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# Application of the IBC controller for nonlinear processes on the example of an induction motor

*Zastosowanie całkowego sterowania (IBC) w procesach nieliniowych na przykładzie silnika indukcyjnego*

***Abstract**. This study introduces a control method for induction motors that merges a nonlinear observer, relying on the circle criterion, with integral Backstepping control (IBC). This approach handles nonlinearities better than traditional methods. Using the Lyapunov theory, the system's stability is assured. Integral action enhances the controller's robustness against uncertainties and disturbances. Three goals; trajectory tracking, disturbance rejection, and steady–state stability are achieved. Simulations demonstrate effectiveness in varied conditions.*

***Streszczenie.** W niniejszym badaniu przedstawiono metodę sterowania silnikami indukcyjnymi, która łączy nieliniowego obserwatora, opierając się na kryterium okręgu, z całkowym sterowaniem Backstepping (IBC). To podejście lepiej radzi sobie z nieliniowościami niż tradycyjne metody. Dzięki teorii Lyapunowa stabilność układu jest zapewniona. Działanie całkowe zwiększa odporność sterownika na niepewności i zakłócenia. Osiągnięto trzy cele: śledzenie trajektorii, odrzucanie zakłóceń i stabilność stanu ustalonego. Symulacje wykazują skuteczność w różnych warunkach.*

**Keywords:** induction motor, circle criterion, integral backstepping control, lyapunov stability
**Słowa kluczowe:** Silnik indukcyjny, kryterium okręgu, sterowanie całkowe backsteppingiem, stabilność lapunowa

## Introduction

Sensorless control has become increasingly popular in recent decades for enhancing the reliability and reducing the cost of electric drives. Key components of this approach include the electrical machine, control strategy, and state observer. By eliminating the need for physical sensors, systems can be more dependable and cost–effective [1–2].

The utilization of induction motors is widespread in many industrial applications because they have many advantages, such as excellent durability, low cost, minimal maintenance, and exceptional robustness [1–2–3]. However, asynchronous machine is also a complex system, with nonlinear, coupled and time–varying dynamics, and some of its state variables are not directly measurable, this poses additional problems for the control, diagnosis and monitoring of this machine [4]. In most industrial applications, speed control of induction motor drives is required. Linear system theory has some limitations for controlling induction motors, especially in transient regimes [7]. Nonlinear pre–compensation is an effective approach for commanding induction motors based on linearization technique, but it neglects the nonlinear part of the system [7–8]. Scalar control is a classical technique for variable speed control, but it only provides basic performance [5]. A more sophisticated technique is Field Oriented Control (FOC), which was proposed by Blaschke and Hasse in 1972 [6,7]. FOC makes the induction motor behave like a DC motor by independently controlling the flux and the torque in a rotating reference frame. However, FOC is sensitive to motor parameter variations and external load disturbances, especially the rotor resistance variation, which affects the flux orientation angle and the decoupling [6,7]. To address these issues and achieve high performance of this machine, several nonlinear control methods have been developed and applied in both simulation and practice. Among these strategies, input–output linearization control, it is a nonlinear control strategy, that gained traction for transforming complex nonlinear motor dynamics into linear equivalents via state feedback, enabling the application of linear control techniques, it simplifies IM dynamics by decoupling nonlinear interactions, enabling precise speed and torque tracking [8–9], sliding mode control [9], flatness control [11–12], passivity control [13] and adaptive methods [14–15] to solve the problem of time varying parameters, Backstepping and Integral Backstepping control [16–19]. As mentioned above, Backstepping control is a nonlinear strategy, widely used in a wide range of nonlinear systems and which provides overall stabilization, on the other hand, it performs well even in the presence of variability. This technique is mainly based on the use of the Lyapunov function [16]. Backstepping control is a nonlinear control technique that has been widely studied and applied to nonlinear systems [16]. It was introduced in 1991 by Petar Kokotovic and colleagues. It offers good performance in transient and relatively in steady state regimes, and it is more resistant to parameter variations and load torque disturbances. However, it has a limitation in steady state regime, as it relies on a proportional derivative that causes a static error [19]. This technique is based on Lyapunov stability tools. To improve the robustness of Backstepping control and eliminate residual errors, a modified Backstepping control with integral action can be used [20–21]. By choosing a suitable Lyapunov function, the integral Backstepping strategy can ensure the stability of the entire system when controlling induction motors [20]. The major benefits of this control technique are good tracking references and robustness under parametric variation constraints [21].

In this paper the robustness of speed, flux and torque ξ_1=1/j T_e controllers have all been enhanced by integrating new integral terms for an induction motor, reducing the impact of rotor resistance variation and load torque disturbance. However, like with all nonlinear control methods, accurate and reliable knowledge of the system's numerous state variables is essential. Utilizing state observers in this situation becomes a necessary course of action.

It should be noted that a state observer is a dynamic system that may observe the non–measurable state variables from the measurements of the system's inputs and outputs that are currently available. This software sensor is crucial for control, as well as for system monitoring, predictive maintenance, diagnostics, and fault–tolerant control strategies.The non–measurable state variables of the induction motor have been estimated in recent years using a variety of estimating techniques. The extended Kalman filter [21], a stochastic recursive estimating algorithm for nonlinear systems, is one of these methods. The simplicity and widespread application of this filter in the observation domain are its main driving forces. Without sacrificing the accuracy of the estimate, the nonlinear Luenberger observer is distinguished by its inherent simplicity when compared to the other approaches [23]. Due to its simplicity of use, excellent stability, less computational effort, and outstanding effectiveness, the MRAS observer (System, Adaptive Reference Model) has been quite popular in Sensorless induction motor control applications [24]. The advantage of the sliding mode observer (SM) [25] is that it is unaffected by changes in the rotor time constant (parameters of the machine). The block triangular constructions, sensitivity to measurement disturbances, and the destabilizing impact of the peaking phenomena (significant fluctuation in the transient response) are however some of their disadvantages. Based on the circle criterion, the nonlinear observer that introduced by Arckak and Kokotovich [26], allows to handle the nonlinearities directly and with less restrictive assumptions than the linearization and high gain methods [27–30].

This work presents a combination study between the observer based on the circle criterion and integral Backstepping control scheme applied to the induction motor, which is motivated by the attributes of the observers and control approaches mentioned above.

In summary, the novelty of this paper lies in the innovative integration of robust Integral Backstepping control with advanced state observers (particularly the circle criterion observer). This integration enhances the robustness of the motor's performance in the presence of parameter variations, such as rotor resistance changes, and external load disturbances. This approach provides a more effective solution to the challenges faced in sensorless control and monitoring of induction motors.

This paper is structured as follows: Part two introduces the nonlinear model of the induction motor. Section three presents the design of the integral Backstepping speed and norm of flux controllers. Section four describes the circle criterion observer. In section five we recall the Backstepping control technique. finally we end with a simulation and interpretation of the results which allows us to give a conclusion to this work.

## Non–Linear Modeling of Induction Motor

In the reference frame of the stator fixed (α–β) axis, the nonlinear model of the IM introduced in this work is given as follows

$$\frac{dx(t)}{dt} = f(x) + g(x).u(t) \tag{1}$$

$$y(t) = Cx(t) \tag{2}$$

We note that the stator currents, rotor flux, and rotor angular velocity are the state variables and the measurable vector components are the currents $i_{s\alpha}$ and $i_{s\beta}$ . The controller vector $u(t) = [u_{s\alpha}, u_{s\beta}, T_l]^T$ .

Where:

$$f(x) = \begin{bmatrix} -\gamma i_{s\alpha} + \frac{\beta}{T_r}\varphi_{r\alpha} + \beta\omega\varphi_{r\beta} \\ -\gamma i_{s\beta} - \beta\omega \quad \varphi_{r\beta} + \frac{\beta}{T_r}\varphi_{r\beta} \\ \frac{m}{T_r} i_{s\alpha} - \frac{1}{T_r}\varphi_{r\alpha} - \varphi_{r\beta} \\ \frac{m}{T_r} i_{s\beta} + \omega\,\varphi_{r\alpha} - \frac{1}{T_r}\varphi_{r\beta} \\ \partial(\varphi_{r\alpha} i_{s\beta} - \varphi_{r\beta} i_{s\alpha}) - k_f\omega - kT_l \end{bmatrix}; \tag{3}$$

$$g(x) = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_S} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \tag{4}$$

Where:

The following notations are introduced in order to simplify the mathematical equation forms:.

$$\gamma = \frac{1}{\sigma}\left(\frac{1}{T_s} + \frac{1-\sigma}{T_r}\right), \sigma = 1 - \frac{m^2}{L_s L_r}, k_l = \frac{n_p}{J}, k_f = \frac{f_r}{J},$$

$$\gamma = \frac{1}{\sigma}\left(\frac{1}{T_s} + \frac{1-\sigma}{T_r}\right), \sigma = 1 - \frac{m^2}{L_s L_r}, k_l = \frac{n_p}{J}, k_f = \frac{f_r}{J},$$

$$\omega = n_p \Omega \, . \tag{5}$$

The following notations are introduced in order to simplify the mathematical equation forms: $x_1 = i_{s\alpha}$ , $x_2 = i_{s\beta}$ ,$x_3 = \varphi_{r\alpha}$ , $x_4 = \varphi_{r\beta}$, $x_5 = \Omega$

## Flux and Speed Integral Backstepping Controller Develop

*Command Aim*

Command's objective is to create a virtual command (suitable functions) that will facilitate a challenging nonlinear control dilemma. By dividing the control design into multiple steps, the process has been simplified. Each stage focuses on a particular input–output structure issue and serves as a model for the following stage. The ELF is employed incrementally to maintain global system stability and keeping track goals [22].

*Step One*

The desired tracks that the system must follow must be identified in this step. The controllers must also be designed to foster the best following accuracy. Rotor speed and rotor flux have reference trajectories that are defined by $\Omega_{ref}\ (x_5)\ and\ \varphi_{ref}^2\ (x_6)$.

The inaccuracy in velocity tracking error $e_1$ and the rotor flux modulus following the error may be commanded with the help of the auxiliary variables $\xi_1^d$ and $\xi_2^d$ respectively:

Following errors. are defined as follows:

(6) $$e_1 = x_{5ref} - x_5$$

(7) $$e_3 = x_{6ref} - x_6$$

With $$x_6 = x_3^2 + x_4^2$$

Their dynamics equations are given by:

(8) $$\dot{e}_1 = \dot{x}_{5ref} - \left[\frac{pM}{jL_r}(x_3x_2 - x_4x_1) - \frac{T_l}{j} - \frac{f}{j}x_5\right]$$

(9) $$\dot{e}_3 = x_{6ref} - \left[\frac{2M}{T_r}(x_3x_1 + x_4x_2)\right] + \frac{2}{T_r}x_6$$

The virtual command expressions are provided as follows:

(10) $$\xi_1 = \left[\frac{pM}{jL_r}(x_3x_2 - x_4x_1)\right]$$

(11) $$\xi_2 = \left[\frac{2M}{T_r}(x_3x_1 + x_4x_2)\right]$$

Expressions corresponding to Equation (8) and (9) can be derived as follows:

(12) $$\dot{e}_1 = \dot{x}_{5ref} - \xi_1 + \frac{T_l}{j} + \frac{f}{j}x_5$$

(13) $$\dot{e}_3 = \dot{x}_{6ref} - \xi_2 + \frac{2}{T_r}x_6$$

The evaluation of stability for the tracking error dynamics relies on the subsequent Control Lyapunov Function (CLF):

(14) $$v_1 = \frac{1}{2}[e_1^2 + e_3^2]$$

The theoretical expression corresponding to Equation (15) represents the derivative of Equation (14).

(15) $$\dot{v}_1 = e_1\dot{e}_1 + e_3\dot{e}_3$$

The selection of the derivative error tracking has been made as below:

(16) $$\dot{e}_1 = -k_1e_1$$

(17) $$\dot{e}_3 = -k_3e_3$$

The minus sign associated with Equations (16) and (17) indicates that the Lyapunov function is negatively defined. Consequently, under these circumstances, the virtual command derived from expressions (12) and (13) can be expressed as follows:

(18) $$\xi_1^* = k_1e_1 + \dot{x}_{5ref} + \frac{T_l}{j} + \frac{f}{j}x_5$$

(19) $$\xi_2^* = k_3e_3 + \dot{x}_{6ref} + \frac{2}{T_r}\left(x_{6ref} - e_3\right)$$

$k_1$ and $k_3$ are positive gains that define the closed loop dynamics'.

The Lyapunov Function's time–varying derivative is certainly less than zero. Then the following errors $e_1$ and $e_3$ can reach a steady state regime.

We want to use the integral action to control the speed and flux of the system, but we cannot directly change the variables $\xi_1$ and $\xi_2$ because they have their dynamics. Therefore, we introduce the virtual controls $\xi_1^*$ and $\xi_2^*$ to make sure the speed and norm of flux loops are stable. The dynamics of the following errors are given by:

(20) $$\xi_1^d = \xi_1^* + \lambda_1\chi_1$$

(21) $$\xi_2^d = \xi_2^* + \lambda_2\chi_2$$

Let $\lambda_1$ and $\lambda_2$ are positive gains and let $\Im_i = \int_0^t e_i(\tau)d\tau$ $i = 1{,}2$ be the integral actions that are defined by the tracking error. By adding them to the virtual control, we guarantee that the error will converge to zero in steady state.

*Step two*

The goal of the command is to make the secondary variable $\xi_1$ follow $\xi_1^d$ and $\xi_2$ follow $\xi_2^d$. The final references are made to guarantee stable dynamics for tracking errors related to velocity and flux modulus. It is crucial to think about the errors between them for the virtual controls.

The consideration of errors between them is crucial for virtual commands. The objective command becomes: oblige the secondary variable $\xi_1$ to follow $\xi_1^d$ while $\xi_2$ has to follow $\xi_2^d$.

Let's specify the following errors in order to do this:

(22) $$e_2 = \xi_1^d - \xi_1 = \xi_1^* + \lambda_1\chi_1 - \xi_1$$

(23) $$e_4 = \xi_2^d - \xi_2 = \xi_2^* + \lambda_2\chi_2 - \xi_2$$

The time derivative of (22) and (23) gives:

(24) $$\dot{e}_2 = \dot{\xi}_1^d - \dot{\xi}_1 = \xi_1^* + \lambda_1e_1 - \dot{\xi}_1$$

(25) $$\dot{e}_4 = \dot{\xi}_2^d - \dot{\xi}_2 = \dot{\xi}_2^* + \lambda_2e_3 - \dot{\xi}_2$$

newly developed expressions (24) and (25) in function of new terms $e_2$ and $e_4$ are given as follows:

(26) $$\dot{e}_1 = -k_1e_1 + e_2$$

(27) $$\dot{e}_3 = -k_3 e_3 + e_4$$

From (24) and (25 It has become possible to obtain novel formulations of error dynamics.

(28) $$\dot{e}_2 = \xi_3 + \left[\frac{pK}{j}\left(x_3 u_{s\beta} - x_4 u_{s\alpha}\right)\right]$$

(29) $$\dot{e}_4 = \xi_4 - \left[2KR_r\left(x_3 u_{s\alpha} + x_4 u_{s\beta}\right)\right]$$

Where

$$\xi_3 = \dot{\xi}_1^d + \frac{pM}{jL_r}\left[\left(\gamma + \frac{1}{T_r}\right)(x_3 x_2 - x_4 x_1)\right] +$$

$$+\frac{pM}{jL_r}\left[x_5[(x_3 x_1 + x_4 x_2) + K x_6]\right]$$

Equations (28) and (29) demonstrate that the control term is a part of the error dynamics formula. Therefore, it is clear how the extended Lyapunov function is evident. This function can be seen in Relation (30).

(30) $$v_2 = \frac{1}{2}\left[e_1^2 + e_2^2 + e_3^2 + e_4^2\right]$$

When we compute equation (30)'s derivative, we get:

(31) $$\dot{v}_2 = -k_1 e_1^2 + e_1 e_2 - k_3 e_3^2 + e_3 e_4 - k_2 e_2^2$$
$$-k_4 e_4^2 + e_2\left(k_2 e_2 + e_1 + \xi_3 + \frac{pK}{j}\left(x_3 u_{s\beta} - x_4 u_{s\alpha}\right)\right)$$
$$+e_4\left(k_4 e_4 + e_3 + \xi_4 - 2KR_r\left[2KR_r\left(x_3 u_{s\alpha} + x_4 u_{s\beta}\right)\right]\right)$$

Where $k_2$ and $k_4$ are the positive constant that determine the closed loop's dynamics.

Finding the following expression will guarantee that the CLF derivative is semi–negative definite:

(32) $$\dot{v}_2 = -k_1 e_1^2 - k_3 e_3^2 - k_2 e_2^2 - k_4 e_4^2 \leq 0$$

The selection of the voltage control is as follows:

(33) $$k_2 e_2 + e_1 + \xi_3 + \frac{pK}{j}\left(x_3 u_{s\beta} - x_4 u_{s\alpha}\right) = 0$$

(34) $$k_2 e_2 + e_1 + \xi_3 + \frac{pK}{j}\left(x_3 u_{s\beta} - x_4 u_{s\alpha}\right) = 0$$

As a result, the following control expressions are provided:

(35) $$u_{s\alpha} = \frac{1}{x_6}\left[\frac{(\xi_4 + e_3 + k_4 e_4)}{2KR_r} x_3 - \frac{j}{pK}\left[\xi_3 + e_1 + k_2 e_2\right] x_4\right]$$

(36) $$u_{s\beta} = \frac{1}{x_6}\left[\frac{(\xi_4 + e_3 + k_4 e_4)}{2KR_r} x_4 + \frac{j}{pK}\left[\xi_3 + e_1 + k_2 e_2\right] x_3\right]$$

**Nonlinear Observer Using the Circle Criteria Method**

The structure of the nonlinear observer that utilizes the circle criterion adopted in this study to estimate the rotor's flux and speed is the focus of this section. Arcak and Kokotovic came up with the first version of this observer [21] [19]. It works for continuous systems that can be split into linear and nonlinear parts, as long as the nonlinearities meet the sector property [21]. The advantage of this approach is to treat system nonlinearities with less restrictive conditions [25] [26], [27] [28]. The essential theory and theorems used in the design of the nonlinear observer are illustrated as the following [21–23, 30].

The nonlinear model (1) – (2) of the IM can be rewritten as:

(37) $$\frac{dx(t)}{dt} = Ax(t) + \psi[(u(t), y(t))] + N.\varphi[M.x(t)]$$

(38) $$y(t) = Cx(t)$$

Where:
$x \in \mathbb{R}^n$ is the state matrix, $y \in \mathbb{R}^p$ is the ouput of the system and $u(t) \in \mathbb{R}^m$ is the control vector. *A*, *C*, and *N* are assumed to be known constant matrices with appropriate dimensions provided that the system must be observable.

In addition, $\psi[(u(t), y(t))]$ is a random real–valued vector that solely depends on the inputs and outputs of system, $u(t)$ and $y(t)$ respectively. The last term of the system (37) $\varphi[M.x(t)]$ which is a vector function that varies over time, thus confirming the sector property represents the mathematical model of the nonlinear part of the system. We note that $\phi(.)$ and $\psi(.)$ are locally Lipchitz.

A primary restriction stating that the nonlinear observer's function is a non–decreasing function $\phi(.)$ is a requirement for its structure.

This restriction means that:

$$(\zeta - \xi)[\varphi(\zeta, t) - \varphi(\xi, t)] \geq 0 \ \forall \zeta, \xi \in R^+$$

With:
$\phi(\eta, t)$ is a nonlinearity function.

(39) If $\zeta - \xi = \eta$ and $[\varphi(\zeta, t) - \varphi(\xi, t)] = \varphi(\eta, t)$

such as $\phi(\eta, t): [0 + \infty[ \times \mathrm{R}^p \rightarrow \mathrm{R}^p$ is claimed to relate to the sector $[0 \ +\infty[$ if $\eta\phi(\eta, t) \geq 0$.

The previous equation is also equal to the following if $\varphi(\eta, t)$ is a continuously differentiable function. [23, 24]:

(40) $$\frac{d}{d\eta}\eta\varphi(\eta, t) \geq 0 \cdots \forall \eta \in R$$

According to these restrictions, the observer will therefore be given as follows:

$$\frac{d\hat{x}(t)}{dt} = A\hat{x}(t) + \psi[u(t), y(t)] + T[y(t) - \hat{y}(t)]$$

(41) $$+N\phi[M\hat{x}(t) + K_o(y(t) - \hat{y}(t))]$$

With: $\hat{x}(t)$ and $\hat{y}(t)$ are the estimate of the state $x(t)$ and the output $y(t)$ vector respectively.

The state estimation error $e(t)$ is computed as a difference between the state $x(t)$ and state estimation.

The gain matrices T and $K_o$ are determined as part of the nonlinear observer dynamic.

In order to carry out the previous observer, the main theorem and the conditions used in this work are recalled while adhering to the sector property as follows:

**Theorem 1:** In accordance with [25], [28], if we take into consideration a nonlinear system described by equations (37) and (38) with the nonlinear part satisfying the equations of the circle criterion provided by equations (39) and (40). Existance of an ensemble of row vectors $K_0 \in R^p$ and a symmetric, positive definite matrix $S \in R^{nxn}$ , must be verify the following linear matrix inequalities (LMI) [21], [24]:

$$(A - TC)^T S + S^T (A - TC) + Q \leq 0 \tag{42}$$

$$PN + (M - K_o C)^T = 0 \tag{43}$$

$Q = \varepsilon I_n$ : Positive gain matrix,
$I_n$ : The identity matrix,
$\varepsilon$ : A positive real number.

From equations (41), (42), and (43), how the state observation error e (t) changes over time can be derived as follows:

$$\frac{de(t)}{dt} = (A - TC)e(t) + N.[\phi(M.x(t)) - \\ - \phi(M.\hat{x}(t) + K_o(y(t) - \hat{y}(t))] \tag{44}$$

Let $\zeta = M.x(t)$ , and $\xi = M.\hat{x}(t) + K_o(y(t) - \hat{y}(t)$ by taking:

$\eta = \zeta - \xi = (M - K_o C)e(t)$

Equation (10) provides the variations of the state estimation error, which may be viewed as a function of the variable and then: $[\varphi(\zeta) - \varphi(\xi)] = \varphi(\eta, t)$.

Thereafter, taking into consideration the prior outcome, the error variations become:

$$\frac{de(t)}{dt} = (A - TC)e(t) + N.h(z,t) \tag{45}$$

$$\eta = (M - K_o C)e(t) \tag{46}$$

From equations (45) and (46), we notice that the design issue of the nonlinear estimator is similar to the stabilization of the dynamics error.

Using a CLF $V = e^T Se$, the stability of the observer error variations is investigated.

The time derivative of the Lyapunov function is expressed as follows:

$$\frac{dV}{dt} = \dot{e}^T Se + e^T S\dot{e} \tag{47}$$

Equations (45) and (46) can be used to get the derivative of the Lyapunov function as follows:

$$(A - TC)^T S + S^T (A - TC) \leq -Q \tag{48}$$

And

$$SN = -(M - K_o C)^T \tag{49}$$

The derivative of the Lyapunov function can be written as follows:

$$\frac{dV}{dt} \leq -e^T Qe - 2.z^T.\phi(\eta, t) \tag{50}$$

The circle criterion has the benefit of handling the system's nonlinearities directly and with less limitation. However, this strategy introduces LMI's limitations.

## Simulation findings and discussion

To highlight the benefits of our proposed study, we examine an IM along with its relevant characteristics, as detailed in Table 1. Additionally, the simulation block diagram for the nonlinear command, combined with a nonlinear observer for the IM model, is depicted in Figure 1. To execute the simulation of our present scheme, two essential steps are involved:

Observation of the State Variable Vector: This step relies on input voltages and output currents.

Utilization of observed Variables for control design : We utilize the estimated variables to calculate the designed control strategy.

Table 1: Induction motor parameters

| Nomination | Definition | Numerical Values |
|---|---|---|
| $P_a$ | Nominal Power | 1.5 kW |
| F | Operating frequency | 50 Hz |
| P | Pair pole number | 220 V |
| U | Supply | 4.85 Ω |
| $R_s$ | Stator resistance | 3.85 Ω |
| $R_r$ | Stator inductance | 0.274 H |
| $L_s$ | Rotor inductance | 0.274 H |
| $L_r$ | Stator inductance | 0.258 H |
| $M$ | Mutual inductance | 0.258 H |
| $\omega$ | Rotor angular velocity | 148.625 rd/s |
| $J$ | Innertia coefficient | 0.0031 Kg²/s |
| $f$ | Friction coefficient | 0.00114N .s/rd |
| $T_l$ | Load Torque | 5 N.m |

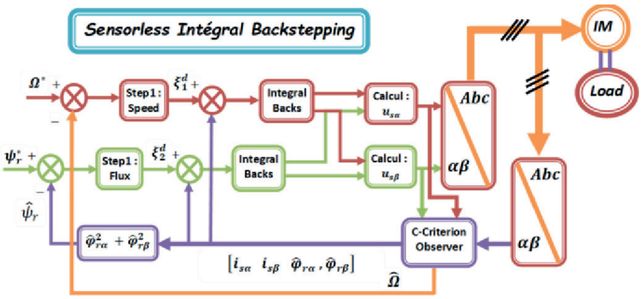


Fig. 1. Block diagram model of the suggested Control

To evaluate the regulation capacity of our controller, we carried out the speed trajectory tracking simulation tests. A test in acceleration and deceleration mode (trapezoidal) is carried out loaded and at reverse speed to observe the performance of this technique during this mode.

For the tracking, we set as admissible trajectory for the speed ramps ∓150 rd/s. Figures (2,3, and 4) show the following of the mechanical rotor speed and electromechanical torque), magnetic (flux and its norm) and electrical (currents) quantities as well as their estimation errors, under the integral Backstepping control without sensor using the circular criterion observer. This tracking is obtained with almost perfect performance despite the application of load torque and a variable trjectory of speed. Figures (3) show the norm flux tracking; the results are given compared with their estimated quantities, returning to this figure we notice that the decoupling is ideal between the flux and the torque despite the speed profile and the applied load torque. As a concululsion we can say that the simulation results obtained show a perfect superposition of the trajectories of the speed and flux norm curves, a good tracking of the torque but with some peaks caused by the injection of the observer and same for the stator currents, while keeping the separation between the torque and the flux.

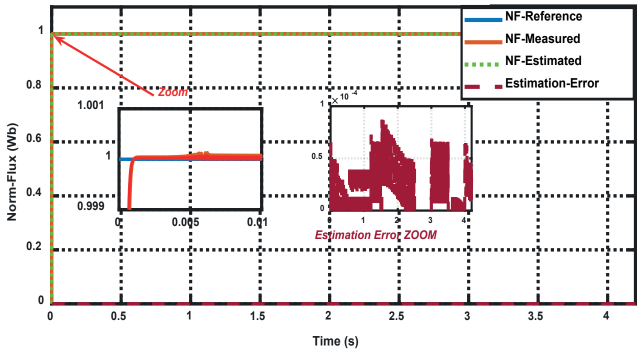


Fig. 3. Reference, Real, Observed and Estimation Error of the rotor flux norm under variations.

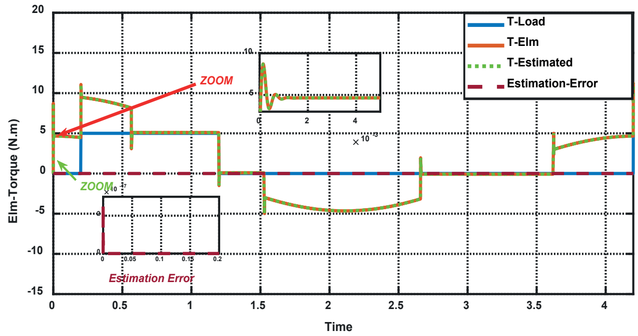


Fig. 4. Changes in Load, Real and Observed Mechanical Torque.

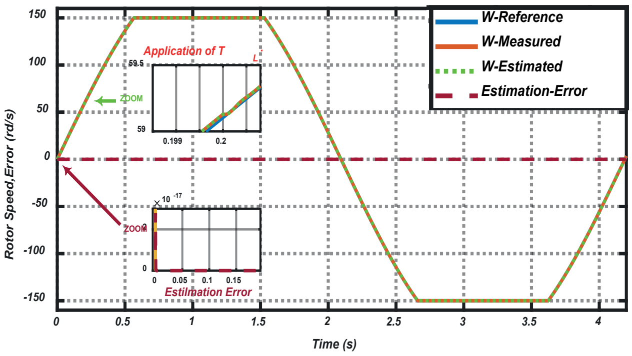


Fig. 2. Reference, Measured, Estimated and Estimation Error evolution of Rotor speed according to variations.

## Conclusion

This manuscript introduces a new control scheme based on the Integral Backstepping control strategy (IBC) combined with the circle criterion observer (CCO). We use the Lyapunov function to ensure the stability of the global system (IM+observer), despite its nonlinearity. The proposed technique is tested via simulation under various operating conditions of the machine, specifically when the load and speed are changing, at constant, increasing, and decreasing speeds, and when the motor's rotor resistance is dynamically changing. The Simulation findings indicate that the suggested control technique achieves high performance and guarantees the ideal decoupling of torque and flux, also it shows that the observer correctly estimates the non–measurable variables, and it presents better performances in terms of, trajectory tracking, disturbance rejection, absence of oscillations and especially during transient regimes. The CCO can handle the system's nonlinearity directly with less restriction, but it requires solving linear matrix inequalities (LMIs). Experimental studies are envisioned as potential directions for future work.

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