو کنترل مستقیم برداری و ریاستگذاری شده است. کنترل کننده پیشنهادی در جهت تعیین باتری های قطع و ریاستگذاری شده است. کنترل کننده پیشنهادی (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب فردی و ریاستگذاری (F-RST) شکل نشان دهنده (F-RST) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم مرجع (Tracking) و (Robustness) می باشد. این دو سیستم مرجع به ترتیب F-RST و (Robustness) شامل دو سیستم M.}