Highly Efficient Control of the Doubly Fed Induction Motor

Saïd Drid†, Abdesslam Makouf*, Mohamed-Saïd Naït-Saïd* and Mohamed Tadjine**

Abstract – This paper deals with the high efficient vector control for the reduction of copper losses of the doubly fed motor. Firstly, the feedback linearization control based on Lyapunov approach is employed to design the underlying controller achieving the double fluxes orientation. The fluxes' controllers are designed independently of the speed. The speed controller is designed using the Lyapunov method especially employed to the unknown load torques. The global asymptotic stability of the overall system is theoretically proven. Secondly, a new Torque Copper Losses Factor is proposed to deal with the problem of the machine copper losses. Its main function is to optimize the torque in keeping the machine saturation at an acceptable level. This leads to a reduction in machine currents and therefore their accompanied copper losses guaranteeing improved machine efficiency. The simulation and experimental results in comparative presentation confirm largely the effectiveness of the proposed DFIM control with a very interesting energy saving contribution.

Keywords : Copper Losses, Doubly Fed Induction Machine, Flux Orientation, Lyapunov Function, Nonlinear Feedback Control, Optimization, Torque Optimization, Vector Control.

1. Introduction

Known since 1899 [1], the doubly fed induction motor (DFIM) is a wound rotor asynchronous machine supplied by the stator and the rotor from two external source voltages. This machine is very attractive for variable speed applications such as the electric vehicle and the production of electrical energy [1-5]. Consequently, it covers all power ranges. Obviously, the requested variable speed domain and the desired performances depend on the application types [1-7]. The use of DFIM offers the opportunity to modulate power flow into and out of 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. Two modes can be associated to slip power recovery: sub–synchronous motoring and super–synchronous generating operations. In general, while the rotor is fed through a cycloconverter, the power range can attain the MW order which presents the size of power often reserved to the synchronous machine [1-10].

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. The disadvantage of two used converters for stator and rotor supplying can be compensated by the best control performances of the powered systems [3]. Indeed, the input commands are performed by means of four precise degrees of control freedom relative to the squirrel cage induction machine where its control appears quite simple. The flux orientation strategy can transform the non-linear and coupled DFIM-mathematical model into a linear model leading to one attractive solution for generating or motoring operations [1-14].

It is known that the motor driven systems account for approximately 65% of the electricity consumed in the world. Implementing high efficiency motor driven systems, or improving existing ones, could save over 200 billion kWh of electricity per year. This issue has become very important, especially following the economic crisis due to the increase in oil prices. As such, innovative energy saving technologies are appearing and developing rapidly in this century. [4, 12, 15-18]. In this framework, the DFIM continues to be of great interest owing to the birth of the idea of double flux orientation [19-20]. The philosophy of this idea is to achieve a simpler machine model expression (ideal machine) [19]. Consequently, at the same time, we can solve a non-linear problem presented by the DFIM control and advance from many digital simulations toward the experimental test by the use of the dSPACE-1103 system. This method gives entire satisfaction and consolidates our theory, especially using the Torque Optimization Factor TOF strategy [20]. The search for a solution always has more optimal, us nap leans towards the minimization of the copper losses in the DFIM. In this paper we developed a new optimization factor known as Torque Copper Losses Optimization (TCLO). The article will be organized as follows. The DFIM mathematical

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model is presented in Section III. In Section IV, the feedback linearization is exposed. Section V concerns the energy optimization strategies of TCLO. In Section VI, simulation results are exposed showing the performances in energy saving of the TCLO.

2. The DFIM Model

The state-all-flux model of DFIM in the synchronous reference frame is written as:

$$\begin{cases} \bar{u}_s = \dfrac{1}{\sigma T_s}\bar{\phi}_s - \dfrac{M}{\sigma T_s L_r}\bar{\phi}_r + \dfrac{d\bar{\phi}_s}{dt} + j\omega_s\bar{\phi}_s \\ \bar{u}_r = -\dfrac{M}{\sigma T_r L_s}\bar{\phi}_s + \dfrac{1}{\sigma T_r}\bar{\phi}_r + \dfrac{d\bar{\phi}_r}{dt} + j\omega_r\bar{\phi}_r \end{cases} \quad (3)$$

Flux equations:

$$\begin{cases} \bar{\phi}_s = L_s\,\bar{i}_s + M\,\bar{i}_r \\ \bar{\phi}_r = L_r\,\bar{i}_r + M\,\bar{i}_s \end{cases} \quad (2)$$

The electromagnetic torque is:

$$C_e = \frac{PM}{\sigma L_s L_r}\Im m\left[\bar{\phi}_s\bar{\phi}_r^*\right] \quad (4)$$

The copper losses are given as:

$$P_{cl} = R_s.i_s^2 + R_r.i_r^2 \quad (5)$$

The motion equation is:

$$C_e - d = J\frac{d\omega}{dt} \quad (6)$$

In DFIM operations, the stator and rotor mmf's (magneto motive forces) rotations are directly imposed by the two external voltage source frequencies. Hence, the rotor speed becomes dependant toward the linear combination of these frequencies, and it will be constant if they too are constant for any load torque, given of course in the machine stability domain. In DFIM modes, the synchronization between both mmf's is mainly required in order to guarantee machine stability [7]. This is a similar situation to the synchronous machine stability problem where without the recourse to the strict control of the DFIM mmf's relative position, the machine instability risk or brakedown mode become imminent.

3. Nonlinear Vector Control Strategy

3.1 Double flux orientation

It consists in simultaneously orienting stator flux and rotor flux. Thus, it results in the constraints given below by (7). Rotor flux is oriented on the d-axis, and the stator flux is oriented on the q-axis. Conventionally, the d-axis remains reserved to the magnetizing axis and q-axis to torque axis, so we can write [19-20]

$$\begin{cases} \phi_{sq} = \phi_s \\ \phi_{rd} = \phi_r \\ \phi_{sd} = \phi_{rq} = 0 \end{cases} \quad (7)$$

Using (7), the developed torque given by (4) can be rewritten as follows:

$$C_e = k_c\phi_s\phi_r. \quad (8)$$

where, $k_c = \dfrac{PM}{\sigma L_s L_r}$

ϕ_s appears as the input command of the active power or simply of the developed torque, while ϕ_r appears as the input command of the reactive power or simply the main magnetizing machine system acting.

3.2 Vector control by Lyapunov feedback linearization

Separating the real and the imaginary part of (3), we can write:

$$\begin{cases} \dfrac{d\phi_{sd}}{dt} = f_1 + u_{sd} \\ \dfrac{d\phi_{sq}}{dt} = f_2 + u_{sq} \\ \dfrac{d\phi_{rd}}{dt} = f_3 + u_{rd} \\ \dfrac{d\phi_{rq}}{dt} = f_4 + u_{rq} \end{cases} \quad (9)$$

Where f_1, f_2, f_3 and f4 are done as follows:

$$\begin{cases} -f_1 = \gamma_1\,\phi_{sd} - \gamma_2\,\phi_{rd} - \omega_s\phi_{sq} \\ -f_2 = \gamma_1\,\phi_{sq} - \gamma_2\,\phi_{rq} + \omega_s\phi_{sd} \\ -f_3 = -\gamma_3\,\phi_{sd} + \gamma_4\,\phi_{rd} - \omega_r\phi_{rq} \\ -f_4 = -\gamma_3\,\phi_{sq} + \gamma_4\,\phi_{rq} + \omega_r\phi_{rd} \end{cases} \quad (10)$$

With: $\gamma_1 = \frac{1}{\sigma T_s}$; $\gamma_2 = \frac{M}{\sigma T_s L_r}$; $\gamma_3 = \frac{M}{\sigma T_r L_s}$; $\gamma_4 = \frac{1}{\sigma T_r}$

Taking into account the constraints given by (7), one can formulate the Lyapunov function as follows:

$$V = \frac{1}{2}\phi_{sd}^2 + \frac{1}{2}\phi_{rq}^2 + \frac{1}{2}(\phi_{sq} - \phi_s)^2 + \frac{1}{2}(\phi_{rd} - \phi_r)^2 > 0 \quad (11)$$

From (11), the first and second quadrate terms concern the fluxes' orientation process defined in (7) with the third and fourth terms characterizing the fluxes' feedback control. Where its derivative function becomes

$$\begin{aligned}\dot{V} = \phi_{sd}\dot{\phi}_{sd} + \phi_{rq}\dot{\phi}_{rq} + (\phi_{sq} - \phi_s)(\dot{\phi}_{sq} - \dot{\phi}_s) + \\ + (\phi_{rd} - \phi_r)(\dot{\phi}_{rd} - \dot{\phi}_r)\end{aligned} \quad (12)$$

Substituting (9) in (12), it results

$$\begin{aligned}\dot{V} = \phi_{sd}\ (f_1 + u_{sd}) + \phi_{rq}\ (f_4 + u_{rq}) + \\ + (\phi_{sq} - \phi_s)\ (f_2 + u_{sq} - \dot{\phi}_s) + \\ + (\phi_{rd} - \phi_r)\ (f_3 + u_{rd} - \dot{\phi}_r)\end{aligned} \quad (13)$$

Let us define the following law control as [21]:

$$\begin{cases} u_{sd} = -f_1 - K_1\ \phi_{sd} \\ u_{rq} = -f_4 - K_2\ \phi_{rq} \\ u_{sq} = -f_2 + \dot{\phi}_s - K_3\ (\phi_{sq} - \phi_s) \\ u_{rd} = -f_3 + \dot{\phi}_r - K_4\ (\phi_{rd} - \phi_r) \end{cases} \quad (14)$$

Hence (14) replaced in (13) gives:

$$\begin{aligned}\dot{V} = -K_1\ \phi_{sd}^2 - K_2\ \phi_{rq}^2 - K_3\ (\phi_{sq} - \phi_s)^2 - \\ - K_4\ (\phi_{rd} - \phi_r)^2 < 0\end{aligned} \quad (15)$$

Function (15) is a negative one. Furthermore, (14) introduced into (9) leads to a stable convergence process if the gains K_i (i=1, 2,3, 4) are evidently all positive, otherwise:

$$\begin{cases} \lim\limits_{t\to+\infty} \phi_{sd} = 0 \\ \lim\limits_{t\to+\infty} \phi_{rq} = 0 \\ \lim\limits_{t\to+\infty}(\phi_{rd} - \phi_r^*) = 0 \\ \lim\limits_{t\to+\infty}(\phi_{sq} - \phi_s^*) = 0 \end{cases} \quad (16)$$

In (16), the first and second equations concern the double flux orientation constraints applied for DFIM-model which are defined above by (7), while the third and fourth equations define the errors after the feedback fluxes' control. This latter offers the possibility of controlling the main machine magnetizing on the d-axis by ϕ_{rd} and the developed torque on the q-axis by ϕ_{sq}.

3.3 Speed control design

The speed control is built from Lyapunov method and is exposed as follows [21]. The control law is designed using this approach which guarantees a torque convergence.

$$\lim_{t\to\infty}(C_e - C_{ref}) = 0 \quad (17)$$

Let us define the Lyapunov function:

$$V_2 = \frac{1}{2}J.e^2 > 0 \quad (18)$$

Where: $e = (\omega - \omega_{ref})$

Taking into account (6), we can write

$$\dot{V}_2 = J.e.\dot{e} = e(C_e - d - J\dot{\omega}_{ref}) \quad (19)$$

If it is supposed that $C_e \to C_{ref}$, the control law is given as follows:

$$C_e = J\dot{\omega}_{ref} - k_5.e - k_6.sign(e) \quad (20)$$

Let us take:

$$k_6 > \max(d) \quad (21)$$

Replace (20) in (19):

$$\dot{V}_2 = -k_5.e^2 + e.[-d - k_6.sign(e)] \quad (22)$$

The term $e[-d - k_6.sign(e)] < 0$ ∀e, ∀d and (21) while will be verified, we can write.

$$\dot{V}_2 < -k_5.e^2 < 0 \quad (23)$$

Thus if (17) is checked then

$$\lim_{t\to\infty}(\omega - \omega_{ref}) = 0 \quad (24)$$

4. Energy Optimization Strategy

4.1 Torque–Copper Losses Optimization (TCLO) design

In many applications, it is required to optimize a given parameter and the derivative plays a key role in the solution of such problems. Suppose the quantity to be minimized is given by the function $f(x)$, and x is our control parameter. We want to know how to choose x to make $f(x)$ as small as possible. Let's pick some x_0 as the starting point in our search for the best x. The goal is to find the relation between fluxes which can optimize the compromise between torque and copper losses in steady state as well as in transient state, (i.e. for all $\{C_e\}$ find (ϕ_s,ϕ_r) let $\min\{P_{cl}\}$). From (2) (5), (7) and (8), the torque and copper losses can be written as:

$$\begin{cases} C_e = k_c.\phi_r.\phi_s \\ P_{cl} = a_1\phi_r^2 + a_2\phi_s^2 \end{cases} \qquad (25)$$

with :

$$a_1 = \left(\frac{R_r}{(\sigma.L_r)^2} + \frac{R_s M^2}{(\sigma.L_r.L_s)^2}\right)$$
$$a_2 = \left(\frac{R_r M^2}{(\sigma.L_r.L_s)^2} + \frac{R_s}{(\sigma.L_s)^2}\right)$$

Fig. 1 represents the layout of (25) for a constant level of torque and copper loss in the (ϕ_s, ϕ_r) plan. These curves present respectively a hyperbole for the iso-torque and ellipse for iso-copper-losses. From (25) we can write:

$$a_1k_c^2\phi_r^4 - k_c^2\phi_r^2\Delta P_{cl} + a_2C_{el}^2 = 0 \qquad (26)$$

To obtain a real and thus optimal solution, we must have:

$$\Delta = k_c^4\Delta P_{cl}^4 - 4a_1k_c^2a_2C_{el}^2 = 0 \qquad (27)$$

Equation (27) represents the energy balance in the DFIM for one working DFIM point as shown in Fig. 1. Then, one can write:

$$\Delta P_{cl} = \sqrt{\frac{4a_1a_2C_{el}^2}{k_c^2}} \qquad (28)$$

This equation shows the optimal relation between the torque and the copper losses.

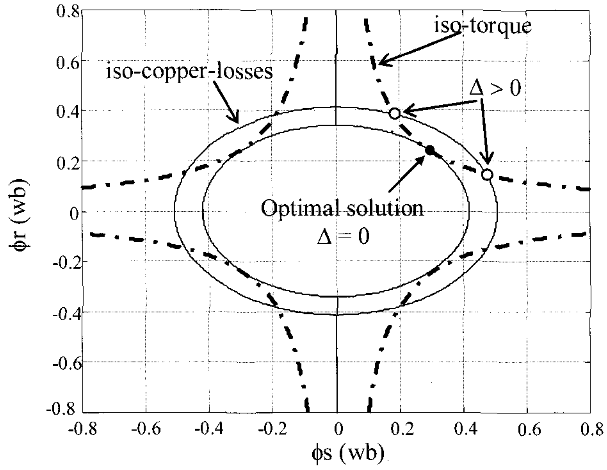

Fig. 1. The iso–torque curves and the iso–losses curves in the plan (ϕ_s, ϕ_r)

4.2 Finding Minimum copper–losses Values

The Rolle's Theorem is the key result behind applications of the derivative to optimization problems. The second derivative test is used to finding minimum point.

We can rewrite (25) as:

$$\begin{cases} \phi_s = \dfrac{C_e}{k_c.\phi_r} \\ P_{cl} = a_1\phi_r^2 + a_2\dfrac{C_e^2}{k_c^2.\phi_r^2} = \dfrac{a_1k_c^2\phi_r^4 + a_2C_e^2}{k_c^2.\phi_r^2} \end{cases} \qquad (29)$$

The computations of the first and second derivatives show that the critical point is given by:

$$\phi_{rc} = \pm\left(\frac{C_e^2a_2}{a_1k_c^2}\right)^{\frac{1}{4}} \qquad (30)$$

For which:

$$\frac{d^2P_{cl}(\phi_{rc})}{d\phi_r^2} = \frac{2a_1k_c^2\phi_{rc}^4 + 6a_2C_e^2}{k_c^2.\phi_{rc}^4} = 8a_1 > 0 \qquad (31)$$

We can see that the second derivative is positive and conclude that the critical point is a relative minimum.

Fig. 2 illustrates a general block diagram of the suggested DFIM control scheme. Here, we can note the placement of optimization block, the first estimator-block which evaluates torque and the second estimator-block which evaluates firstly the modulus and position fluxes, respectively ϕ_s, ϕ_r, ρ_s

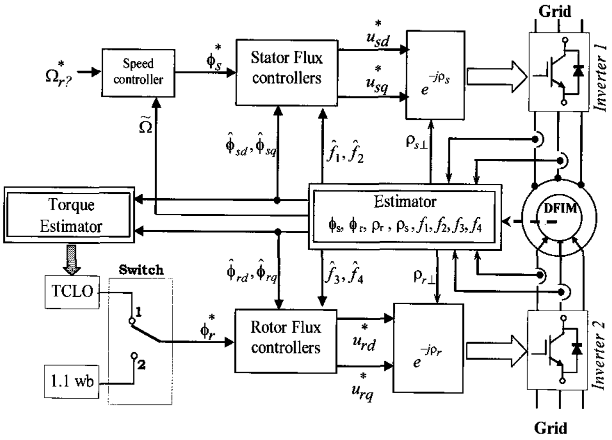

Fig. 2. General block diagram of control scheme

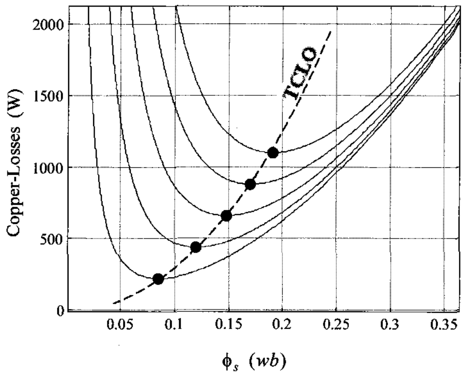

Fig. 4. Minimized copper losses in steady state operation with TCLO

and ρ_r, from the measured currents using (2) and secondly the feedback functions f_1, f_2, f_3, f_4 given by (10). The optimization process allows adapting the main flux magnetizing defined by rotor flux to the applied load torque characterized by the stator flux. With the analogical switch we can select the type of the reference rotor flux. Switch position 1 for the TCLO optimized operation and switch position 2 for a magnetizing constant level.

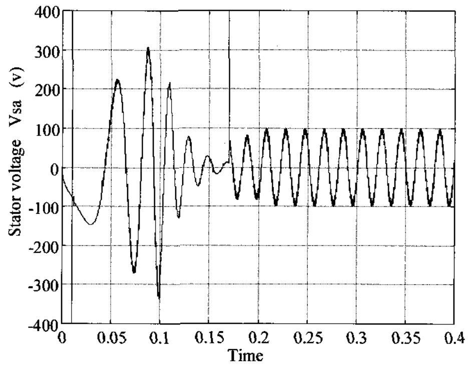

Fig. 5. The input control stator voltage response with TCLO

5. Simulation results

Fig. 3 shows the speed response versus time according to its desired profile drawn on the same figures. Figure 4 presents the copper losses according to the stator flux variations in steady state operation and we can see the contribution of the TCLO. Figures 5 and 6 indicate respectively the stator and the rotor input control voltages versus time during the test. Finally Figures 7 and 8 present respectively the copper losses and the dissipated energy versus time from which we can observe clearly the influence of the three switch positions on the copper losses in transient state. We can conclude that the TCLO is the best optimization.

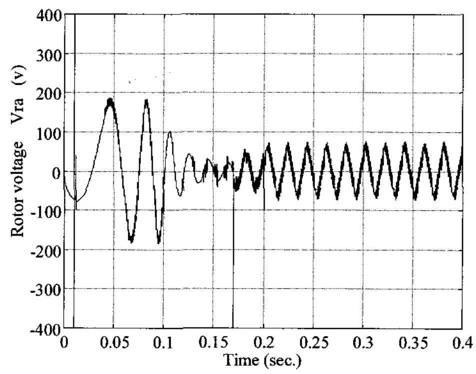

Fig. 6. The input control rotor voltage response with TCLO

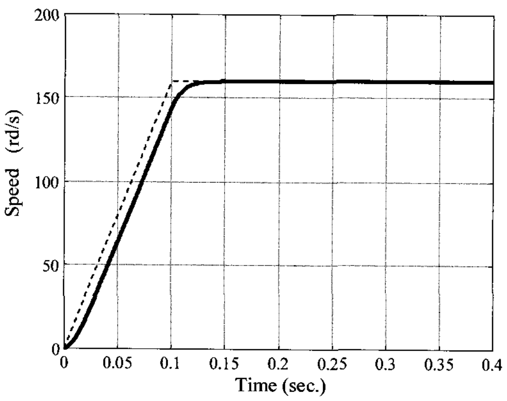

Fig. 3. Speed response for a ramp reference speed

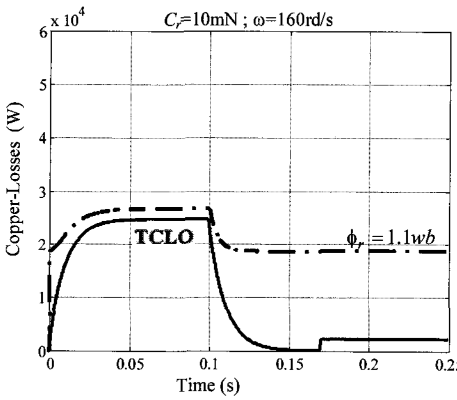

Fig. 7. Optimization of the copper losses in transient state operation

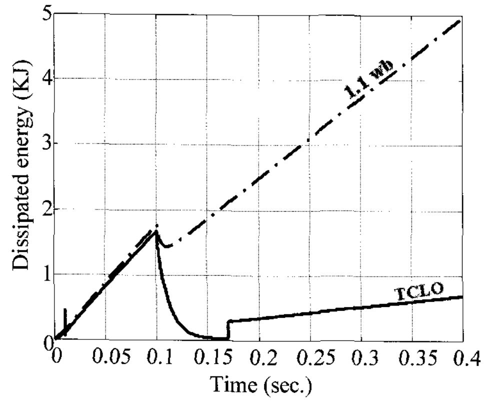

Fig. 8. Total dissipated energy during test for the two switch positions (Energy saving illustration)

6. Conclusion

This paper presented a vector control intended for doubly fed induction motor (DFIM) mode. The use of the state-all-flux induction machine model with a flux orientation constraint gives place to a simpler control model. The stability of the nonlinear feedback control is proven using the Lyapunov function and the control robustness is achieved by sliding mode speed controller. The simulation results of the suggested DFIM system control based on double flux orientation which is achieved by the proposed DFIM control demonstrates clearly the suitable obtained performances required by the references profiles defined above. The speed tracks its desired reference without any effect of the load torque. Therefore, the high control performances can be well affirmed. To optimize the machine operation we chose to minimize the copper losses. Indeed, the energy saving process can be well achieved if the magnetizing flux decreases in the same way as the load torque. It results in an interesting balance between the core losses and the copper losses into the machine, so the machine efficiency may be largely improved. The simulation results confirm largely the effectiveness of the proposed DFIM control system.

Appendix

The machine parameters are:

Rs =1.2 Ω; Ls =0.158 H; Lr =0.156 H; Rr =1.8 Ω; M =0.15 H; P =2 ;J = 0.07 Kg.m^2 ; Pn = 4 Kw ; 220/380V ; 50Hz ; 1440tr/min ; 15/8.6 A ; cosφ = 0.85.

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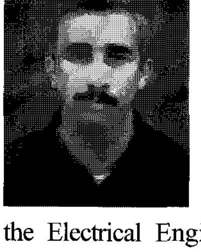

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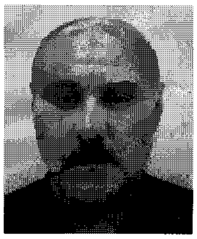

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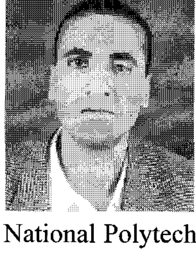

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