Comparison Study Between Field Oriented Control and a Nonlinear Control For a Doubly Fed Induction Motor

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Abstract: In this paper a comparative study have been done between The filed oriented control (FOC) and an input output feedback linearization control which are used to track the torque and rotor flux . Simulations results have been performed under Simulink/Matlab to show the control system performances as well as leads us to predict the advantages and disadvantages inherent in the use of particular methods.

Keywords: DFIM, Nonlinear Control,FOC,I-O Feedback Linearization

1. INTRODUCTION

Known since 1899 , the doubly fed induction ma- chine (DFIM) is a wound rotor asynchronous machine supplied by the stator and the rotor from two external, source voltages. This solution is very attractive for the variable speed applications such as the electric vehicle and the electrical energy production (G.Salloum (2008)). Consequently, it covers all powers ranges. Obviously, the requested variable speed domain and the desired performances depend of the application kinds (G.Salloum (2008)). The use of DFIM offers the opportunity to modulate power flow into and out the rotor winding in order to have, at the same time, a variable speed in the characterized super-synchronous or sub-synchronous modes in motor or in generator regimes. Advanced control of electrical machines requires an independent control of magnetic flux and torque. For that reason it was not surprising, that the DC-machine played an important role in the early days of high performance electrical drive systems, since the magnetic flux and torque are easily controlled by the stator and rotor current, respectively.

The Wound rotor doubly fed asynchronous machine has been the subject of most research primarily for its operation as a generator in applications of wind energy. Our work involves the operation in variable speed motor, for improving the robustness of the control of the DFIM (Paul-Etienne (1958)).

In the control structure shown in Figure (1) , the DFIM is supplied to its stator by the network, while the rotor is fed through a conversion system which comprises a rectifier, a filter and an inverter.

The DFIM has some distinct advantages compared to the conventional squirrel-cage machine. The DFIM can be controlled from the stator or rotor by various possible combinations

In this paper we improved the performance of the field oriented control of a doubly fed induction motor DFIM by an input output feedback control that is used to track the torque and rotor flux ,both control strategies are applied to the structure of figure (1)

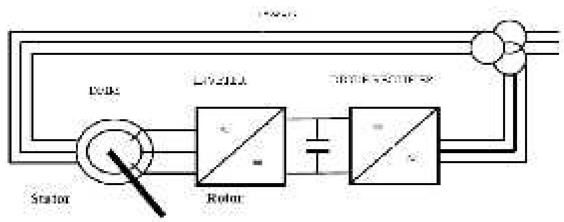


Fig. 1. Diagram of the power of the DFIM for motor application

The rest of this paper is organized as follows . section (2) describes the dynamical modeling of the DFIM.section (3) describes the main idea behind the field oriented control. section (4) describes the design of an input output feedback linearization controller .section (5) shows the simulation results .conclusion and perspectives are given in section (6).

2. DOUBLY-FED INDUCTION MACHINE MODEL

Under the simplification assumptions and balanced condition, the equivalent two phase model of Doubly fed induction motor in the stator (d, q) fixed reference frame related to the stator can be obtained. so The model can be written in a compact form as:

$$\dot{x} = f(x) + gu \tag{1}$$

where the state vector x is defined as:

$$x = [i_{sd}, i_{sq}, \varphi_{rd}, \varphi_{rq}, \Omega]^T \tag{2}$$

and the input vector is:

$$u = [u_{sd},\ u_{sq}]^T \tag{3}$$

with

$$\underline{f}(x) = \begin{bmatrix} -\gamma i_{sd} + \omega_r i_{sq} + \frac{K}{T_r}\varphi_{rd} - K\omega\varphi_{rq} - K u_{rd} \\ -\gamma i_{sq} - \omega_r i_{rd} + \frac{K}{T_r}\varphi_{rq} + K\omega\varphi_{rd} - K u_{rq} \\ \frac{M}{T_r} i_{sd} - \frac{1}{T_r}\varphi_{rd} + \omega_s\varphi_{rq} + u_{rd} \\ \frac{M}{T_r} i_{sq} - \frac{1}{T_r}\varphi_{rq} - \omega_s\varphi_{rd} + u_{rq} \\ \frac{pM}{J_m L_r}(\varphi_{rd} i_{sq} - \varphi_{rq} i_{sd}) - \frac{f_m}{J_m}\Omega - \frac{1}{J_m} c_r \end{bmatrix}^T \quad (4)$$

$$g = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 \end{bmatrix}^T . \quad (5)$$

where the parameters σ, γ, K, T_s, T_r are defined as follows

$$\sigma = 1 - \frac{M^2}{L_r L_s}, \quad \gamma = \frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_r}$$
$$K = \frac{1-\sigma}{\sigma}, \quad T_s = \frac{L_s}{R_s}, \quad T_r = \frac{L_r}{R_r} \quad (6)$$

σ is the scattering coefficient, T_r, T_s are the time constant of the rotor and stator dynamics, J_m is the rotor inertia, f_m is the mechanical viscous damping , p is the number of pole pairs, c_r is the external load torque.

The state variables i_{sd}, i_{sq}, φ_{rd}, φ_{rd}, φ_{rq}, u_{sd}, u_{sq}, u_{rd}, u_{rq} are the stator currents, rotor flux linkages, stator terminal voltage, rotor terminal voltage respectively and L_r, L_s, M, R_r, R_s are rotor inductance, stator inductance, mutual inductance, stator resistance and rotor resistance respectively.

3. FIELD ORIENTED CONTROL

Oriented vector control of rotor flux is the most used because it eliminates the influence of the leakage reactance rotor and stator and give better results than methods based on the orientation of the stator flux or air-gap (G.Salloum (2008); AKKARI (2010)) This control is achieved by orienting the rotor flux following the direct axis d of the rotating frame as shown in Fig (2) :

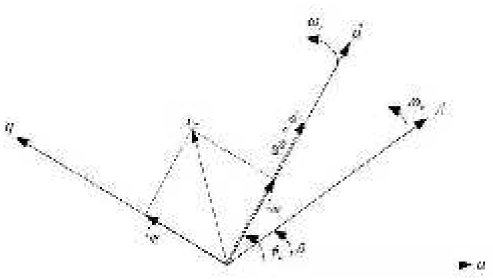


Fig. 2. the orientation of rotor flux

so that

$$\begin{cases} \varphi_{rd} = \varphi_r \\ \varphi_{rq} = 0 \end{cases} \quad (7)$$

So that by introducing equation (7) into equation (4) we get:

$$u_{sd} = R_s i_{sd} + L_s\sigma\frac{di_{sd}}{dt} + \frac{M\,d\varphi_r}{L_r dt} - \omega_s L_s \sigma i_{sq} \quad (8)$$

$$u_{sq} = R_s i_{sq} + L_s\sigma\frac{di_{sq}}{dt} + \omega_s\frac{M\varphi_r}{L_r} + \omega_s L_s \sigma i_{sd} \quad (9)$$

with a rotor flux and the rotor angel estimation written as follows:

$$T_r\frac{d\varphi_r}{dt} + \varphi_r = M\, i_{sd} + T_r v_{rd} \quad (10)$$

$$\omega_r = \frac{M\; i_{sq} + T_r\, v_{rq}}{T_r\varphi_r} \quad (11)$$

The electromagnetic torque will be reduced to:

$$C_e = \frac{pM}{L_r}\varphi_r i_{sq} \quad (12)$$

The PI controller is used to control the current vector, but this controller can only control a linear system, so equations (8) and (9) must be linearized first by the following decoupling equations

$$u_{sd} = v_{sd} + e_d \quad (13)$$
$$u_{sq} = v_{sq} + e_q \quad (14)$$

where:

$$v_{sd} = R_s i_{sd} + L_s\sigma\frac{di_{sd}}{dt} \quad (15)$$

$$v_{sq} = R_s i_{sq} + L_s\sigma\frac{di_{sq}}{dt} \quad (16)$$

$$e_d = \frac{M\,d\varphi_r}{L_r dt} - \omega_s L_s \sigma i_{sq} \quad (17)$$

$$e_q = \omega_s\frac{M\,\varphi_r}{L_r} + \omega_s L_s \sigma i_{sd} \quad (18)$$

Where :

e_d, e_q: represent the electromotive forces compensation that must be added to the output of each regulator.
v_{sd}, v_{sq}: represent the emf of compensation that allow decoupling of the control current i_{sd} and current i_{sq}.

where by introducing laplace transform to equations (15) and (16),so that the model that we will use for compensation is shown in figure (6)

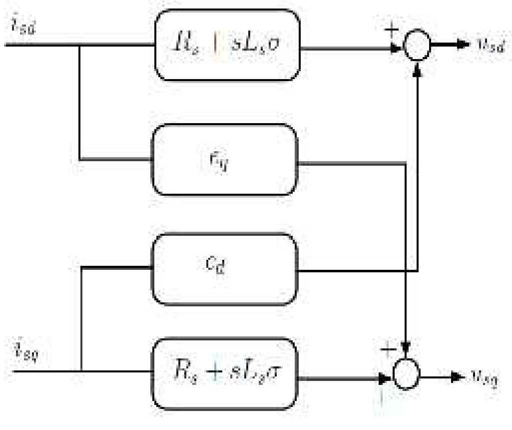


Fig. 3. Compensation scheme

4. I-O FEEDBACK LINEARIZATION CONTROL

Using nonlinear feedback allows to control the model in the stator fixed (α, β) reference frame avoiding the transformation in a rotating reference frame. The model can be written in a compact form as:

$$\dot{x} = f(x) + gu \quad (19)$$

where the state vector x is defined as:

$$x = [i_{s\alpha}, i_{s\beta}, \varphi_{r\alpha}, \varphi_{r\beta}, \Omega]^T \quad (20)$$

and the input vector is:

$$u = [u_{s\alpha},\ u_{s\beta}]^T \quad (21)$$

with

$$f(x) = \begin{bmatrix} -\gamma i_{s\alpha} + \frac{K}{Tr}\varphi_{r\alpha} + pK\Omega\varphi_{r\beta} - K u_{r\alpha} \\ -\gamma i_{s\beta} + \frac{K}{Tr}\varphi_{r\beta} - pK\Omega\varphi_{r\alpha} - K u_{r\beta} \\ \frac{M}{Tr} i_{s\alpha} - \frac{\varphi_{r\alpha}}{Tr} - p\Omega\varphi_{r\beta} + u_{r\alpha} \\ \frac{M}{Tr} i_{s\beta} - \frac{1}{Tr}\varphi_{r\beta} + p\Omega\varphi_{r\alpha} + u_{r\beta} \\ \frac{pM}{J_m L_r}(\varphi_{r\alpha} i_{s\beta} - \varphi_{r\beta} i_{s\alpha}) - \frac{f_m}{J_m}\Omega - \frac{1}{J_m} c_r \end{bmatrix} \quad (22)$$

$$g = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma L_s} & 0 & 0 \end{bmatrix}^T . \quad (23)$$

The delicate case for the input-output linearization control is the choice of output variable. In this paper, we chose to control the torque and the square of the rotor flux modulus, so that the output vector will be (M.CHENAFA (2005)):

$$y = \begin{bmatrix} h_1(x) \\ h_2(x) \end{bmatrix} = \begin{bmatrix} \varphi_{r\alpha}^2 + \varphi_{r\beta}^2 \\ \frac{pM}{L_r}(i_{s\beta}\varphi_{r\alpha} - i_{s\alpha}\varphi_{r\beta}) \end{bmatrix} \quad (24)$$

The following notation used for the Lie derivatives of a function (A. Isidori (1992))

$$h(x) : \Re^n \rightarrow \Re \quad (25)$$

along a vector field :

$$f(x) = (f_1(x), \ldots, f_n(x)) \quad (26)$$

$$L_f h(x) = \sum_{i=1} \frac{\partial h}{\partial x_i} f_i(x) \quad (27)$$

Iteratively we define

$$L_f h(x) = L_f(L_f^{i-1} h) \quad (28)$$

where D(x) is the decoupling matrix which define as follows:

$$D(x) = \begin{bmatrix} L_{g_1}L_f h_1 & L_{g_2}L_f h_1 \\ L_{g_1}h_2 & L_{g_2}h_2 \end{bmatrix} \quad (31)$$

where :

$$L_{g_1}L_f h_1 = \frac{2M}{T_r\sigma L_s}\varphi_{r\alpha}u_{s\alpha} \quad (32)$$

$$L_{g_2}L_f h_1 = \frac{2M}{T_r\sigma L_s}\varphi_{r\beta}u_{s\beta} \quad (33)$$

$$L_{g1} h_2 = -\frac{pM}{L_r\sigma L_s}\varphi_{r\beta}u_{s\alpha}, \qquad L_{g2} h_2 = \frac{pM}{L_r\sigma L_s}\varphi_{r\alpha}u_{s\beta} \quad (34)$$

$$\begin{aligned} L_f^2 h_1(x) = {} & (2u_{r\alpha} - \frac{4\varphi_{r\alpha}}{T_r} + \frac{2M\ i_{s\alpha}}{Tr})(u_{r\alpha} - \frac{\varphi_{r\alpha}}{Tr} \\ & - p\varphi_{r\beta}\Omega + \frac{M\ i_{s\alpha}}{Tr}) + (2u_{r\beta} - \frac{4\varphi_{r\beta}}{T_r} \\ & + \frac{2M\ i_{s\beta}}{T_r})(u_{r\beta} - \frac{\varphi_{r\beta}}{T_r} + p\varphi_{r\alpha}\Omega + \frac{M\ i_{s\beta}}{T_r}) \\ & - \frac{2M\ \varphi_{r\alpha}}{T_r}(K u_{r\alpha} + \gamma i_{s\alpha} - \frac{K\varphi_{r\alpha}}{T_r} - Kp\varphi_{r\beta}\Omega) \\ & - \frac{2M\ \varphi_{r\beta}}{T_r}(K u_{r\beta} + \gamma i_{s\beta} - \frac{K\varphi_{r\beta}}{T_r} + Kp\varphi_{r\alpha}\Omega) \end{aligned} \quad (35)$$

$$\begin{aligned} L_f^1 h_2(x) = {} & -\frac{pM}{L_r}(\gamma + \frac{1}{T_r})(i_{s\beta}\varphi_{r\alpha} - \varphi_{r\beta}i_{s\alpha}) \\ & - \frac{pM}{L_r} pK\Omega(\varphi_{r\alpha}^2 + \varphi_{r\beta}^2) \\ & - \frac{pM}{L_r} p\Omega(\varphi_{r\alpha}i_{s\alpha} + \varphi_{r\beta}i_{s\beta}) \\ & + \frac{pM}{L_r}(K\varphi_{r\beta} + i_{s\beta})u_{r\alpha} \\ & - \frac{pM}{L_r}(K\varphi_{r\alpha} + i_{s\alpha})u_{r\beta} \end{aligned} \quad (36)$$

the matrix D(x) is nonsingular ,since its determinant is not zero, which is :

$$D(x) = \begin{bmatrix} \frac{2M}{T_r\sigma L_s}\varphi_{r\alpha} & \frac{2M}{T_r\sigma L_s}\varphi_{r\beta} \\ -\frac{pM}{L_r\sigma L_s}\varphi_{r\beta} & \frac{pM}{L_r\sigma L_s}\varphi_{r\alpha} \end{bmatrix} \quad (37)$$

$$\det(D(x)) = 0 \quad (38)$$

so that we can draw the vector $[u_{s\alpha}, u_{s\beta}]^T$ from equation (48):

$u_{s\alpha}$ D $^{-1}$ efine the change of $-L_f^2 h_1(x) + v_1$ coor dinates as :

$$z_1 = h_1(x) \qquad z_2 = h_2(x) \tag{29}$$

So in order to obtain the control law we have to differentiate equation (47) so that:

$$\begin{matrix} \ddot{z}_1 \\ \dot{z}_2 \end{matrix} = \begin{matrix} L_f^2 h_1(x) \\ L_f h_2(x) \end{matrix} + D(x) \begin{matrix} u_{s\alpha} \\ u_{s\beta} \end{matrix} \tag{30}$$

$$u_{s\beta} = [\,D(x)\,] \quad - L_f h_2(x) + v_2 \tag{39}$$

so that the block diagram will be as shown in Figure (4) where the v_1 , v_2 are the new vector control :

$$\ddot{z}_1 = v_1 \qquad \dot{z}_2 = v_2 \tag{40}$$

It is seen, that the problem of controlling torque and flux is rendered to controlling an integrator for the torque loop

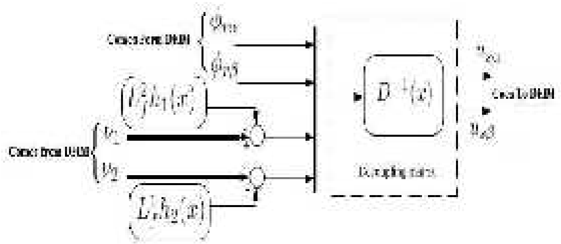


Fig. 4. The block diagram of the Nonlinear controller

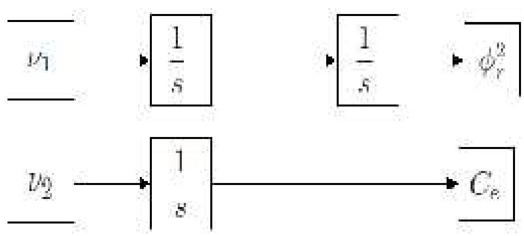


Fig. 5. The input-output linearized system

and a double integrator for the flux loop as shown in Figure (5).
In order to track the reference trajectory of h_1 and h_2 so the variation v_1 and v_2 are calculated as follows:

$$v_1 = \ddot{h}_{1ref} - k_{d1}(\dot{h}_1 - \dot{h}_{1ref}) - k_{p1}(h_1 - h_{1ref}) \quad (41)$$

$$v_2 = \dot{h}_{2ref} - k_{p2}(h_2 - h_{2ref})$$

where by an appropriate choice of the positive constants k_{p1} and k_{p2} ensures the exponential convergence of the tracking errors .

5. SIMULATIONS AND RESULTS

We have performed simulations using Matlab-Simulink,the doubly fed induction motor parameters are given in Table A.1, and the benchmark of Figure (6) and

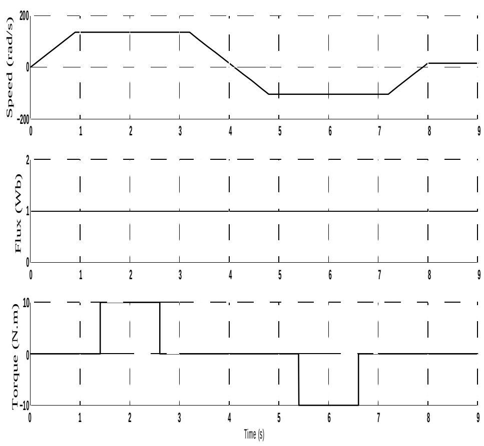


Fig. 6. Reference trajectories

5.1 Performance of Linearizing Control

Speed error tracking: The speed error tracking is cancelled.The peaks appear at the time of the abrupt variations in the load torque and the reference speed as shown in Figure (7) for both controllers with a small errors in the nonlinear controllers rather than FOC

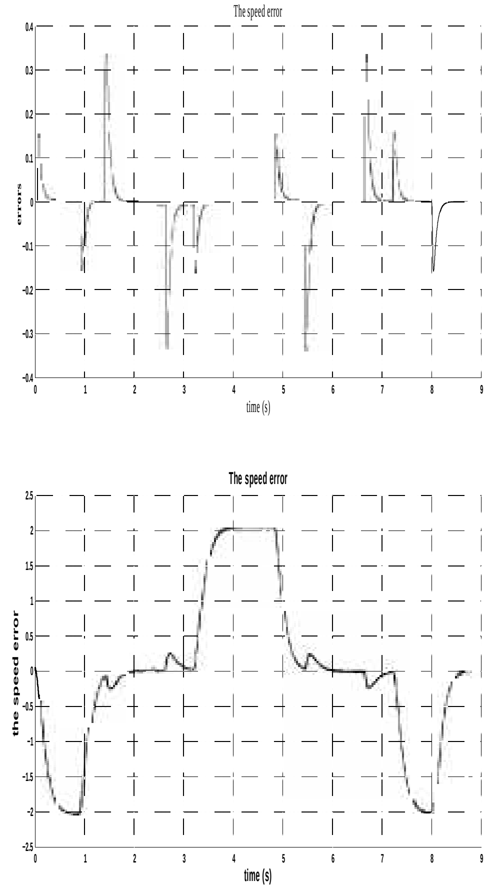
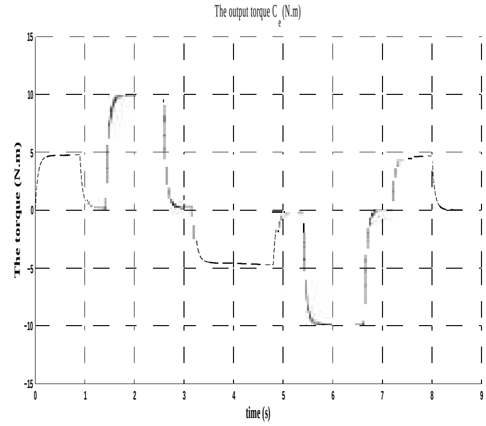


Fig. 7. Simulation results of the error of both NLC and FOC respectively with the application of a load torque

Torque : We note from Figure (8) that the drive torque follows the load torque when the speed is constant. During an increase or decrease in the speed, a difference of almost ± 5 N.m appears between the two torques, for both controllers. Rotor Flux: Figure (9) shows the rotor flux



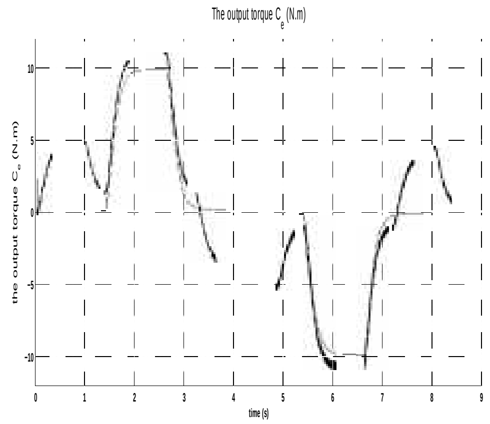


Fig. 8. Simulation results of the torque of both NLC and FOC respectively with the application of a load torque

with a ripple around the reference for the FOC and a very good flux tracking for the NLC

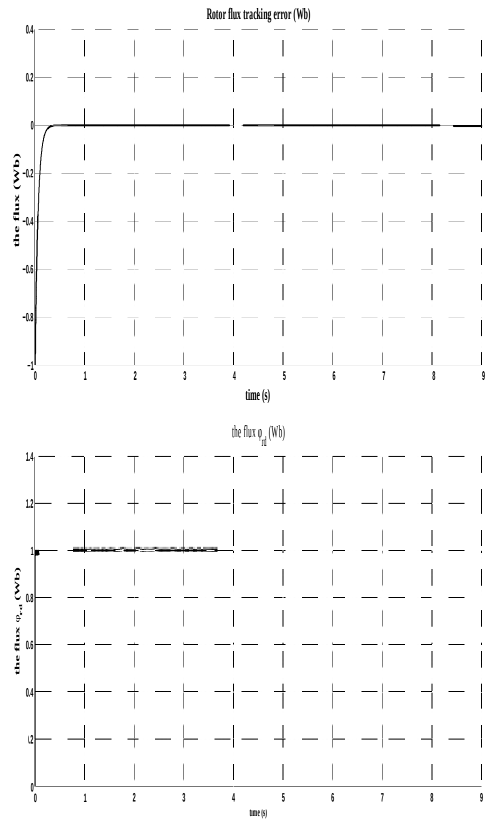


Fig. 9. Simulation results of the flux of both the NLC and FOC respectively with the application of a load torque

6. CONCLUSION

in this paper ,two control techniques have been compared for the doubly fed induction machine classical Field Oriented control, and input-output feedback linearizing control. From the comparative study, one can conclude that the two methods demonstrate nearly the same dynamic behaviour. However, the input-output feedback linearizing controller shows better performance than the Field Oriented controller in speed tracking at high speed ranges. The numerical simulations validate the performances of the proposed method and even in the unknown parameter case and achieve better speed and rotor flux tracking.

Perspectives: This paper is a continuation of the studies on the DFIM which needs a continuation in another directions so after all the obtained results we should look ahead to the following perspectives :

- We wish to validate these results in real time.
- The use of other control strategy like sliding mode and beckstepping controllers with comparison to FOC.
- The use of a nonlinear observer in order to improve the performance of such controller

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Appendix A. PARAMETERS OF THE DFIM

Table A.1. Parameters of the DFIM

Designation	Parameter	Value
Rotor resistance	R_r	3.805 Ω
Stator resistance	R_s	4.85 Ω
Mutual inductance	M	0.258 H
Stator cyclic inductance	L_s	0.247 H
Rotor cyclic inductance	L_r	0.247 H
Rotor inertia	J_m	0.031 Kg/m^3
Pole pair	p	2
Viscous friction coefficient	f_m	0.008 N.m.s/rd
Mechanical power	P_m	15 KW
Nominal Stator Voltage	V_s	220 V
Nominal Rotor Voltage	V_r	12 V
Nominal Stator Current	I_s	3.46 A
Nominal Rotor Current	I_r	6.31 A
Nominal speed	Ω_n	1500 rev/min