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Research Article

ROBUST NONLINEAR INTEGRAL BACKSTEPPING OF SPEED AND ROTOR FLUX CONTROL DESIGN FOR A WOUND ROTOR INDUCTION MOTOR MODEL WITH UNCERTAIN PARAMETERS

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Abstract

Magnetic flux saturation and variation of the temperature during the operation of the motor causes a variation of inductive and resistive stator and rotor parameters. This article deals with these disturbances by backstepping technique with two Actions full. The first integral action applied to the speed and torque control aims to reinforce the robustness of the controller in the face of varying parameters. Second integral action is to reinforce the robustness of the control flow and the stator currents and rotor facing the parameter variation. The control technique is applied from a new model in the reference frame (α/β) whose state variables are constant in steady state unlike the conventional model. The performance of the control system is tested in a simulation in the Matlab/Simulink environment. The results show good transient performance and good tracking of the speed and rotor flux references. There has also been a good rejection of interference, due to variations load torque, of the reference of the rotor flux, mutual inductance and the rotor resistance.

Keywords: Wound rotor induction motor, Backstepping control, Integral action, Speed control, Rotor flux control.

INTRODUCTION

The control of asynchronous motors has undergone considerable evolution over the last four decades thanks to the advent of power electronics and computers. These motors can now be used at variable speed and thus optimize their energy consumption. In addition, asynchronous motor because of the advantages it presents (robustness, lower costs, reduced maintenance) occupies a large share in the drive systems market. The first advanced techniques for controlling asynchronous motors, called vector control, made those of Branchk and Hass. This control technique made a radical change to the control of induction motors, as it brought good quality of motor performance in dynamic regime (Singh *et al.,* 2005; Santisteban and Stephan, 2001). The input-output linearization control generalizes the flow orientation control by ensuring the decoupling and the linearization between the inputs and the outputs (Chiasson *et al.,* 1992; Zaidi *et al.,* 2014). This method assumes that all the state vectors are measurable and thus design a nonlinear state feedback control which ensures the stability of the closed loop system. This design is made possible by using the mathematical tools of differential geometry for the change of variable, and this in the Park coordinate system (d/q) in order to ensure that the new state variables are constant in steady state (Bodson *et al.,* (1994). This change of reference increases the calculation time of the command. The direct torque control (DTC) gives the possibility of directly controlling the torque and the flux of the machine without going through tedious calculations of reference transformation (Ozkop and Okumus, 2008). But its drawback lies in the variation of the flux when it is outside its hysteresis band and its switching frequency which has given rise to some research work (Kang, Jun-Koo, and Seung-Ki Sul, 1999; Lascu, Cristian *et al.,* 2016; Zahraoui *et al.,* 2019).

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Since the 1990s, the nonlinear control called "Backstepping" will become one of the most popular controls for a wide range of classes of nonlinear systems including the asynchronous motor (Kristic *et al.,* 1995; Okou *et al.,* 2009). It is distinguished by its ability to easily ensure the overall stabilization system (Khalil and Grizzle, 2002). The design of the control law is mainly based on the construction of the associated Lyapunov functions. The application of the Backstepping command for the asynchronous motor can be done in two ways. The first method, the most used, is applied with oriented flow control. This method simplifies the asynchronous motor model, and the implementation of the Backstepping technique becomes easier (Tan, 1999; Fateh and Abdellatif, 2017). The second method uses the engine model by performing a deep analysis in order to build a regression matrix. This method is seldom used. The engine parameters change due to temperature change (rotor resistance) and magnetic saturation (in stator inductance, rotor and mutual) (Ostovic, 2012), during operation considerably affects the efficiency of the order. This variation of the parameters generally has the effect of establishing a steady state error when following the trajectory of the velocity and the flow. This problem has led to robust versions s and adaptive controls mentioned above (Barambones and Alkorta, 2011; Mehazzem *et al.,* 2011; Zaidi *et al.,* 2014; Hajji *et al.,* 2019; Aichi *et al.,* 2020). However, these controls are designed in the axe (d/q) to ensure that the state variable model of engine is constant steady state. In practice, the calculation of the rotor angle θ r necessary for the change of reference frame (abc to dq) increases the execution time of the control algorithm. In the art work of (Ekang *et al.,* 2020), a new model is proposed. This model has the advantage of having state variables expressed in the reference (α / β) are constant in steady state. In order to deal with the problem of parameter variation, we apply in this research the Backstepping technique with two integral actions for the control of the speed and the rotor flux. The Backstepping technique with integral action is designed from the energy model proposed by (Ekang *et al.,* 2020). The advantage of applying this technique to this model is to reduce the execution time of the control algorithm. This saving in calculation time offers the possibility of adding two integral actions to ensure the robustness of the command in the face of parameter variations. This is the main contribution of this article. In order to achieve the objective of controlling the speed and the rotor flux in the face of the variation of the motor parameters, virtual models in the form of regression are obtained after analysis from the energy model. This article begins with a presentation of the new energy model of the engine in section II. In section III, the design of the Backstepping control with integral action is carried out. The analysis of the overall stability of the control is performed in this section. In section IV, the results following a test protocol are presented and discussed. This study was validated by simulation in the Matlab/Simulink environment.

WOUND ROTOR OF INDUCTION MOTOR MODEL

Variables of new dynamic model of wound rotor of induction motor

The energy model (Marino, R and al (2010))is suitable for the numerical simulation of the asynchronous machine with a view to making an analysis of its dynamic behavior. It would be inappropriate for the design of a control system for the machine using non-design techniques linear moderns.

$$\begin{aligned}
\frac{di_{s\alpha}}{dt} &= -\frac{L_r R_s}{\Delta} i_{s\alpha} + \frac{MR_r}{\Delta} i_{r\alpha} + \frac{M^2\omega}{\Delta} i_{s\beta} + \frac{ML_r\omega}{\Delta} i_{r\beta} + \frac{L_r}{\Delta} u_{s\alpha} \\
\frac{di_{s\beta}}{dt} &= -\frac{L_r R_s}{\Delta} i_{s\beta} + \frac{MR_r}{\Delta} i_{r\beta} - \frac{M^2\omega}{\Delta} i_{s\alpha} - \frac{ML_r\omega}{\Delta} i_{r\alpha} + \frac{L_r}{\Delta} u_{s\beta} \\
\frac{di_{r\alpha}}{dt} &= -\frac{L_s R_r}{\Delta} i_{r\alpha} + \frac{MR_s}{\Delta} i_{s\alpha} - \frac{ML_s\omega}{\Delta} i_{s\beta} - \frac{L_S L_r\omega}{\Delta} i_{r\beta} - \frac{M}{\Delta} u_{s\alpha} \\
\frac{di_{r\beta}}{dt} &= -\frac{L_s R_r}{\Delta} i_{r\beta} + \frac{MR_s}{\Delta} i_{s\beta} + \frac{ML_s\omega}{\Delta} i_{s\alpha} + \frac{L_S L_r\omega}{\Delta} i_{r\alpha} - \frac{M}{\Delta} u_{s\beta}
\end{aligned} \qquad (1)$$

With: $\Delta = L_s L_r - M^2$

L_r L_s and M: are respectively the rotor, stator and mutual inductances. R_r and R_s are rotor and stator resistance .$i_{s\alpha}$, $i_{s\beta}$: are the components of the rotor currents in the **(α/β)** reference frame. ω is the rotor speed in rad /s.

In fact, these methods of design require of models whose variables of state are constant permanent regime. That's not the case of the model energy whose components alpha and beta stator currents and rotor are sinusoidal in scheme permanent. This problem could be solved by transforming the frame of reference (α/β) to the frame of reference d/q. It is well known that the components d/q variable machine power is constant permanent regime. However,the main disadvantage of the d/q transformation is that it must be used in conjunction with its inverse transformation and both transformations are nonlinear and variables over time. Indeed, it depends on the angle of the rotor which is a variable dynamic. The use of these two transformations can therefore be very costly in computing time. In the work of (Ekang *et al.,* 2020), a new representation of the asynchronous machine is made in the repository (α/β) with the constant state variables steady. The change of variables which is proposed is nonlinear and static. The new model is therefore ideally suited for the use of modern nonlinear design methods such as feedback linearization and the recursive Backstepping command. The state variables for modelling the asynchronous machine are as follows:

$$\Sigma = i_{r\alpha} i_{s\beta} - i_{r\beta} i_{s\alpha} \qquad (2)$$

$$\Phi = i_{s\alpha} i_{r\alpha} + i_{s\beta} i_{r\beta} \qquad (3)$$

$$R = \frac{1}{2}\left(i_{r\beta}^2 + i_{r\alpha}^2\right) \qquad (4)$$

$$S = \frac{1}{2}\left(i_{s\beta}^2 + i_{sa}^2\right) \qquad (5)$$

The variable $\sum$ is proportional to the electromagnetic torque. The variable Φ is the dot product between the stator and rotor currents. The physical meaning of this variable remains to be determined. The variable R is the square of the RMS rotor current. The variable S is the square of the RMC stator current.

New model of wound rotor of induction motor

The dynamics of the new model is obtained by deriving the new variables identified by equations (2) (3) (4) and (5) and by taking into account the dynamics of the motor speed. The model is:

$$\begin{aligned}
\dot{\Sigma} =& -\frac{R_r L_s + R_s L_r}{\Delta}\Sigma - \frac{2ML_s\omega(t)}{\Delta} S - \frac{2ML_r\omega(t)}{\Delta} R - \frac{M^2 + L_s L_r}{\Delta}\omega(t)\Phi \\
&+ \frac{M}{\Delta}\left(i_{sa}u_{sb} - i_{sb}u_{sa}\right) + \frac{L_r}{\Delta}\left(i_{ra}u_{sb} - i_{rb}u_{sa}\right)
\end{aligned} \qquad (6)$$

$$\begin{aligned}
\dot{\Phi} =& -\frac{R_s L_r + R_r L_s}{\Delta}\Phi + \frac{2MR_r}{\Delta} R + \frac{2MR_s}{\Delta} S + \frac{M^2 + L_r L_s}{\Delta}\omega\Sigma \\
&+ \frac{L_r}{\Delta}\left(i_{ra}u_{sa} + i_{rb}u_{sb}\right) - \frac{M}{\Delta}\left(i_{sa}u_{sa} + i_{sb}u_{sb}\right)
\end{aligned} \qquad (7)$$

$$\dot{R} = -\frac{2R_r L_s}{\Delta} R - \frac{ML_s}{\Delta}\omega(t)\Sigma + \frac{R_s M}{\Delta}\Phi - \frac{M}{\Delta}\left(i_{r\alpha}u_{s\alpha} + i_{r\beta}u_{s\beta}\right) \qquad (8)$$

$$\dot{S} = -\frac{2R_s L_r}{\Delta} S + \frac{R_r M}{\Delta}\Phi - \frac{ML_r}{\Delta}\omega(t)\Sigma + \frac{L_r}{\Delta}\left(i_{s\alpha}u_{s\alpha} + i_{s\beta}u_{s\beta}\right) \qquad (9)$$

$$\dot{\omega} = \frac{M}{J}\Sigma - \frac{T_L}{J} \qquad (10)$$

Where T_L is the load torque N.m. J is the moment of inertia.

We note the presence U_{sr} and U_{ss} inputs defined as follows:

$$\begin{aligned}
u_{sr} &= i_{r\alpha} u_{s\alpha} + i_{r\beta} u_{s\beta} \\
u_{ss} &= i_{s\alpha} u_{s\alpha} + i_{s\beta} u_{s\beta}
\end{aligned} \qquad (11)$$

These new inputs are the dot products of the components of the stator voltages and the rotor currents respectively. The dynamic of the angles of the rotor flux at their reference values. They are not shown for simplicity but also because they are not useful for the design brought to e to the next section.

BACKSTEPPING CONTROL DESIGN

The model shown in the previous section is used in this section for the design of the control system. It should be remembered that all machine state variables are measurable. We propose to control the mechanical speed and the rotor flux at their reference values. The model of the machine is nonlinear. Therefore, we propose the use of the recursive design method called Backstepping to obtain the structure of the control system and the control laws. The design method makes it possible to structure control system in two loops consisting of a speed control in series with a torque control and flux control in series with a current control.

Integral Backstapping control for speed and torque

For the design of speed and torque control loop, dynamics of mechanical speedω and that of Σshould be used such that:

$$\begin{cases} \dot{\Omega}_\omega = \omega - \omega_{ref} \\ \dot{\omega} = \frac{M}{J}\Sigma - \frac{T_L}{J} \\ \dot{\Sigma} = -\frac{R_r L_s + R_s L_r}{\Delta}\Sigma - \frac{2ML_s\omega(t)}{\Delta}S - \frac{2ML_r\omega(t)}{\Delta}R \\ \quad -\frac{M^2 + L_s L_r}{\Delta}\omega(t)\Phi + U_1 \end{cases} \tag{12}$$

With: $U_1 = \frac{M}{\Delta}\left(i_{s\alpha}u_{s\beta} - i_{s\beta}u_{s\alpha}\right) + \frac{L_r}{\Delta}\left(i_{r\alpha}u_{s\beta} - i_{r\beta}u_{s\alpha}\right)$

The integrator is defined for the speed and torque control by considering the dynamics of speed error as a state variable.

$e_1$error is therefore $\Omega_\omega$and its dynamic is :

$$\dot{e}_1 = \omega - \omega_{ref} \tag{13}$$

$\omega_{ref}$is reference value of the mechanical speed.

Expression ofωfor which the dynamic of error is defined negative is :

$$\omega^* = -k_1 e_1 + \omega_{ref} \tag{14}$$

ω*is not real input of the system, we defined an errore_2.

$$e_2 = \omega - \omega^* \tag{15}$$

From equations (13) and (14), we can rewrite dynamics of $e_1$error as function e_2 :

$$\dot{e}_1 = -k_1 e_1 + e_2 \tag{16}$$

From equations (13) and (15), dynamics of$e_2$error gives:

$$\dot{e}_2 = \frac{M}{J}\Sigma - \frac{T_L}{J} - k_1\left(\omega - \omega_{ref}\right) \tag{17}$$

Equation (17) makes it possible to determine the value that the variable Σshould have in order to make's speed errors converge towards zero. This desired value of Σvariable has the expression :

$$\Sigma^* = \frac{J}{M}\left(\frac{T_L}{J} - k_2 e_2 + k_1\left(\omega - \omega_{ref}\right) - e_1\right) \tag{18}$$

Next step will make it possible to determine the expression of U1which causeΣvariable to converge towards its reference which is Σ^*. To do it we define the following error.

$$e_3 = \Sigma - \Sigma^* \tag{19}$$

Equations (18) and (19)make it possible to rewrite the dynamics of speed error $e_2$as follows:

$$\dot{e}_2 = -e_1 - k_2 e_2 + \frac{M}{J}e_3 \tag{20}$$

Dynamics of$e_3$error give:

$$\begin{aligned} \dot{e}_3 &= \dot{\Sigma} - \dot{\Sigma}^* \\ &= -\frac{R_r L_s + R_s L_r}{\Delta}\Sigma - \frac{2ML_s\omega(t)}{\Delta}S - \frac{2ML_r\omega(t)}{\Delta}R \\ &\quad -\frac{M^2 + L_s L_r}{\Delta}\omega(t)\Phi + \frac{J}{M}\left(k_1 + k_2\right)\left(\frac{M}{J}\Sigma - \frac{T_L}{J}\right) \\ &\quad +\frac{J}{M}\left(k_1 k_2 + 1\right)\left(\omega - \omega_{ref}\right) + U_1 \end{aligned} \tag{21}$$

Expression of $U_1$is determined in such a way that the dynamic $e_2$error converges towards zero in a closed loop. We obtained

$$\begin{aligned} U_1 &= \frac{R_r L_s + R_s L_r}{\Delta}\Sigma + \frac{2ML_s\omega(t)}{\Delta}S + \frac{2ML_r\omega(t)}{\Delta}R \\ &\quad +\frac{M^2 + L_s L_r}{\Delta}\omega(t)\Phi - \frac{J}{M}\left(k_1 + k_2\right)\left(\frac{M}{J}\Sigma - \frac{T_L}{J}\right) \\ &\quad -\frac{J}{M}\left(k_1 k_2 + 1\right)\left(\omega - \omega_{ref}\right) - k_3 e_3 - \frac{M}{J}e_2 \end{aligned} \tag{22}$$

Close-loop dynamics of $e_3$error obtained by substituting equation (21) in equation (22).

$$\dot{e}_3 = -k_3 e_3 + \frac{2R_r}{L_r}e_4 \tag{23}$$

In the next section, design of flux control is presented. Backstepping control with integral action is also used to structure this control loop.

Backstepping control design for rotor flux and current

The objective being to control the rotor flux, it is necessary to express this stream depending on variables state of the machine. In addition to integrators, virtual model into triangular form to control the flux control and current control is:

$$\begin{cases} \dot{\Omega}_\Psi = \Psi_{2r} - \Psi_{2rref} \\ \dot{\Psi}_{2r} = -\frac{R_r}{L_r}\Psi_{2r} + \frac{2R_r}{L_r}\mathrm{K} \\ \dot{\mathrm{K}} = \left(\frac{ML_s L_r^2}{\Delta} - \frac{M^3 L_r}{\Delta}\right)\omega(t)\Sigma - \frac{2R_s L_r M^2}{\Delta}S \\ \quad +\left(\frac{R_r M^3}{\Delta} - \frac{R_s M L_r^2}{\Delta}\right)\Phi + \frac{2R_r L_s L_r^2}{\Delta}R + U_2 \end{cases} \tag{24}$$

With $U_2 = \frac{M^2 L_r}{\Delta}\left(i_{s\alpha}u_{s\alpha} + i_{s\beta}u_{s\beta}\right) + \frac{ML_r^2}{\Delta}\left(i_{r\alpha}u_{s\alpha} + i_{r\beta}u_{s\beta}\right)$

And $\Delta = L_s L_r - M^2$

The controller for flux control and current stator and rotor is thus designed from the system equation (24). Integral action is added to the controller by defining the change in variable described by the first equation of the system (24).

The dynamics of the flux modulus error which introduces the integral action is described as follows:

$$\dot{e}_4 = \Psi_{2r} - \Psi_{2rref} \qquad (25)$$

ExpressionΨ_{2r} which makes it possible to converge dynamic e_4 towards zero is :

$$\Psi^*_{2r} = -k_4\Omega_\Psi + \Psi_{2rref} \qquad (26)$$

Equation (26) is not real input to the system, so we defineits error as:

$$e_5 = \Psi_{2r} - \Psi^*_{2r} \qquad (27)$$

From equations (26) and (27) we can rewrite the dynamic of $e_4$error as a function ofe_5 error:

$$\dot{e}_4 = e_5 - k_4\Omega_\Psi \qquad (28)$$

By deriving equation (27) and substituting equation (24), (26) we determine dynamic e_5 error:

$$\dot{e}_5 = -\frac{R_r}{L_r}\Psi_{2r} + \frac{2R_r}{L_r}\mathrm{K} + k_4\left(\Psi_{2r} - \Psi_{2rref}\right) \qquad (29)$$

Equation (29) gives the expression of Kvariable must have in order to make the dynamics of $e_5$converge towards zero. This value is noted K* and has for the expression:

$$\mathrm{K}^* = \frac{L_r}{2R_r}\left(-k_5e_5 - e_4 + \frac{R_r}{L_r}\Psi_{2r} - k_4\left(\Psi_{2r} - \Psi_{2rref}\right)\right) \qquad (30)$$

The following section will determine the expression of U2 which will allow K to converge towards its reference K^*.

We define the following error of currents:

$$e_6 = \mathrm{K} - \mathrm{K}^* \qquad (31)$$

Equation (29) of dynamics$e_5$error can be rewritten as a function of $e_6$errors such that:

$$\dot{e}_5 = -k_5e_5 - e_4 + \frac{2R_r}{L_r}e_6 \qquad (32)$$

Differentiating equation (31) and by substituting equations (24), (29) and (30) we obtain the dynamics of e_6 error following:

$$\begin{aligned}\dot{e}_6 = {} & \frac{2R_rL_sL_r^2}{\Delta} - \frac{2R_sL_rM^2}{\Delta}S + \frac{\left(R_rM^3 - R_sML_r^2\right)}{\Delta}\Phi \\ & + \frac{\left(ML_sL_r^2 - M^3L_r\right)}{\Delta}\omega\Sigma + U_2 + \frac{L_r}{2R_r}\left(\Psi_{2r} - \Psi_{2rref}\right) \\ & + \frac{L_r}{2R_r}\left(k_4 + \frac{R_r}{L_r}\right)\left(-\frac{R_r}{L_r}\Psi_{2r} + \frac{2R_r}{L_r}\mathrm{K}\right) \\ & + \frac{L_r}{2R_r}k_5\left(-\frac{R_r}{L_r}\Psi_{2r} + \frac{2R_r}{L_r}\mathrm{K} + k_4\left(\Psi_{2r} - \Psi_{2rref}\right)\right)\end{aligned} \qquad (33)$$

Following equation is proposed for U_2 :

$$\begin{aligned}U_2 = {} & -\frac{2R_rL_sL_r^2}{\Delta} + \frac{2R_sL_rM^2}{\Delta}S - \frac{\left(R_rM^3 - R_sML_r^2\right)}{\Delta}\Phi \\ & - \frac{\left(ML_sL_r^2 - M^3L_r\right)}{\Delta}\omega\Sigma + \frac{L_r}{2R_r}\left(\Psi_{2r} - \Psi_{2rref}\right)\left(k_4k_5 + 1\right) \\ & - \left(-\Psi_{2r} + 2\mathrm{K}\right)\left(\frac{R_r}{L_r} - k_4 + \frac{1}{2}k_5\right) - \frac{2R_r}{L_r}e_5 - k_3e_6\end{aligned} \qquad (34)$$

The closed-loop dynamics of e_6 obtained by substituting equation (33) in the equation (34).

$$\dot{e}_6 = -k_6e_6 - \frac{2R_r}{L_r}e_5 \qquad (35)$$

Output Controller expression

This section allows to determine the expressions s of the motor control inputs which are the α/β components of the stator voltages u_{sa} and u_{sb}. They are obtained from U_1 and U_2 determine previously. Equations (22) and (34) allow us to have the following matrix system of equations:

$$\begin{bmatrix} -\left(\frac{M}{\Delta}i_{s\beta} + \frac{L_r}{\Delta}i_{r\beta}\right) & \left(\frac{M}{\Delta}i_{s\alpha} + \frac{L_r}{\Delta}i_{r\alpha}\right) \\ \left(\frac{L_r^2M}{\Delta}i_{r\alpha} + \frac{L_rM^2}{\Delta}i_{s\alpha}\right) & \left(\frac{L_r^2M}{\Delta}i_{r\beta} + \frac{L_rM^2}{\Delta}i_{s\beta}\right)\end{bmatrix}\begin{bmatrix}u_{s\alpha}\\ u_{s\beta}\end{bmatrix} = \begin{bmatrix}U_1\\ U_1\end{bmatrix} \qquad (36)$$

Real input u_{sa} and u_{sb} have for expression:

$$\begin{bmatrix}u_{s\alpha}\\ u_{s\beta}\end{bmatrix} = \begin{bmatrix} -\left(\frac{M}{\Delta}i_{s\beta} + \frac{L_r}{\Delta}i_{r\beta}\right) & \left(\frac{M}{\Delta}i_{s\alpha} + \frac{L_r}{\Delta}i_{r\alpha}\right) \\ \left(\frac{L_r^2M}{\Delta}i_{r\alpha} + \frac{L_rM^2}{\Delta}i_{s\alpha}\right) & \left(\frac{L_r^2M}{\Delta}i_{r\beta} + \frac{L_rM^2}{\Delta}i_{s\beta}\right)\end{bmatrix}^{-1}\begin{bmatrix}U_1\\ U_1\end{bmatrix} \qquad (37)$$

Figure 1 following represents the structure of the speed control system and the proposed stream. There are indeed two control loops. The first loop consists of a control of speed followed by a control of torque. The speed command generates a reference to the torque command. The second loop contains a flux module control in series with a current control. The reference of the current control is generated by the flow control. The control structure obtained by applying the recursive method Backstepping is similar to the conventional control structure of asynchronous motors. It nevertheless has a considerable advantage which is that it is nonlinear and it makes it possible to guarantee the closed-loop stabilization of the system. The proof of stability is shown in the next section.

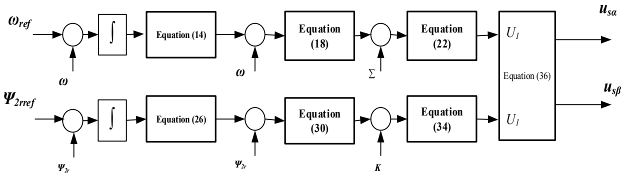

Figure 1. Backstepping with integralactions structure control

Global stability analysis

Stability analysis is done by the Lyapunov method. We define the following Lyapunov candidate function:

$$V = \frac{1}{2}\left(e_1^2 + e_2^2 + e_3^2 + e_4^2 + e_5^2 + e_6^2\right) \quad (38)$$

V derivative is obtained from equation (38), it gives:

$$\dot{V} = e_1\dot{e}_1 + e_2\dot{e}_2 + e_3\dot{e}_3 + e_4\dot{e}_4 + e_5\dot{e}_5 + e_6\dot{e}_6 \quad (39)$$

By replacing (22),(26), (37)and (34)in equation (39) we have:

$$\begin{aligned}\dot{V} &= e_1\left(-k_1e_1 + \frac{M}{J}e_2\right) + e_2\left(-k_2e_2 - \frac{M}{J}e_1\right) \\ &+ e_3\left(-k_3e_3 + \frac{2R_r}{L_r}e_4\right) + e_4\left(-k_4e_4 - \frac{2R_r}{L_r}e_3\right) \\ &+ e_5\left(-k_5e_5 - e_4 + \frac{2R_r}{L_r}e_6\right) + e_6\left(-k_6e_6 - \frac{2R_r}{L_r}e_5\right) \\ &= -k_1e_1^2 - k_2e_2^2 - k_3e_3^2 - k_4e_4^2 - k_5e_5^2 - k_6e_6^2\end{aligned} \quad (40)$$

$\dot{V} \le 0$ for all$k_i \ge 0$ {i=1,2,3,4,5,6}. It is easily noted that this candidate function is positive definite the system is therefore asymptotically stable. Therefore, the motor speed and the rotor flux will converge towards their reference values.

Global Structure Control

components (abc). This three-phase voltage is applied to the module of the converter DC/AC power electronics. The outputs of this inverter are applied to the stator of the motor. The gains k_1, k_2, k_3, k_4, k_5 and $k_6$of the controller, the maximum values of the stator voltages are as well as the motor parameters given in the appendix. The following section presents the results of the simulations performed to validate the performance of the proposed control system.

RESULTS AND DISCUSSION

A. Test Description

A single test over 10s is carried out in order to verify the performance of the proposed command faced with the variation of the load torque (TL), of the reference speed (ω_{ref}), of the reference flow (Ψ_{ref}) and of the parameters of motor. From 0 to t=4s the machine is in steady state and e c load torque is TL = 4902.6 Nm. The mechanical speed ω_{ref}= 378.14 rad/s, the rotor flux is Ψ_{2rref}= 4.494 Wb. At t = 3s, Rs increases by 10 times its nominal value. We wish to observe the robustness of the speed control in the face of this variation. At t=4s, the mechanical torque of the load is increased to TL=8171 Nm. The speed and flow set points are respectively ω_{ref}= 378.14 rad / s and Ψ_{2rref}= 4.494 Wb. We wish to observe the dynamics of the electric torque Te, of the mechanical speed ω and of the rotor flux during an increase in the load TL.

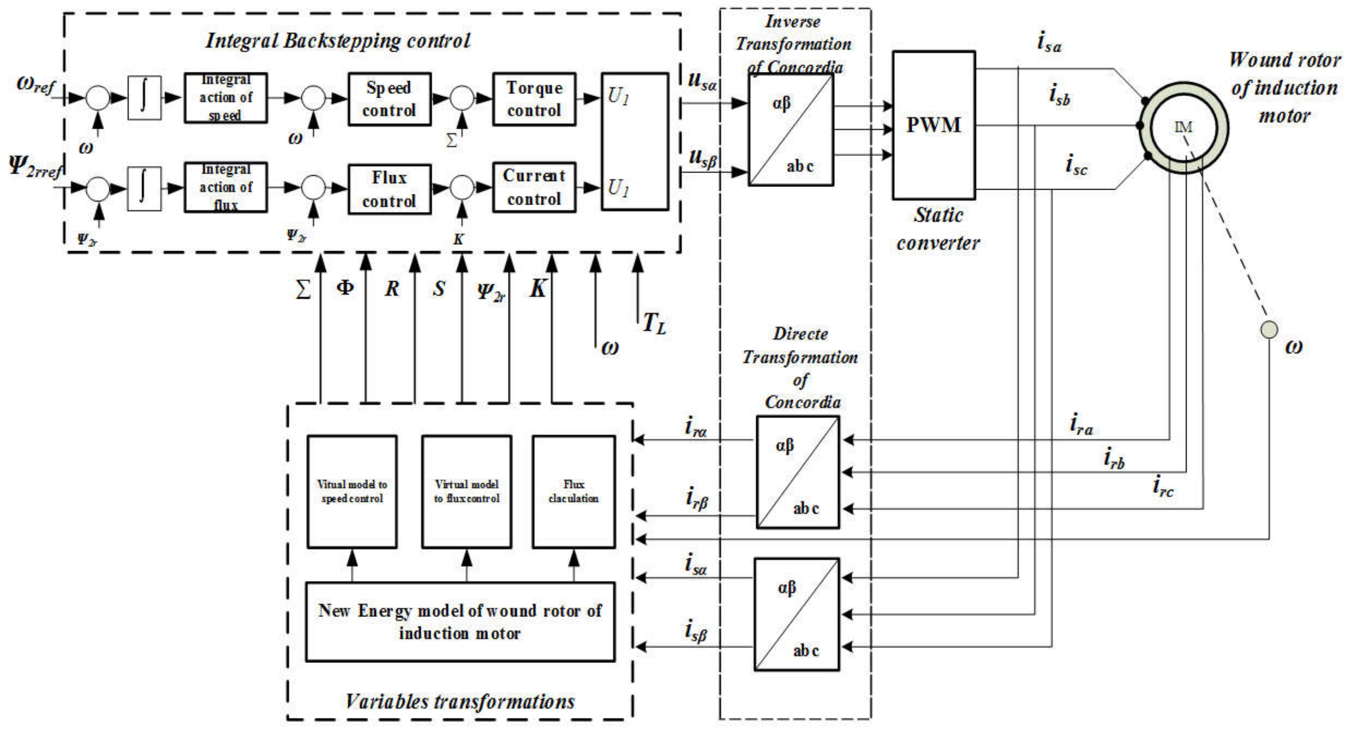

Figure 2. Global Structure Controller

Figure 2 shows the control system of the induction motor rotor is wound. It is noted that the three-phase stator and rotor currents as well as the speed of the motor are measured. The α/β components of the currents are then obtained using two Clark transformation moduli. Then, the variable change module proposed in this article is used to power the module which calculates the α/β components of the stator voltages applied to the motor. The module transforms the α/β components of the stator voltage into three-phase

At t =5s, R_r=5R_{rN} the rotor resistance increases by 5 times its nominal value. We wish to observe the robustness in the face of the variation of the rotor resistance. At t=6s, the value of the speed reference is reduced to ω_{ref}=295.51 rad/s. The mechanical torque and the flux reference remain unchanged: TL=8171Nm and Ψ_{2rref}= 4.494 Wb. We wish to observe the dynamics of the electric torque T_e, of the speed of rotation ω and of the rotor flux when the reference speed is reduced. At t=7s the L_r, L_s and Lm increase respectively by

40% of their nominal value. At t=8s, the reference value of the rotor flux is reduced to $\Psi_{2rr\ ef}$=3.177 Wb. The mechanical torque and the mechanical speed reference are unchanged: TL=8171 Nm and ω_{ref}=295.51 rad/s. We wish to observe the dynamics of the electric torque Te, of the mechanical speed ω and of the rotor flux during a reduction of the reference flux.

Results of the test

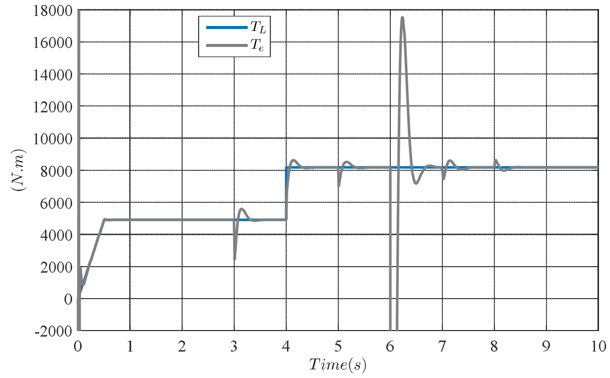

Figure 3. Load torque and electric torque variation

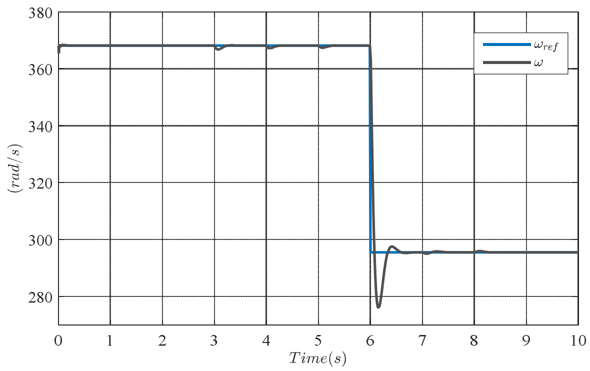

Figure 4. Speed variation

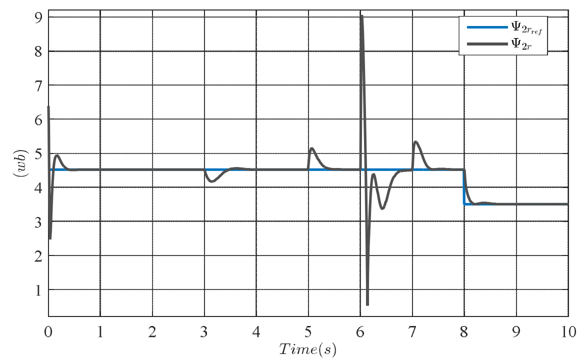

Figure 5. Flux modulusvariation

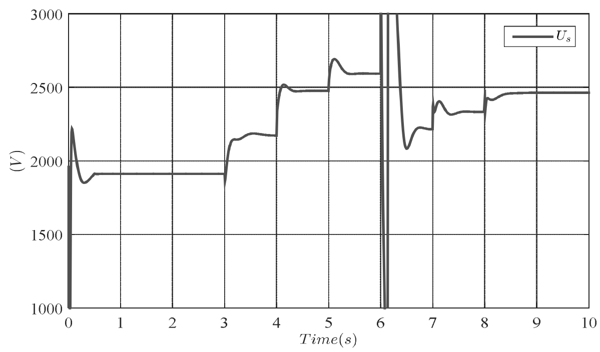

Figure 6. Stator voltage variation

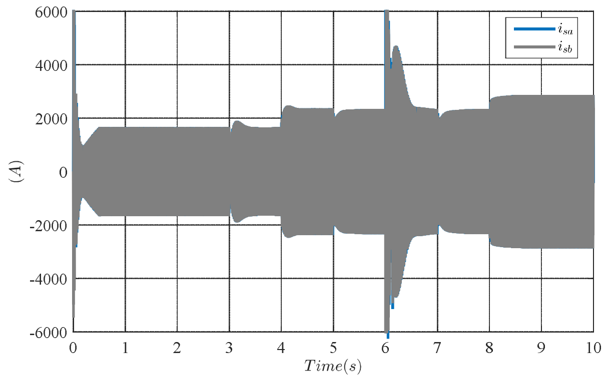

Figure 7. Stator current variation

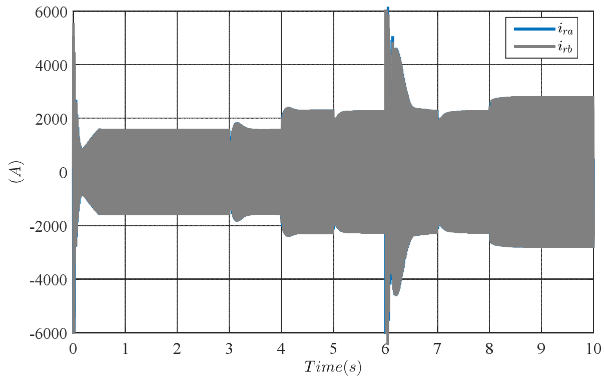

Figure 8. Rotor current variation

Discussion

At t = 4s, the load torque varies (Figure 3) increasing up to 8171 N.m, we observe in figure 4 a slight variation in speed then quickly returns to its reference trajectory. At t = 6s the speed varies, in FIG. 3, a reduction in the electric torque is observed, then quickly returns to the value of the load torque. In figure.5, the rotor flux increases and then stabilizes at its reference value. At t = 8s, the flux (figure 5) is reduced; in figure. 4 and figure.5, a slight variation in the electrical torque and in the speed is observed, then return to their reference value. The control system is robust against the variation of load torque, speed and rotor flux as in (Horch *et al.,* 2017). At t = 3s, 5s and 7s, the stator and rotor resistance and the stator, rotor and mutual inductances varying. It can be seen in FIG. 3 that the electric torque reduces and quickly returns to the value of the load torque. In figure.4, the speed reduces then quickly returns to its reference value. In Figure 5, the rotor flux is reduced then returns to its reference value. The control force U is then increased (figure 6) and the amplitudes of the stator and rotor currents remain constant (figure 7 and figure 8). The system is therefore robust in the face of variations or uncertainties to motor parameters such as in (Mehazzem *et al.,* 2011). This robustness is provided by the addition of integral action in the control loops.Failure to do so will result in a steady state error in rotor speed and flux rotor.

CONCLUSION

In this work, Backstepping control with integral action for controlling the speed and rotor flux has been applied to wound rotor motor of induction motor in order to enhance its robustness to the variation of these parameters. The control was designed on an energy model in which the state variables in the α/β frame of reference are constant in steady state.

Moreover, the triangular structure of this model corresponds to the recursive character necessary for the design of the Backstepping control. The recursive Backstepping design method with integral action was used to propose a control structure in which a speed control loop in series with a torque command to control the mechanical motor speed, and a different loop flow control in series with a current control to control the rotor flux of the machine. The proposed control system was then tested in simulation in my Matlab/Simulink environment. The results show the effectiveness of the proposed command. The speed and flux controller is robust against disturbances due to variations in load torque and variations in motor parameters. The motor model does not take into account the saturation functions of the magnetic flux.

Appendix:

Wound rotor of induction motor parameters

Motorloadinertia	J=63.87 Kgm2
Stator resistance	R_s=0.029 ohm
Rotor resistance	R_r=0.022 ohm
Stator inductance	L_s=0.0352 H
Rotor inductance	L_r=0.0352 H
Mutual inductance	M=0.0346 H
Max voltage stator	2.5 kV

Gains of controller

K_1	20
K_2	100
K_3	50
K_4	12
K_5	60
K_6	30

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