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Loss-Minimizing with Backstepping Technique Control for Induction Motors and on Line Adaptation of the Stator and Rotor Resistance

Chiheb Ben Regaya, Abderrahmen Zaafouri and Abdelkader Chaari

University of Tunis, Unit C3S, Higher School of Sciences
and Techniques of Tunis (ESSTT), 5 Av. Taha Hussein, BP 56, 1008 Tunis, Tunisia

Abstract: The efficiency of induction motor drives under partial load can be improved by the minimization of the electrical energy consumption. This method has become an objective in the design of control systems while maintaining the performance and features required by these systems. Among groups of optimization to minimize losses electromagnetic proposed in the literature, the family which includes flux optimization methods based on electromagnetic torque. In this paper, a scheme for minimizing losses using the method below has been developed, we present a solution for minimizing energy losses in the induction motor trained, taking into account the simplicity of the algorithm to control the system. This method is based on finding optimal magnetic flux in an operating point defined by the electromagnetic torque. The control algorithm is proved by the simulation tests. Analysis of the results shows the characteristic robustness and efficiency of the proposed method.

Key words: Energy saving · Backstepping control · Induction motor · Vector control · Loss-minimizing

INTRODUCTION

About half of the power in the world today is consumed by the electric motors and the majority of them are induction motors. The latter are broadly used in industrial applications because of their benefits over other types of rotating electrical machines, such as robustness, reliability, reduced maintenance... [1, 2] and their efficiency varies significantly with their operating condition. Energy savings by reducing operating loss can be obtained with robust control strategies.

Induction motors constitute a classical test bench in the control theory field due to the fact that represents a coupled Multiple-Input Multiple-Output nonlinear system, resulting in a challenging control problem. The first field oriented control technique for induction motors was developed by Blaschke [3].

Recently, various control approaches have been studied for performance improvement. The researches include many types of control like sliding mode [4], backstepping control [5, 6]... Among others, it was noted that these methods were based on a mathematical induction motor model that doesn't consider power core losses and degrades the efficiency of the motor in operation at under-load.

That's why standardization and maintenance costs, industries recommend using the same engines for a variety of applications, which reduce the overall efficiency of the drive system due to under-loaded motors. In [7] it was noted that about 45% of training loads engines below 40% of their rated load (Table 1).

The power losses in an induction motor includes stator, rotor copper and iron losses. In order to achieve a high efficiency in power consumption one must have into consideration the power of these losses.

There are two main groups of optimization to minimize losses. The first group includes flux optimization methods based on electromagnetic torque, $\square_r=f(C_{em})$. The second group synthesizes optimization methods as an expression connecting the two components of the stator current $i_{ds}=f(i_{qs})$. Several models have been proposed and losses used in the literature, including the work of these researchers [8-10] taking into account the joule losses of the stator, rotor windings and iron losses, modeled from the classic pattern of the equivalent machine.

Corresponding Author: Chiheb Ben Regaya, University of Tunis, Unit C3S, Higher School of Sciences and Techniques of Tunis (ESSTT), 5 Av. Taha Hussein, BP 56, 1008 Tunis, Tunisia.

Table I: Loading by horsepower. [5]

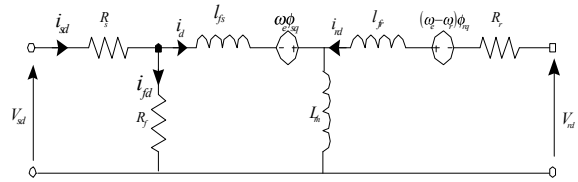
	Horsepower				
Partial load	1-5	6-20	21-50	51-100	101-200
<40%	42%	48%	39%	45%	24%
40 to 120%	54%	51%	60%	54%	75%
>120%	4%	1%	1%	1%	1%

The proposed method for electric energy saving is already developed in [11]. As a result, power and energy losses are reduced. We have also noted its high sensitivity to motor parametric variations. To improve the robustness of the optimization algorithm, in [7] the author integrate an online adaptive mechanism of rotor and stator resistances. The used adaptation approach is based on the comparison of two expressions of the reactive power of the induction motor introduced in [12]. This method gives good estimation results around the nominal operation point of the induction machine. To overcome this drawbacks, we propose in this paper a robust solution to estimate the motors resistances based on the backstepping theory. By the other in [7] the expression of optimal flux depends on two variables ω_s and T_{em}, so we need two estimator. For this we develop another expression that requires one estimator of the electromagnetic torque.

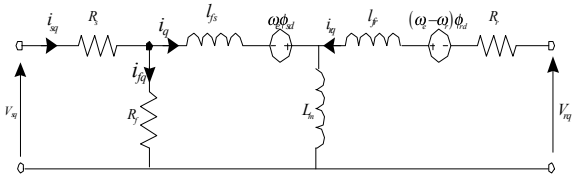
Our work aims is not only to keeping better dynamic performance of the asynchronous machine by using backstepping control, but also to minimize its electric power losses. To address this optimization problem, we need to define the magnitude of the rotor flux according the load torque, taking into account the algorithm simplicity of our solution.

First we are going to present the mathematical model of the induction motor taking into account the core loss. Then we are going to describe the stages of designing the control law using backstepping method. The adaptive backstepping design is established in Section 4. In section 5 the rotor flux modulus optimization for reducing the core and copper losses is calculated. Finally, simulations are presented in the last section using Matlab environment and some comments conclude this work.

Induction Motor Modeling with Core Loss and Backstepping Control: The induction motor model with the core loss is considered as a nonlinear system. In [8] the author gives the per-phase equivalent circuit of the induction motor in d-q frame (Figure 1). The dynamic equation of the induction motor can be described in a reference connected to the rotating field as follows [9, 13].



(a) Equivalent circuit of the d-axis.



(b) Equivalent circuit of the q-axis.

Fig. 1: Equivalent circuit of the induction machine by taking into account core loss in the arbitrary frame ω_e.

$$\frac{d}{dt}i_d = -\eta_0 i_d + \omega_s i_q + k\beta_r\phi_{rd} + k\omega_r\phi_{rq} + \mu V_{sd}$$
$$\frac{d}{dt}i_q = -\omega_s i_d - \eta_0 i_q - k\omega_r\phi_{rd} + k\beta_r\phi_{rq} + \mu V_{sq}$$
$$\frac{d}{dt}\phi_{rd} = L_m\beta_r i_d - \beta_r\phi_{rd} + \omega_{sl}\phi_{rq}$$
$$\frac{d}{dt}\phi_{rq} = L_m\beta_r i_q - \omega_{sl}\phi_{rd} - \beta_r\phi_{rq}$$
$$\frac{d}{dt}\omega_r = \frac{n_p}{JL_r}i_q\phi_{rd} - \frac{T_l}{J} - \frac{f}{J}\omega_r \quad (1)$$

where ω_r is the rotor velocity, V_{sd},, V_{sq} are the stator voltages, i_d, i_q are the stator currents, are the rotor currents and □$_{rd}$, □$_{rq}$ are the rotor fluxes.

The constant parameters are defined as follows:

$$\eta_0 = \frac{b}{\sigma L_s}, \mu = \frac{a}{\sigma L_s}, a = \frac{R_f}{R_f + R_s}, b = \frac{R_f R_s}{R_f + R_s} + \frac{\beta_r L_m^2}{L_r}$$
$$\beta_r = \frac{R_r}{L_r}, k = \frac{M}{\sigma L_s L_r}, \sigma = 1 - \frac{L_m^2}{L_r L_s}$$

where σ is the mutual and leakage inductance.

To design the complete model we must necessarily add the mechanical equation. The electromagnetic torque developed by the machine is expressed by:

$$T_{em} = \frac{3}{2}\frac{L_m n_p}{L_r}\left(\phi_{rd} i_q - \phi_{rq} i_d\right) \quad (2)$$

To consider the iron losses, the equivalent circuit of the machine can be modified by adding a resistor in parallel to the magnetizing branch [5, 9, 10].

By aligning the d-axis of the synchronous reference frame with the rotor flux vector, the system of equations of the induction motor can be put in the following form:

$$\begin{aligned}
&\frac{d}{dt}i_d = \Gamma_1 + \mu v_{sd} \\
&\frac{d}{dt}i_q = \Gamma_2 + \mu v_{sq} \\
&\frac{d}{dt}\phi_{rd} = L_m\beta_r i_d - \beta_r\phi_{rd} \\
&\frac{d}{dt}\omega_r = \frac{n_p}{JL_r}\phi_{rd}i_q - \frac{T_l}{J} - \frac{f}{J}\omega_r
\end{aligned} \tag{3}$$

where:

$$\Gamma_1 = -\eta_0 i_d + \omega_r i_q + k\beta_r\phi_{rd} + L_m\beta_r\frac{i_q^2}{\phi_{rd}}$$

$$\Gamma_2 = -\omega_r i_d - L_m\beta_r\frac{i_d i_q}{\phi_{rd}} - \eta_0 i_q - k\omega_r\phi_{rd}$$

The synthesis of the control law using backstepping technique with taking into account core loss can be obtained by several steps. Each step will be a reference for the next step. Stability and performance of our system will be studied using Lyapunov theory [4, 14, 17].

In the first step, we consider the trajectories of speed and flux as a reference and this amount defines the tracking errors as follows:

$$\begin{aligned}
&e_\omega = \omega_{ref} - \omega_r \\
&e_\phi = \phi_{ref} - \phi_{rd}
\end{aligned} \tag{4}$$

The derived equations (4) give us:

$$\begin{aligned}
&\dot{e}_\omega = \dot{\omega}_{ref} - \dot{\omega}_r \\
&\dot{e}_\phi = \dot{\phi}_{ref} - \dot{\phi}_{rd}
\end{aligned} \tag{5}$$

By replacing $\dot{\omega}, \dot{\phi}_{rd}$ with these expressions from the system of equations (3), the system of equations (5) becomes:

$$\begin{aligned}
&\dot{e}_\omega = \dot{\omega}_{ref} - \frac{n_p^2 L_m}{JL_r}\phi_{rd}i_q + \frac{f}{J}\omega_r + \frac{n_p}{J}T_l \\
&\dot{e}_\phi = \dot{\phi}_{ref} - L_m\beta_r i_d + \beta_r\phi_{rd}
\end{aligned} \tag{6}$$

To achieve the objective of pursuit, the Lyapunov function associated with the error and flux velocity is chosen as follows:

$$L_1 = \frac{1}{2}\left(e_\omega^2 + e_\phi^2\right) \tag{7}$$

The derivate of equations (7) is written as follows:

$$\dot{L}_1 = -k_\omega e_\omega^2 - k_\phi e_\phi^2 \tag{8}$$

With k_ω and k_ϕ are positive constant, chosen so as to guarantee the exponential convergence errors of flux and speed. To satisfy equation (8), it is necessary to choose the dynamic errors of the following form:

$$\begin{aligned}
&\dot{e}_\omega = -k_\omega e_\omega \\
&\dot{e}_\phi = -k_\phi e_\phi
\end{aligned} \tag{9}$$

Considering that $\phi_{rd}i_q$ and i_d as virtual control inputs. Then equations (6) and (9) can generate the stabilizing functions which are based on the stability condition of Lyapunov theory to achieve the objective of pursuit, which can be written as follows:

$$\begin{aligned}
&\left(i_d\right)_{st} = \frac{1}{L_m\beta_r}\left(\dot{\phi}_{ref} + \beta_r\phi_{rd} + k_\phi e_\phi\right) \\
&\left(\phi_{rd}i_q\right)_{st} = \frac{JL_r}{n_p^2 L_m}\left(\dot{\omega}_{ref} + \frac{f}{J}\omega_r + \frac{n_p}{J}T_l + k_\omega e_\omega\right)
\end{aligned} \tag{10}$$

The system of equations (10) highlights the desired behavior of flux and the stator currents to ensure the pursuit of speed and rotor flux.

To achieve these desired behaviors, we will define in the second step the error between stator currents, direct flux and their references as follows:

$$\begin{aligned}
&e_{i_{q\phi}} = \left(\phi_{rd}i_q\right)_{st} - \phi_{rd}i_q \\
&e_{i_d} = \left(i_d\right)_{st} - i_d
\end{aligned} \tag{11}$$

By combining equation (10) into equation (11) we obtain:

$$\begin{aligned}
&e_{i_{q\phi}} = \frac{JL_r}{n_p^2 L_m}\left(\dot{\omega}_{ref} + \frac{f}{J}\omega_r + \frac{n_p}{J}T_l + k_\omega e_\omega\right) - \phi_{rd}i_q \\
&e_{i_d} = \frac{1}{L_m\beta_r}\left(\dot{\phi}_{ref} + \beta_r\phi_{rd} + k_\phi e_\phi\right) - i_d
\end{aligned} \tag{12}$$

Then equation (9) can be written as follows:

$$\begin{aligned}
&\dot{e}_\omega = -k_\omega e_\omega + \frac{n_p^2 L_m}{JL_r}e_{i_{q\phi}} \\
&\dot{e}_\phi = -k_\phi e_\phi + L_m\beta_r e_{i_d}
\end{aligned} \tag{13}$$

The dynamics errors of $e_{i_{q\phi}}$ and e_{i_d} are respectively given by:

$$\dot{e}_{i_{q\phi}} = \frac{JL_r}{n_p^2 L_m}\left(\ddot{\omega}_{ref} + \frac{f}{J}\dot{\omega}_r - k_\omega^2 e_\omega\right) + k_\omega e_{i_{q\phi}} - \phi_{rd}\left(\Gamma_1 + \mu v_{sq}\right)$$
$$\dot{e}_{i_d} = \frac{1}{L_m \beta_r}\left(\ddot{\phi}_{ref} + L_m \beta_r^2 i_d - \beta_r^2 \phi_{rd} - k_\phi^2 e_\phi\right) + k_\phi e_{id} - \left(\Gamma_2 + \mu v_{sd}\right) \quad (14)$$

In order to have an exponential decrease error of $e_{i_{q\phi}}$ and e_{i_d} we must impose that:

$$\dot{e}_{i_{q\phi}} = -k_{i_{q\phi}} e_{i_{q\phi}}$$
$$\dot{e}_{i_d} = -k_{i_d} e_{i_d} \quad (15)$$

Where $k_{i_{q\phi}}$ and k_{i_d} are positive parameters.

The final step in the design of the control law using backstepping technique is to determine the expressions of the stator voltages v_{ds} and v_{qs} from a suitable choice of the new Lyapunov function associated with flux errors, speed and errors of currents which is given by the following expression:

$$L_2 = \frac{1}{2}\left(e_\omega^2 + e_\phi^2 + e_{iq\phi}^2 + e_{id}^2\right) \quad (16)$$

Substituting equations (9) and (15) in the derivative of the Lyapunov function L_2 we have:

$$\dot{L}_2 = -k_\omega e_\omega^2 - k_\phi e_\phi^2 - k_{i_{q\phi}} e_{i_{q\phi}}^2 - k_{i_d} e_{i_d}^2 + e_{i_{q\phi}} k_{i_{q\phi}} e_{i_{q\phi}} + e_{i_{q\phi}}\left(\dot{\phi}_{rd} i_q\right)_{st}$$
$$- e_{i_{q\phi}} \phi_{rd}\left(\Gamma_1 + \mu v_{sq}\right) + k_{i_d} \left[k_{i_d} e_{i_d} + \left(\dot{i}_d\right)_{st} - \left(\Gamma_2 + \mu v_{sd}\right)\right] \quad (17)$$

To ensure that the derivative of the Lyapunov function L_2 must be negative:

$$k_{i_{q\phi}} e_{i_{q\phi}} + \left(\dot{\phi}_{rd} i_q\right)_{st} - \phi_{rd}\left(\Gamma_1 + \mu v_{qs}\right) = 0$$
$$k_{i_d} e_{i_d} + \left(\dot{i}_d\right)_{st} - \left(\Gamma_2 + \mu v_{ds}\right) = 0 \quad (18)$$

According to the equation system (18), the expression of the control law is:

$$v_{sd} = \frac{k_{i_d} e_{i_d} + \left(\dot{i}_d\right)_{st} - \Gamma_2}{\mu}$$
$$v_{sq} = \frac{k_{i_{q\phi}} e_{i_{q\phi}} + \left(\dot{\phi}_{rd} i_q\right)_{st} - \phi_{rd}\Gamma_1}{\mu \phi_{rd}} \quad (19)$$

Adaptive Backstepping Observer Design: In this section, we focus on the drawbacks of the proposed controls action. The first problem is the measurability of the rotor fluxes and magnetization currents. This problem is solved using a backstepping observer. The second problem concerns the estimation of rotor and stator resistance to design a robust optimization losses.

The model of the Backstepping observer can be described in a reference connected to the stator frame by the following equations:

$$\frac{d}{dt}\hat{i}_\alpha = -\hat{\eta}_0 \hat{i}_\alpha + k\hat{\beta}_r \hat{\phi}_{r\alpha} + k\omega_r \hat{\phi}_{r\beta} + \mu v_\alpha + v_x$$
$$\frac{d}{dt}\hat{i}_\beta = -\hat{\eta}_0 \hat{i}_\beta - k\omega_r \hat{\phi}_{r\alpha} + k\hat{\beta}_r \phi_{r\beta} + \mu v_\beta + v_y$$
$$\frac{d}{dt}\hat{\phi}_{r\alpha} = L_m \hat{\beta}_r \hat{i}_\alpha - \hat{\beta}_r \phi_{r\alpha} - \omega_r \hat{\phi}_{r\beta}$$
$$\frac{d}{dt}\hat{\phi}_{r\beta} = L_m \hat{\beta}_r \hat{i}_\beta + \omega_r \hat{\phi}_{r\alpha} - \hat{\beta}_r \hat{\phi}_{r\beta} \quad (20)$$

where:

$$\hat{\beta}_r = \beta_r + \Delta\beta_r = \frac{R_r}{L_r} + \frac{\Delta R_r}{L_r}$$
$$\hat{\eta}_0 = \eta_0 + \Delta\eta_0 = \frac{1}{\sigma L_s}\left(\frac{R_f R_s}{R_f + R_s} + \frac{\hat{\beta}_r L_m^2}{L_r}\right)$$

v_x and v_y are the control input to be designed.

All the parameters of induction motor are considered constant except rotor and stator resistance with its nominal value R_{rn}, R_{sn}.

The stator resistance is calculated after estimating the value of the rotor resistance. The stator error can be defined as follows:

$$e_{i\alpha} = i_\alpha - \hat{i}_\alpha, \; e_{i\beta} = i_\beta - \hat{i}_\beta$$
$$e_{\phi_{r\alpha}} = \phi_{r\alpha} - \hat{\phi}_{r\alpha}, \; e_{\phi_{r\beta}} = \phi_{r\beta} - \hat{\phi}_{r\beta} \quad (21)$$

Using equations (20) and (21), the dynamical equations errors are given by the following system:

$$\dot{e}_{i\alpha} = -\eta_0 e_{i\alpha} + k\left[\left(\beta_r e_{\phi_{r\alpha}} + \omega_r e_{\phi_{r\beta}}\right) + \Delta\beta_r\left(L_m i_\alpha - \hat{\phi}_{r\alpha}\right)\right] - v_x$$
$$\dot{e}_{i\beta} = -\eta_0 e_{i\beta} + k\left[\left(\beta_r e_{\phi_{r\beta}} - \omega_r e_{\phi_{r\alpha}}\right) + \Delta\beta_r\left(L_m i_\beta - \hat{\phi}_{r\beta}\right)\right] - v_y$$
$$\dot{e}_{\phi_{r\alpha}} = -\left(\beta_r e_{\phi_{r\alpha}} + \omega_r e_{\phi_{r\beta}}\right) - \Delta\beta_r\left(L_m i_\alpha - \hat{\phi}_{r\alpha}\right) + L_m \beta_r e_{i\alpha}$$
$$\dot{e}_{\phi_{r\beta}} = -\left(\beta_r e_{\phi_{r\beta}} - \omega_r e_{\phi_{r\alpha}}\right) - \Delta\beta_r\left(L_m i_\beta - \hat{\phi}_{r\beta}\right) + L_m \beta_r e_{i\beta} \quad (22)$$

To solve the problem of pursuit and the convergence of estimation errors, a control algorithm will be proposed using a backstepping observer type [5, 15].

The first step of our observer design is to define the functions stabilizing fs_1 and fs_2 of the virtual variables $e_{i\hat{a}}$ and $e_{i\hat{a}}$. Assuming that:

$$\begin{aligned} e_{i\alpha} &= \dot{e}_{xd} \\ e_{i\beta} &= \dot{e}_{xq} \end{aligned} \tag{23}$$

The tracking error $e_{p\hat{a}}$ and $e_{p\hat{a}}$ of the estimation errors of the stator currents e_{ids} and e_{iqs} can be defined as follows:

$$\begin{aligned} e_{p\alpha} &= e_{i\alpha} - f_{s_1} \\ e_{p\beta} &= e_{i\beta} - f_{s_2} \end{aligned} \tag{24}$$

where:

$$\begin{aligned} f_{s_1} &= -\gamma_1 e_{xd} \\ f_{s_2} &= -\gamma_2 e_{xq} \end{aligned} \tag{25}$$

γ_1 and γ_2 are positive constant to guarantee the exponential convergence of the observer.

Using equations (22), (23), (24), (25) and we choose the control law as follows:

$$\begin{aligned} v_x &= k\left(\beta_r e_{\phi_{r\alpha}} + \omega_r e_{\phi_{r\beta}}\right) + \gamma_1 e_{i\alpha} + \gamma_2 e_{p\alpha} + e_{xd} \\ v_y &= k\left(\beta_r e_{\phi_{r\beta}} - \omega_r e_{\phi_{r\alpha}}\right) + \gamma_1 e_{i\beta} + \gamma_2 e_{p\beta} + e_{xq} \end{aligned} \tag{26}$$

We can get the dynamics of tracking errors e_{pd} and e_{pq} as follows:

$$\begin{aligned} \dot{e}_{p\alpha} &= -\eta_0 e_{i\alpha} + k\Delta\beta_r\left(L_m i_\alpha - \hat{\phi}_{r\alpha}\right) - \gamma_2 e_{p\alpha} - e_{xd} \\ \dot{e}_{p\beta} &= -\eta_0 e_{i\beta} + k\Delta\beta_r\left(L_m i_\beta - \hat{\phi}_{r\beta}\right) - \gamma_2 e_{p\beta} - e_{xq} \end{aligned} \tag{27}$$

Finally, we can design the observer of the rotor resistance using the following Lyapunov function [6, 9]:

$$L = \frac{1}{2}\left(e_{xd}^2 + e_{xq}^2 + e_{p\alpha}^2 + e_{p\beta}^2 + e_{\phi_{r\alpha}}^2 + e_{\phi_{r\beta}}^2 + \frac{\Delta R_r^2}{k_{R_r}}\right) \tag{28}$$

After the derivation of this function and taking into account that the derivative must be defined negative, we can write the mechanism of adaptation of the rotor resistance as follows [4, 6]:

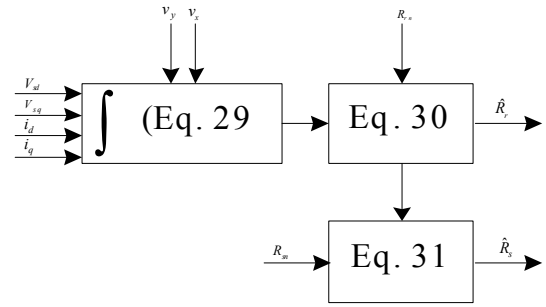


Fig. 2: On-line rotor and stator estimator diagram.

$$\begin{aligned} \frac{d\Delta R_r}{dt} = \frac{k_{R_r}}{L_r}[&k.L_m.e_{p\beta}.i_\beta + \phi_{r\alpha}.e_{\phi_{r\alpha}} - L_m.i_\alpha.e_{\phi_{r\alpha}} + \phi_{r\beta}.e_{\phi_{r\beta}} \\ &-L_m.i_\beta.e_{\phi_{r\beta}} - k.e_{p\alpha}.\phi_{r\alpha} + k.L_m.e_{p\alpha}.i_\alpha - k.e_{p\beta}.\phi_{r\beta}] \end{aligned} \tag{29}$$

With

$$\hat{R}_r = R_{rn} + \Delta R_r \tag{30}$$

Assuming that the rotor temperature is very close to that of the stator and the rotor and stator coils are of the same materials, so the mechanism of adaptation of the stator resistance is given by the following equation:

$$\hat{R}_s = \frac{R_{sn}}{R_{rn}}\hat{R}_r \tag{31}$$

Since the currents $i_{\hat{a}}$ and $i_{\hat{a}}$ are not really measurable, then they must be expressed in terms of stator currents. In [7], the author gives an expression which subsequently assembled magnetizing currents and stator currents as follows:

$$\left[1 + \frac{R_s}{R_f}\right] i_s - \frac{Vs}{R_f} = i_{\alpha\beta} \tag{32}$$

By examining the influence of the variation of resistance of the three-phase induction motor we can consider that
$R_f >> R_s$, then the equation (32) becomes:

$$i_s - \frac{Vs}{R_f} = i_{\alpha\beta} \tag{33}$$

Optimal Rotor Flux Calculation for Maximum Efficiency: The copper and core losses are obtained by the corresponding resistances and currents. There are two types of induction machine energy losses. One is called

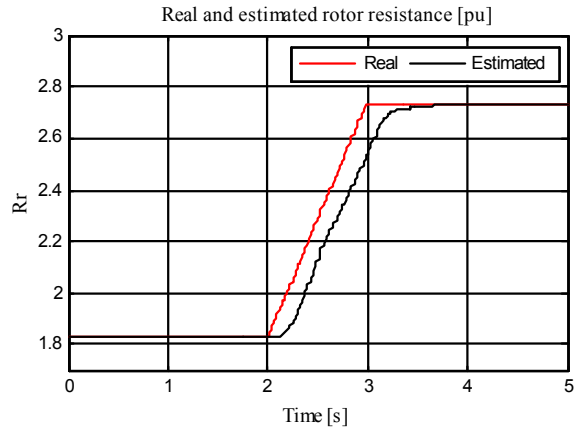


Fig. 3: Simulation result of the adaptation of the rotor resistance.

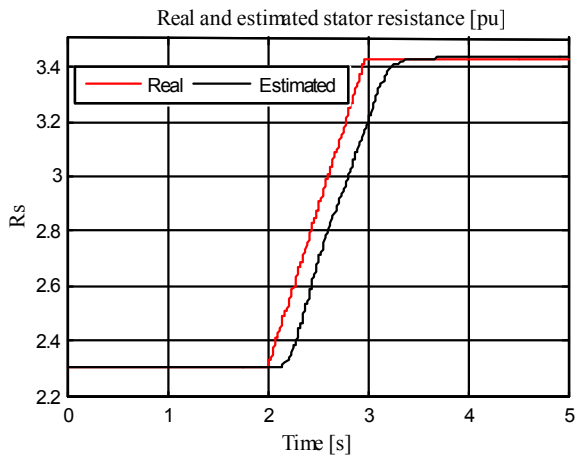


Fig. 4: Simulation result of the adaptation of the stator resistance.

intrinsic losses, such as windage, friction and stray losses which represent about 7% of total motor losses. The other type of losses includes the extrinsic energy losses, such as iron losses caused chiefly by hysteresis and eddy-current effects and copper losses [6-8]. The intrinsic losses can be optimized only by induction motor design changes. These extrinsic losses can be minimized by drive control technique.

The iron and copper losses are greater than 80% of all losses in the induction motor and we will focus on it in this section. The power lost in copper and core is expressed as follows [7, 16, 18-20]:

$$P_L = P_{Cu}^s + P_{Cu}^r + P_{Fe} \tag{34}$$

With

$$\begin{aligned} P_{Cu}^s &= R_s\left(i_{sd}^2 + i_{sq}^2\right) \\ P_{Cu}^r &= R_r\left(i_{rd}^2 + i_{rq}^2\right) \\ P_{Fe} &= R_f\,\phi_r^2 / L_m^2 \end{aligned} \tag{35}$$

P_{Cu}^s : Joule losses in the stator circuit.

P_{Cu}^r : Joule losses in the rotor circuit.

P_{fe} : Iron losses.

Under steady state and in the d-q frame, all variables become continuous quality, then their derivates will be equal to zero. Thus, all dynamic terms are ignored and we have:

$$\phi_{rd} = L_m i_d \tag{35}$$

By developing expression (34) and calculating the optimal flux depending on the couple, we have:

$$P_L = \chi_1 \phi_r^2 + \chi_2 \frac{T_{em}^2}{\phi_r^2} \tag{36}$$

With

$$\chi_1 = \frac{\left(R_s + R_f\right)}{L_m^2}$$

$$\chi_2 = \frac{L_r^2 R_s + R_r L_m}{n_p^2 L_m^2}$$

The energetic losses are minimal if:

$$\frac{\partial P_L}{\partial \phi_r} = 0 \tag{37}$$

Hence

$$2\chi_1 = \frac{2\chi_2 T_{em}^2}{\phi_r^4} \tag{38}$$

The expression of the optimal flux is given by the following equation:

$$\phi_r^{optimal} = \sqrt[4]{\frac{\chi_2}{\chi_1} T_{em}^2} \tag{39}$$

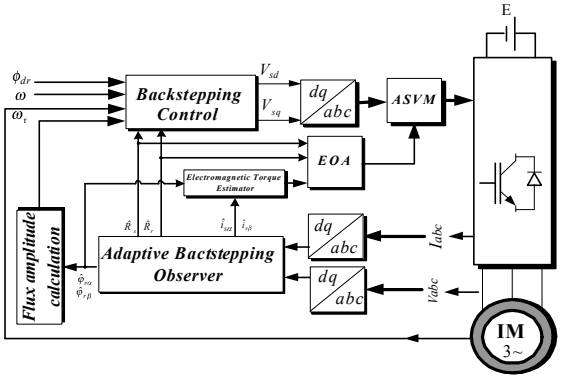


Fig. 5: Block diagram of the backstepping control including R_r and R_s estimators and core losses minimization (EOA: Energy Optimization Algorithm)

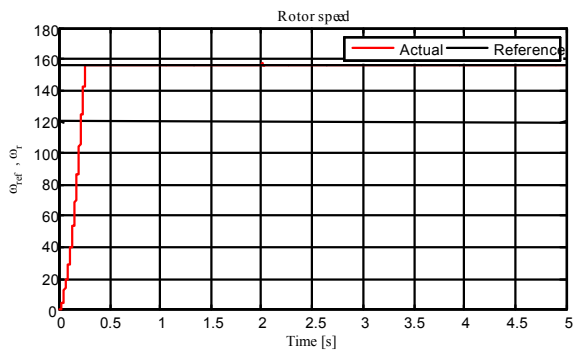


Fig. 6: Simulation result of the rotor speed.

DISCUSSION

The performances of the proposed solution are evaluated using Matlab -Simulink. A dynamic three phase induction motor model with core loss was built to emulate the motor for simulation, as well as the optimization algorithm, the backstepping control and observer. The three phase induction motor parameters are given in Table 2. Figure 5 shows the architecture of the vector control algorithm incorporating the backstepping full-order observer.

The backstepping observer can estimate the rotor flux, the stator currents and the values of the stator and rotor resistance which are injected into the following blocks:

- Block of Flux amplitude calculation: to calculate the rotor flux along the d-axis and will be compared with the reference flux.
- Block of the Backstepping control: make the control more responsive to changes in stator and rotor resistances.

Table II: Parameters of induction motor

Designation	Notations	Rating values
Stator Resistance	R_s	2.3Ω
Rotor Resistance	R_r	1.83Ω
Equivalent iron core-loss	R_c	92Ω
Stator self-inductance	Ls	261µH
Rotor self-inductance	L_r	261µH
Mutual inductance	Lm	245µH
Moment of inertia	J	0.03kgm^2
Friction coefficient	f	0.002Nm
Number of poles	n_p	2
Rated power	P_n	5.1Kw
Rated voltage	V_{sn}	380V

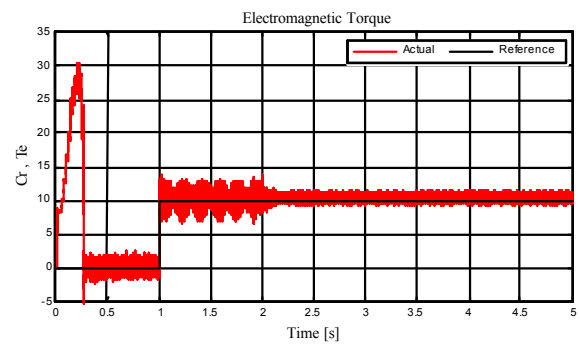


Fig. 7: Simulation result of the electromagnetic torque.

- Block of Electromagnetic torque estimator: used to estimate the electromagnetic torque from the measured variables, which will allow us to calculate the optimal flux.
- Block of Energy Optimization Algorithm: allows the energy optimization and the calculation of the optimal flux.

All the above blocks are used to design a robust control that reflects the parametric variations and the minimization of the energy of consummation.

Figure 6 show the speed system response under a load torque of 10 Nm, after 0.4 s the motor reaches the steady state. The curve of the electromagnetic torque in different regime is illustrated by Figure 7. At t=2 s the simulator balanced from the nominal value of the flux to the optimal value of the rotor flux that will ensure maximum efficiency.

Figures 8 show the response of the rotor flux. The optimal flux that must be injected into the command is shown in Figure 9.

From Figure 10 it's clearly that the power dissipation is reduced approximately to 27%.

This decrease may be more important when the machine more under loaded, it can reach 50% when the machine is exposed to a load torque equal to 5Nm.

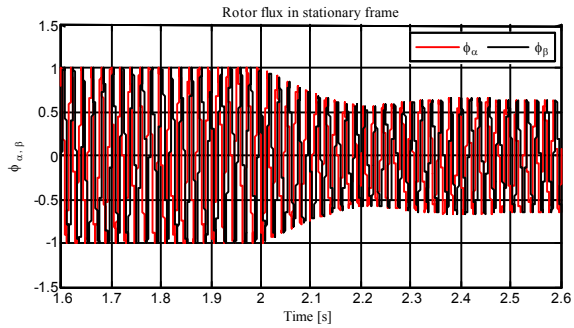


Fig. 8: Simulation result of the rotor flux.

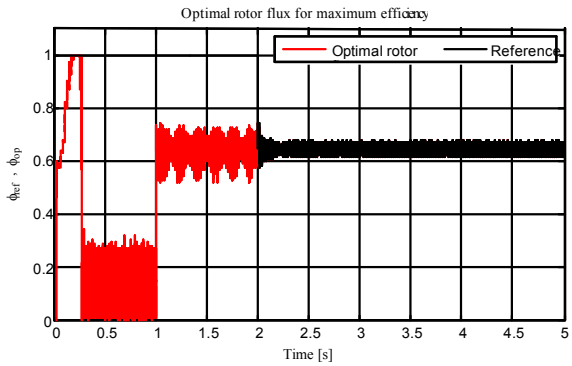


Fig. 9: Simulation result of the optimal rotor flux.

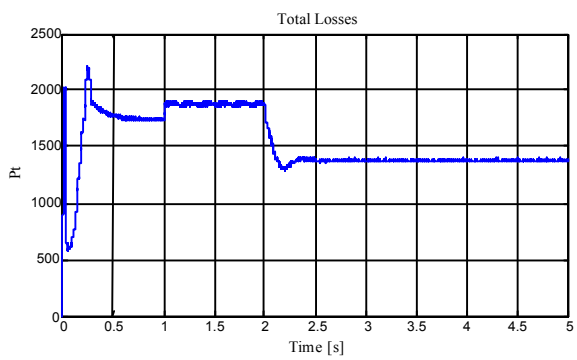


Fig. 10: Simulation result of the total losses.

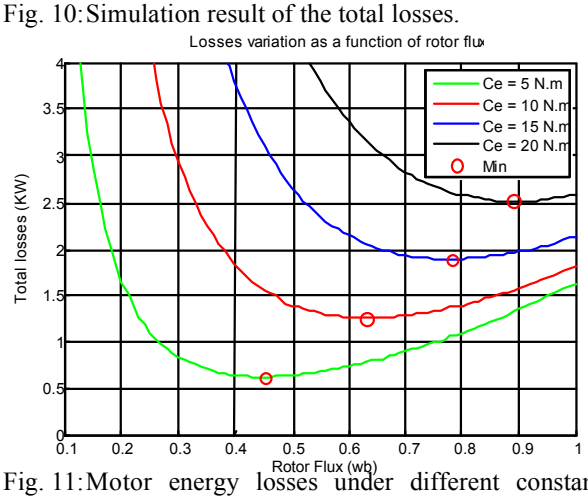


Fig. 11: Motor energy losses under different constant load.

Table III: Total motor energy losses and optimal flux under constant load torque

	Load Torque			
	5Nm	10Nm	15Nm	20Nm
ΔP_l(%)	~ 47.22%	~27.63%	~14.5%	~ 4.77%
$\phi_r^{optimal}$	0.46wb	0.65wb	0.78wb	0.9wb

Figure 11 shows the optimal values ??of the flux that must be injected into the control to ensure a minimum of power dissipation. Other simulation test were performed and the results is shown in Table III.

CONCLUSION

It is clarified that the classical method of control are based on the operation of the motor at rated flux causing considerable degradation of the efficiency of the induction motor drive under load. Thus, an optimal vector control system against the electric energy losses as well as the rotor and stator resistance estimation was constructed.

The proposed method is based on backstepping technique and it's capable on the one hand of tracking the rotor and stator resistance variation, on the other hand minimizing the electric energy losses. Finally, simulation results confirm the efficiency optimization obtained with proposed method when comparing to the operation of the motor rated flux.

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