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Robust MRAC-based adaptive control of a Doubly Fed Induction Generator (DFIG) in a Wind energy system using a fractional order Integrator

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Abstract: This paper presents a robust control of doubly fed induction generator for wind generation system. The whole system is presented in d-q-synchronous reference frame. We propose the implementation of adaptive control with integer model reference MRAC, fractional model reference FOMRAC with integer and fractional order control law design for active and reactive power supervision control in the doubly fed induction generator (DFIG) for wind energy systems.

The objective is to realize a comparative study between the classical regulator MRAC and the proposed FO-MRAC with integer and fractional order control law in order to demonstrate the robustness of the fractional order adaptive control with fractional order integral in control law comparatively to integer order one. Performance and robustness results obtained will be presented and analyzed.

Keywords: Doubly fed induction generator (DFIG); Renewable energy; MRAC; FOMRAC; Robustness

1. INTRODUCTION

Currently, the wind using a doubly-fed induction generator « DFIG» are the more used for production of the electric energy [1, 4]. Nowadays, wind generation system based on a doubly fed induction generator (DFIG) are employed widely in large wind farms fat has its many advantages: a very good energy efficiency, robust sensorless operation [5,6] . In addition, the power converter is usually rated at 25-30% of the generator power rating [7-10] , For such several advantages, this machine has generated a lot of curiosity on the part of researchers have tried to develop strategies to best exploit its strong points [11].

The problematic studied in this paper is to find a type of control independent to the parametric variations of the machine , that is realized by adaptive control with integer order model reference MRAC and fractional order model reference FOMRAC.

Beginning with the earlier works of Vinagre at al [12] and Ladaci et al [13,15], fractional-order model reference adaptive control (FO-MRAC) has gathered a great interest from the community of control engineering researchers. This popularity is mainly due to its simple principle and easiness to implement on one hand and its improved performance and robustness comparatively to classical adaptive control schemes on the other [16].

Many application of fractional-order model reference adaptive control schemes are also available in literature in different science and engineering fields like: in Electric Vehicle Using a fractional order model reference adaptive strategy[17], Voltage control of DC/DC converter in multi sources renewable [18], and a multi-source renewable energy system using fractional-Order Integrals [19]...etc.

Finally, a comparative study is carried on using the quadratic error criterion, calculating this last for integer MRAC and fractional order model reference FOMRAC in each case for active and reactive powers.

The paper is organized as follows. Section 2, describes the modeling studied system with the control of active and reactive power. Then fractional order MRAC control theory will be presented in section 3. The results of simulations obtained are presented and discussed for validating the proposed controller in Section 4. We propose a robustness test with parameters fluctuation by rotor resistance change in section 5. Finally, the conclusion is drawn in section 6.

2. DFIG SYSTEM MODELLING

When modeling a doubly fed induction machine, it is essential to consider that this kind of wound rotor machine has to be fed both from stator and rotor sides, as sketched in Fig.1. normally, the stator is directly connected to the grid and the rotor is interfaced through a variable frequency power converter. In order to cover a wide operation range from subsynchronous to synchronous speeds, the power converter placed on the rotor side bas to able to operate with power flowing in both directions [4].

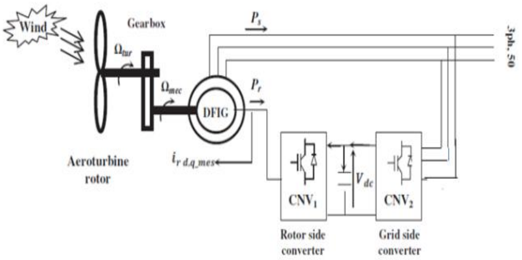

Fig.1 Doubly fed induction machine basic configuration for wind turbine.

The mathematical model can be expressed as [5]:

The stator voltage equation:

$$\begin{cases} V_{sq} = R_s I_{sq} + \dfrac{d}{dt}\left(\phi_{sq}\right) + \omega_s \phi_{sd} \\ V_{sd} = R_s I_{sd} + \dfrac{d}{dt}\left(\phi_{sd}\right) - \omega_s \phi_{sq} \end{cases} \tag{1}$$

The rotor voltage equation:

$$\begin{cases} V_{rd} = R_r I_{rd} + \dfrac{d}{dt}\left(\phi_{rd}\right) - \left(\omega_s - \omega_r\right)\phi_{rq} \\ V_{rq} = R_r I_{rq} + \dfrac{d}{dt}\left(\phi_{rq}\right) + \left(\omega_s - \omega_r\right)\phi_{rd} \end{cases} \tag{2}$$

The stator flux linkage equation:

$$\begin{cases} \phi_{sd} = L_s I_{sd} + M I_{rd} \\ \phi_{sq} = L_s I_{sq} + M I_{rq} \end{cases} \tag{3}$$

The rotor flux linkage equation:

$$\begin{cases} \phi_{rd} = L_r I_{rd} + M I_{sd} \\ \phi_{rq} = L_r I_{rq} + M I_{sq} \end{cases} \tag{4}$$

Electromagnetic torque equation:

$$J\frac{d\Omega}{dt} = \left(\frac{J}{p}\frac{d\omega_r}{dt}\right) = -\frac{3}{2}p\frac{M}{L_s}\left(\phi_{rd}I_{sq} - \phi_{rd}I_{sd}\right) - C_r - f_r\Omega \tag{5}$$

2.1 Reference frame

By choosing a reference frame linked to the stator flux, rotor currents will be related directly to the stator active and reactive power. If the stator flux is linked to the *d*-axis of the frame we have [8]:

$$\psi_{ds} = \psi_s \text{ and } \psi_{qs} = 0 \tag{6}$$

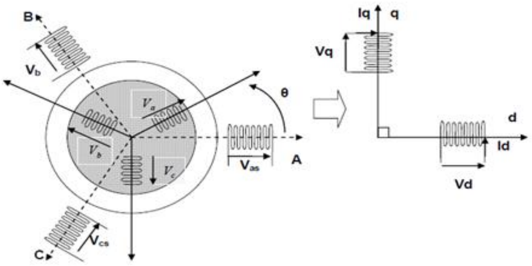

Fig. 2 PARK’s model of DFIG.

2.2 Control strategy

The torque and consequently the active power only depend on the *q*-axis rotor current component. If the per phase stator resistance is neglected, the stator voltage vector is in quadrature advance in comparison with the stator flux vector [9].

$$V_{ds} = 0 \text{ and } V_{qs} = V_s = \omega_s \psi_s \tag{7}$$

The stator active and reactive power can then be expressed only versus these rotor currents as:

$$\begin{cases} P = -V_s \dfrac{M}{L_s} i_{qr} \\ Q = \dfrac{V_s \phi_s}{L_s} - \dfrac{V_s M}{L_s} i_{dr} \end{cases} \tag{8}$$

$$\begin{cases} V_{rd} = R_r I_{rd} + \left(L_r - \dfrac{M^2}{L_s}\right)\dfrac{di_{dr}}{dt} - g\omega_s\left(L_r - \dfrac{M^2}{L_s}\right)i_{qr} \\ V_{rq} = R_r I_{rq} + \left(L_r - \dfrac{M^2}{L_s}\right)\dfrac{di_{qr}}{dt} + g\omega_s\left(L_r - \dfrac{M^2}{L_s}\right)i_{qr} + g\omega_s\dfrac{MV_s}{\omega_s L_s} \end{cases} \tag{9}$$

The inputs block relating V_{dq} to V_{dqr} present a simplified rotor converter model.

3. FRACTIONAL ORDER MRAC CONTROL

Adaptive control is the control method used by a controller which must adapt to a controlled system with parameters which vary, or are initially uncertain.

3.1 Linear approximation of fractional order Transfer function

In order to approximate the fractional order model reference we use the so-called singularity function method proposed by Charef (see [13-14]). For fractional second order system with m a positive real number such that 0<m<1,

$$H(s)=\frac{1}{\left(\frac{s^2}{\omega^2}+2\xi\frac{s}{\omega}+1\right)^m} \qquad (10)$$

Can be expressed as:

$$H(s)=\frac{\left(\frac{s}{\omega}+1\right)\left(\frac{s}{\omega+1}\right)^{\beta}}{\left(\frac{s^2}{\omega^2}+2\alpha\frac{s}{\omega}+1\right)} \qquad (11)$$

with $\alpha=\xi^m$ and $\beta=1-2m$, which can also be approximated by the function (19):

$$H(s)=\frac{\left(\frac{s}{\omega}+1\right)}{\left(\frac{s^2}{\omega^2}+2\alpha\frac{s}{\omega}+1\right)}\frac{\prod_{i=1}^{N-1}(1+\frac{s}{z_i})}{\prod_{i=1}^{N}(1+\frac{s}{p_i})} \qquad (12)$$

3.2. Model Reference Adaptive Control

The controller parameter adjustment is achieved by mean of the error between the output of the plant and the model reference output. This can be represented in fig. 3.

The control signal is computed using the following relation,

$$u=\varphi^T.\theta \qquad (13)$$

Where φ is the regression vector containing the measured input signals u and output signals y and the input reference signal u_c.

3.3. M.I.T. Rule:

We consider a closed loop system where the controller has an adjustable parameter vector θ. A model which output is y_m specifies the desired closed loop response. Let **e** be the error between the closed loop system output **y** and the model one y_m, one possibility is to adjust the parameters such that the cost function:

$$J(\theta)=\frac{1}{2}e^2 \qquad (14)$$

Be minimized. In order to make **J** small it is reasonable to change parameters in the direction of negative gradient **J**, so:

$$\frac{d\theta}{dt}=-\gamma\frac{\partial J}{\partial\theta}=-\gamma e\frac{\partial e}{\partial\theta} \qquad (15)$$

Wish leads to the following blocs scheme of fig.3,

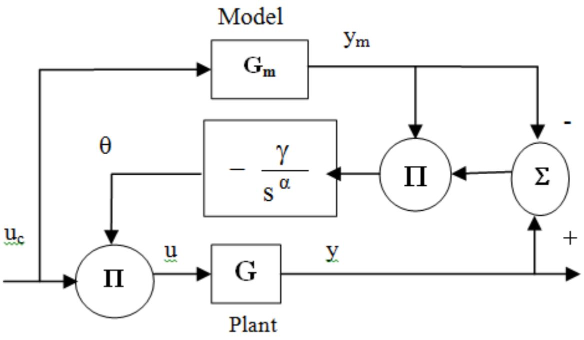

Fig. 3Adaptation algorithm

3.4 Introducing Fractional Integration:

Let $\alpha\in C$, $\Re(\alpha)>0$, $c\in R$ and f a locally integrable function defined on [c,+∞[. The α order integral of *f*, of lower bound c is defined as [12-23]:

$$I_c^{\alpha}f(t)\overset{\Delta}{=}\int_c^t\frac{(t-\tau)^{\alpha-1}}{\Gamma(\alpha)}f(\tau)d\tau \qquad (16)$$

With $t\geq c$, and Γ is the Euler function. The formula (18) is called *Riemann-Liouville Integral*.

Usually, the control loop is discreet, and we use a sampled approximation of (18) given by:

$$I_c^{\alpha}f(k\Delta)=\frac{\Delta}{\Gamma(\alpha)}\sum_{\tau=0}^{k-1}(k\Delta-\tau\Delta)^{\alpha-1}f(\tau\Delta) \qquad (17)$$

With, Δ: Sampling Period.

In the adjusting algorithm represented by the bloc-scheme of figure.4, we put an order integration with **α** non-zero positive real such that: 0<**α**< 2. We get then:

$$\theta=-\frac{\gamma}{s^{\alpha}}y_m(y-y_m)=-\frac{\gamma}{s^{\alpha}}y_m e \qquad (18)$$

3.5 Application of Model Reference adaptive control to DFIG active and reactive power control in wind energy conversion

The block diagram of the MRAC control of active and reactive power of DFIG is shown in fig. 4, by adding the parameters of the DFIG system presented in table 1.

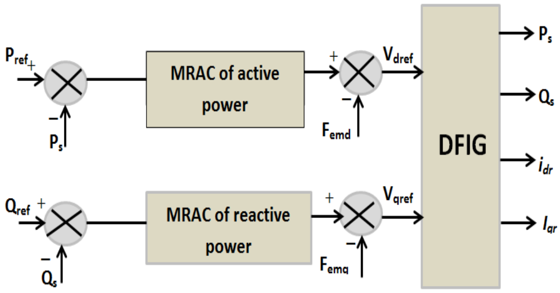

Fig. 4 Model reference adaptive control MRAC of active and reactive power of DFIG in wind system

Table 1 Characteristic parameters of the DFIG

Parameter	Value
V_{seff}	*230 V*
p	*2 pairs of poles.*
R_s	*0.455 Ω*
R_r	*0.19 Ω*
L_s	*0.07 H*
L_r	*0.0213 H*
M_{sr}	*0.034 H*
f	*50 Hz*

4. RESULTS AND INTERPRETATION

In this section, we will have the results of simulation of the uncoupled control from the active and reactive powers generated doubly fed induction generator DFIG of the wind energy, using fractional order FO-MRAC, whose objective is to compare the responses powers active and reactive compared to the references desire.

4.1 MRAC controller

The system is described using the following equation:

$$\mathrm{H(S)} \;=\; \frac{M\,.V_s}{L_s.R_r + S.L_s\left(L_r - \frac{M^2}{L_s}\right)} \tag{19}$$

The numerical replacement gives the following transfer function:

$$\mathrm{H(S)} \;=\; \frac{Y\,(s)}{U\,(S)} = \frac{2.334\,e04}{S+39.7} = \frac{B}{A} \tag{20}$$

According to the characteristics of the system studies, the reference model is chosen as:

$$\mathrm{G_M(S)} = \frac{6.4.10^7}{(S^2 + 15200\,S + 6.4.10^7)^m} \tag{21}$$

The RST control structure is characterized by the Diophantine equation:

$$A.R + B.S = A_r = A_0.A_m \tag{22}$$

Where R, S and T are polynomials and A_0 is a stable polynomial called the "observer" polynomial.
Therefore, the regulation parameters vector is given as:

$$\theta = \begin{bmatrix} r_0 & s_0 & s_1 & t_0 & t_1 \end{bmatrix} \tag{23}$$

and the regression vector,

$$\varphi^T = \frac{b_0}{A_0 A_m}\begin{bmatrix} U & Sy & y & -Suc & -uc \end{bmatrix} \tag{24}$$

s : Laplace operator.

The recurrence equation of φ^T obtained after the discretization (T=0.001 s) is given by :

phi(t+1,:)=-0.0008007*phi(t,:)-2.505e-07*phi(t-1,:)+alpha(t,:) (25)

4.2 FOMRAC controllers

The reference model is a fractional order system of second order-like of the from (10) with m = 0,4. Using Charef's approximation method we obtain the approximating rational transfer function given by:

$$G_m(S) = \frac{6.4.10^{07}}{(S^2 + 15200\,.\,S + 6.4.10^{07})^{0.4}} \tag{26}$$

The approximation function is of order 5:

$$G_{ap}^{0.4}(S) = \frac{7.308.10^{-09}.S^2 + 0.0001806\;S + 1}{6.376.10^{-22}S^5 + 7.412.10^{-17}S^4 + 2.909.10^{-12}S^3 + 4.893.10^{-8}S^2 + 0.0003641S\; + 1} \tag{27}$$

Then deg (A_m) = 5 and from the Diophantine equation (22) we obtain: deg(S) = deg(R) = deg(S) = 4.
Therefore, the regulation parameters vector is given as:

$$\theta = \begin{bmatrix} r_1 & r_2 & r_3 & r_0 & s_0 & s_1 & s_2 & s_3 & s_4 & t_0 & t_1 & t_2 & t_3 & t_4 \end{bmatrix} \tag{28}$$

and the regression vector,

$$\varphi^t = \frac{b_0}{A_0 A_m}\begin{bmatrix} s^{k-1}u \ldots. u & s^l y \ldots. y & -s^m u_c \ldots. -u_c \end{bmatrix} \tag{29}$$

Fig. 5 and 6 show comparative results for active and reactive power control respectively using integer and fractional order MRAC.

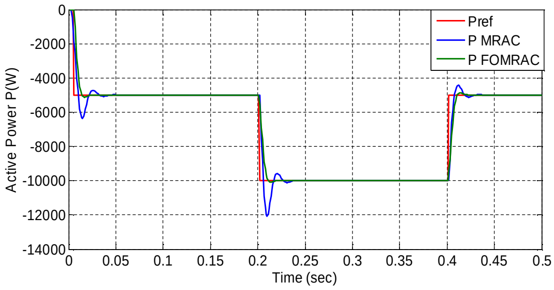

Fig. 5 Active power output comparison between integer reference model (blue) and Fractional order reference models (green) with m=0.4

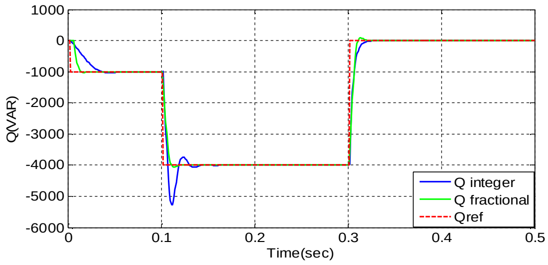

Fig. 6 Reactive power output comparison between integer reference model (blue) and Fractional order reference model (green) with m=0.4

4.3 FOMRAC with random output noise

Let us consider the proposed FOMRAC controller for m = 0,4 in presence of random output noises of 30% of the reference signal amplitude. The simulation results are given in Fig. 7 for active power and Fig. 8 for reactive power respectively.

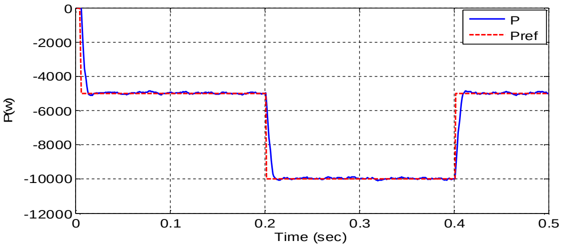

Fig. 7 Active power with FO-MRAC with random output noise of 30% of the reference signal amplitude.

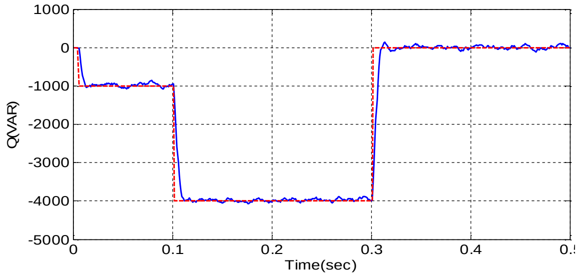

Fig. 8 Reactive power with FO-MRAC with random output noise of 30% of the reference signal amplitude.

And let us define the quadratic cost function criteria for the tracking error *Je* and the input energy *Ju* as follows,

$$J_e = \sqrt{\sum_{n=0}^{N_{\max}} (u_c(n) - y(n))^2} \qquad (30)$$

$$J_u = \sqrt{\sum_{n=0}^{N_{\max}} u(n)^2} \qquad (31)$$

Computing these criteria for different values of the fractional order m and the integer case, we obtain,

Table 2 J_e and J_u criteria for active power with FO-MRAC (m = 0.4, 0.7, 0.9, 1).

M	Je(P)	Ju(P)
0.4	**14667.7**	312.66
0.7	16109.7	**309.19**
0.9	25115.1	349.02
1	16088.0	337.80

Table 3 J_e and J_u criteria for reactive power with fractional order reference models FO-MRAC (m = 0.4, 0.7, 0.9, 1).

M	Je(Q)	Ju(Q)
0.4	**8995.1**	122.58
0.7	10054.3	**120.14**
0.9	11895.9	135.48
1	10044.8	135.67

4.5 Fractional order integration

The reference model is a fractional order system of second order-like of the from (10) with m = 0,4. Using fractional order integration (17) with α the fractional order of integral (control law), we obtain,

Table 4. Quadratic error criteria J_e with different approaches of adaptive control of active power

		J_e for P(w)
MRAC	m=1	16088.027
FOMRAC	m=0.4	14667.699
FOMRAC with integration	m=0.4 α=1.2	14657.843
FOMRAC with integ + random	m=0.4 α=1.2 Random15%	14666.596

Table 5 Quadratic error criteria J_e with different approaches of adaptive control of reactive power

		J_e for Q(VAR)
MRAC	m=1	10044.879
FOMRAC	m=0.4 α=0.4	8995.089
FOMRAC With integration	m=0.4 α=1.2	8985.089
FOMRAC With integ. + random	m=0.4- α=1.2 Random15%	9006.728

5. PARAMETRIC ROBUSTNESS TEST

The test consists in varying the parameters of the model of GADA used (test of robustness) with the maintenance of the conditions of the first test. We suppose that the rotor resistance of the doubly fed induction generator DFIG increases by +25% and 50% between *t* = [0.25-0.27] s, as represented in Table 6.

Table 6. System TF with Rotor resistance variation.

Rr increase	G{P,Q} (s)
0%	$\frac{23340}{s+39.7}$
25%	$\frac{23340}{s+45.63}$
50%	$\frac{23340}{s+59.55}$

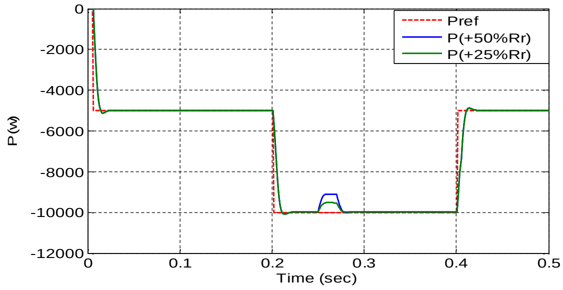

Fig.9 Active power P(W) output with fractional reference model FO-MRAC with different increases in rotor resistance R_r (+25% and +50%).

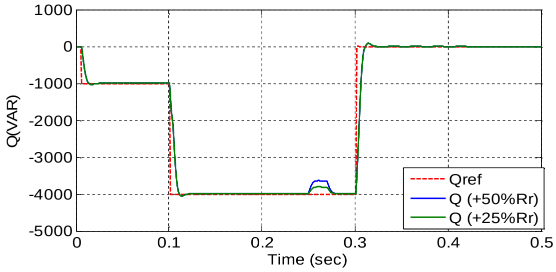

Fig.10 Reactive power Q(VAR) output with FO-MRAC with different R_r (+25% and +50%).

Whereas fig. 5 and 6 prove that the FOMRAC control with fractional order reference gives better performance than the integer order MRAC because the responses of active and reactive power follow perfectly the suggested references, besides, Tables 2 and 3 which confirm that the tracking error obtained for FO-MRAC (m = 0.4) is smaller than that obtained for the MRAC for active and reactive power control.

6. CONCLUSIONS

In this paper, fractional Model reference adaptive control algorithm (FOMRAC) which includes the use of fractional integral was presented that can guarantee the stability with a satisfying level of performances.

First, a fractional order model reference adaptive control (FOMRAC) is designed to supervise the active and reactive powers of a doubly fed induction generator (DFIG) for wind energy conversion. Simulation results show that the proposed FOMRAC control strategy is more powerful than classical MRAC controls in regards of error, response time and overshoot. Then, including the fractional integral in control law presented a satisfying level of performances. Simulation results illustrate the reliability and robustness of FO-MRAC control towards this change of parameters, where the active and reactive powers follow perfectly the proposed references.

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