Implementing Non-Linear Control for the Three-Phase Asynchronous Machine via Status Feedback

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ABSTRACT

This paper focuses on the implementation of a nonlinear control technique called control by state feedback for regulating the speed of a three-phase asynchronous motor. The unique aspect of this approach is the utilization of nonlinear state feedback, resulting in an interconnected mathematical structure. The main advantage of this control technique is its ability to ensure robustness against abrupt parametric variations in the motor, particularly during full load or prolonged traction tasks. To demonstrate the effectiveness of the proposed control, a series of simulations were conducted using the MATLAB-SIMULINK environment. These simulations highlighted the robustness, stability, and reliability of the control strategy. Overall, the study showcases the application of nonlinear control by state feedback as a viable solution for controlling the speed of three-phase asynchronous motors, offering enhanced resilience in the face of varying operational conditions.

I. Introduction

Achieving high-performance electric actuation using AC motors necessitates the application of advanced control strategies. In particular, the control of three-phase asynchronous motors requires careful consideration of their nonlinear state structure. To address this challenge, various control techniques have been developed, and one promising approach is the technique of linearization by state feedback [1]. This method, which is a recent advancement in the control of nonlinear systems, involves transforming nonlinear dynamical systems into linear ones through the identification of appropriate state transformations.

In this paper, we explore the implementation of the input-output linearization technique by state feedback to develop nonlinear control strategies specifically derived from the motor model. The primary motivation behind this endeavor is to address the increasing demand for efficient control techniques for three-phase asynchronous motors, given their growing prominence in industrial applications. These motors are finding applications in diverse fields, such as robotics, vehicles, and are even being considered as alternatives to hydraulic and pneumatic actuators in aerospace and metro ports [2, 3]. This widespread adoption is mainly due to their advantages, including low manufacturing costs, robustness, and reliability. Notably, the inherent short-circuiting of the windings in asynchronous motors eliminates the need for an external power supply, further enhancing their appeal [4].

Despite their advantages, controlling asynchronous motors presents several challenges. The fundamental model of these motors is inherently nonlinear and characterized by strong coupling, which contrasts with their structurally simple design. Moreover, the accurate estimation of motor parameters is often challenging, as they are subject to variations over time, such as changes in temperature [5, 6]. The presence of modeling uncertainties and measurement noise further complicates the control process. In response to these complexities, extensive research has been conducted in recent decades, with a particular focus on vector control and nonlinear control techniques for asynchronous motors [7, 8].

The theory of control by nonlinear state feedback has undergone significant advancements and is rooted in the principles of differential geometry, specifically applied to the control of nonlinear systems. Of particular interest is the technique of linearization by state feedback with input-output decoupling, which has exhibited promising results across various applications. This approach aims to transform multi-input nonlinear systems into linear systems by employing suitable linearizable state feedback, thereby achieving input-output decoupling [9]. By leveraging established techniques from linear systems theory, this methodology simultaneously ensures linearity and effective decoupling between torque and flux, two crucial variables in motor control [10].

The main objective of this study is to introduce a novel technique, referred to as nonlinear control type linearization by state feedback, which offers practical applicability without requiring an excessively intricate mathematical background. The intention is to develop a control approach that is accessible and feasible for real-world implementation. By utilizing a mathematical foundation comparable to existing techniques, this novel approach seeks to bridge the gap between theoretical advancements and practical utilization, making it more accessible to control engineers and practitioners [10]. In conclusion, the control of three-phase asynchronous motors for high-performance electric actuation demands the utilization of advanced control strategies. The technique of linearization by state feedback has emerged as a promising approach for addressing the nonlinear nature of these motors. Through appropriate state transformations, this technique allows for the transformation of nonlinear systems into linear ones, facilitating the application of established linear control methods. By introducing a new variant of this technique, this paper aims to enhance the practicality and accessibility of nonlinear control for three-phase asynchronous motors, thereby promoting their effective utilization in various industrial applications.

II. Non-Linear Model of The Induction Motor

In order to improve the control by flux orientation, and knowing that it is necessary to wait until the flux has reached a constant reference to be able to adjust the speed, an exact input output linearization with decoupling has been developed for the asynchronous machine controls.

We rewrite the model of the asynchronous motor in the “Clarck” two-phase frame, given by equation as follows [7]:

$$\begin{cases} \dot{x} = f(x) + g(x).U \\ y = h(x) \end{cases} \quad (1)$$

With:

$\begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T = \begin{bmatrix} i_{s\alpha} & i_{s\beta} & \Phi_{r\alpha} & \Phi_{r\beta} \end{bmatrix}^T$: The state vector or state variable.

$U = \lfloor U_{s\alpha} \quad U_{s\beta} \rfloor$: Variables de commande.

y: selected output

h(x): is an analytic function

Such as :

$$f(x)=\begin{bmatrix} f_1(x)\\ f_2(x)\\ f_3(x)\\ f_4(x)\end{bmatrix}=\begin{bmatrix} R_t.x_1+\frac{1-\sigma}{\sigma}.\frac{1}{T_r.M}.x_3+\frac{1-\sigma}{\sigma}.\frac{1}{M}.x_4\\ R_t.x_2-\frac{1-\sigma}{\sigma}.\frac{1}{M}.x_3+\frac{1-\sigma}{\sigma}.\frac{1}{T_r.M}.x_4\\ \frac{M}{T_r}.x_1-\frac{1}{T_r}.x_3-\omega.x_4\\ \frac{M}{T_r}.x_2+\omega.x_3-\frac{1}{T_r}.x_4 \end{bmatrix} \quad (2)$$

With: $R_t=-(\frac{1}{\sigma.T_s}+\frac{1}{T_r}.\frac{1-\sigma}{\sigma})$

$$g(x)=[g_1(x) \quad g_2(x)].\begin{bmatrix} \frac{1}{\sigma.L_s} & 0\\ 0 & \frac{1}{\sigma.L_s}\\ 0 & 0\\ 0 & 0\end{bmatrix} \quad (3)$$

III. Control By Status Feedback Of The Three-Phase Asynchronous Machine

III.1. Choice Of Output Variables

The choice of output variable is a delicate case for the principle of linearization by decoupling by state feedback. A poor choice of outputs is a main obstacle to the implementation of this linearization method. We would then be in the case where the the decoupling matrix E(x) is non-invertible, in which case the command is rejected.

If we want to control the electromagnetic torque as well as the square of the flux modulus, the output vector will be:

$$y=\begin{bmatrix} h_1(x)\\ h_2(x)\end{bmatrix}=\begin{bmatrix} \frac{1}{2}(\Phi_{r\alpha}{}^2+\Phi_{r\beta}{}^2)\\ p.\frac{M}{L_r}.(i_{s\beta}.\Phi r_\alpha-i_{s\alpha}.\Phi_{r\beta})\end{bmatrix} \quad (4)$$

Likewise, if we want to control the flux and the speed, the output vector will be:

$$y=\begin{bmatrix} h_1(x)\\ h_2(x)\end{bmatrix}=\begin{bmatrix} \frac{1}{2}(\Phi_{r\alpha}{}^2+\Phi_{r\beta}{}^2)\\ \Omega\end{bmatrix} \quad (5)$$

In the first choice (torque and flux), the command is used to control the current inrush of the machine by acting on the torque. Unlike the second choice (flux and speed), the current therefore becomes inaccessible to control.

III.2. Speed And Flow Control

The linearization condition allowing to check if a nonlinear system admits an input-output linearization is the order of the relative degree of the system. For a first case, the variable to be controlled is the speed and the flux given by equation (5).

To obtain the nonlinear control law, we calculate the relative degree of the output y. i.e. the number of times it is necessary to derive the output in order to make the input U appear.

The chosen output variations are given by equation (5) such that:

$$\begin{cases} h_1(x) = y_1 = \frac{1}{2}.(\Phi_{r\alpha}^2 + \Phi_{r\beta}^2) \\ h_2(x) = y_2 = \Omega \end{cases} \tag{6}$$

• Degree relative to the output is already calculated on the screen r=2.

• Degree relative to the output (speed).

$$\dot{h}_2(x) = L_f h_2(x) + L_g h_2(x).U$$

$$= \frac{C_e - C_r}{J} - f.\frac{\Omega}{J} = \frac{p.\frac{M}{L_r}(x_2.x_3 - x_1.x_4) - C_r}{J} - f.\frac{\Omega}{J} \tag{7}$$

With: $L_g h_2(x) = 0$

The Lie derivative of $h_2(x)$ relative to g is zero.

$$h_2(x) = L_f h_2(x)$$

We will derive a second time:

$$\ddot{h}_2(x) = L_f^2 h_2(x) + L_g L_f h_2(x).U \tag{8}$$

After all the calculations, we obtain:

$$L_f^2 h_2(x) = -\frac{p}{L_r.J}.(\frac{1-\sigma}{\sigma}).\omega.(x_3^2 + x_4^2) - \frac{p.M}{L_r.J}.\omega.(x_1.x_3 + x_2.x_4) + (\frac{p.M}{L_r.J}.(\frac{1}{T_r} - R_t) + \frac{f}{J^2}).(x_1.x_4 - x_2.x_3) + \frac{f}{J^2}.C_r + \frac{f^2}{J^2}.\Omega \tag{9}$$

With:

$$L_f L_g h_2(x) = \begin{bmatrix} -\frac{p.M}{L_r.L_s.\sigma.J}.x_4 & \frac{p.M}{L_r.L_s.\sigma.J}.x_3 \end{bmatrix} \tag{10}$$

Through the Lie derivative, the relative degree of the velocity is $r_2 = 2$ and that of the flux is $r_1 = 2$, then the relative degree of the system is $r = r_1 + r_2 = 4 = n$ so the system is completely linear

The output derivatives are given by:

$$\begin{bmatrix} \ddot{h}_1(x) \\ \ddot{h}_2(x) \end{bmatrix} = \begin{bmatrix} L_f^2 h_1(x) \\ L_f^2 h_2(x) \end{bmatrix} + E'(x).\begin{bmatrix} U_{s\alpha} \\ U_{s\beta} \end{bmatrix} \tag{11}$$

With :

$$E'(x) = \begin{bmatrix} L_{g1} L_f h_1(x) & L_{g2} L_f h_1(x) \\ L_{g1} L_f h_2(x) & L_{g2} L_f h_2(x) \end{bmatrix} \tag{12}$$

The determinant is given by:

$$\det E'(x) = p.\frac{M^2}{(L_s.\sigma)^2.T_r.L_r.J}.(x_3^2 + x_4^2)$$

The determinant of $E'(x)$ is non-zero except when the motor is stationary; So, the matrix $E'(x)$ is reversible.

In this case, we can derive $[U_{s\alpha} \;\; U_{s\beta}]^T$ from equation (11) as follows:

$$\begin{bmatrix} U_{s\alpha} \\ U_{s\beta} \end{bmatrix} = [E'(x)]^{-1}.\begin{bmatrix} -L_f^2 h_1(x) + v_1 \\ -L_f^2 h_2(x) + v_2 \end{bmatrix} \qquad (13)$$

If the determinant of the decoupling matrix is nonzero, the nonlinear control law is defined by a relation that relates the new internal inputs (v_1, v_2) to the physical inputs $(U_{s\alpha}, U_{s\beta})$.

This command linearizes and decouples the system such that:

$$\begin{cases} \ddot{h}_1(x) = v_1 = \ddot{y}_1 \\ \ddot{h}_2(x) = v_2 = \ddot{y}_2 \end{cases} \qquad (14)$$

III.3. Pole Imposition Control Algorithm

As already given in (14), and to ensure perfect flux and torque regulation towards their respective reference Φ_{ref} and C_{ref} , these variations v_1 and v_2 are calculated as follows:

$$\begin{cases} v_1 = \ddot{\Phi}_{ref} + \beta_{11}.(\dot{\Phi}_{ref} - \dot{\Phi}_r) + \beta_{12}.(\Phi_{ref} - \Phi_r) \\ v_2 = \ddot{\Omega}_{ref} + \beta_{21}.(\dot{\Omega}_{rerf} - \dot{\Omega}) + \beta_{22}.(\Omega_{ref} - \Omega) \end{cases} \qquad (15)$$

In closed loop the following error is:

$$\begin{cases} \ddot{e}_1 + \beta_{11}.\dot{e} + \beta_{12}.e_1 = 0 \\ \ddot{e}_2 + \beta_{21}.\dot{e}_2 + \beta_{22}.e_2 = 0 \end{cases} \qquad (16)$$

With:

$$\begin{cases} e_1 = \Phi_{ref} - \Phi_r \\ e_2 = \Omega_{ref} - \Omega \end{cases}$$

The coefficients β_{ij} are chosen such that the two polynomials $s^2 + \beta_{11}.s + \beta_{12}$ and $s^2 + \beta_{21}.s + \beta_{22}$ have roots with negative real part.

To keep the flux constant, for a looped system of the second order, we choose $\beta_{11} = 2.\zeta.\omega_0$ et $\beta_{12} = \omega_0^2$

IV. Simulation And Results

The figure below represents the flow-speed control simulation block diagram of the MAS, it includes the block diagrams of the machine and the nonlinear control as well as the block diagrams of the new inputs v_1, v_2.

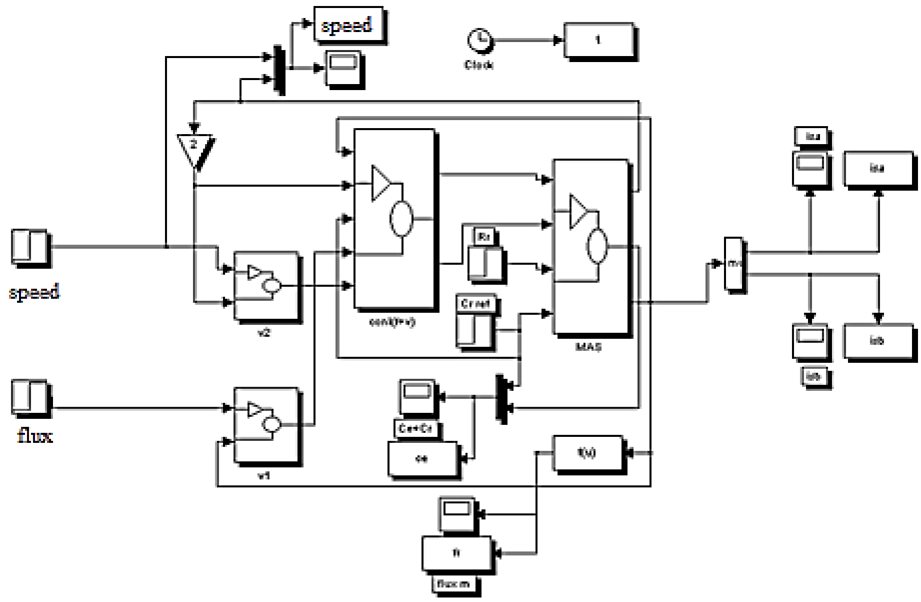

Figure 1. control simulation block diagram Flux-speed of the MAS

IV.1. Results Interpretation

- **No-Load And Load Operation Of The MAS**

As we see in the figure concerning the speed, the evolution of the speed takes the linear form with a negative drop in the first instant of the application of the load, after this instant the speed is established in steady state.

The torque characteristic illustrates the high torque at the first instants of starting, especially when operating under load.

At the first moments of starting, the stator currents show excessive overruns at low speed, but they disappear after a few half cycles and a sinusoidal shape of constant amplitudes and frequency corresponding to the imposed load is obtained.

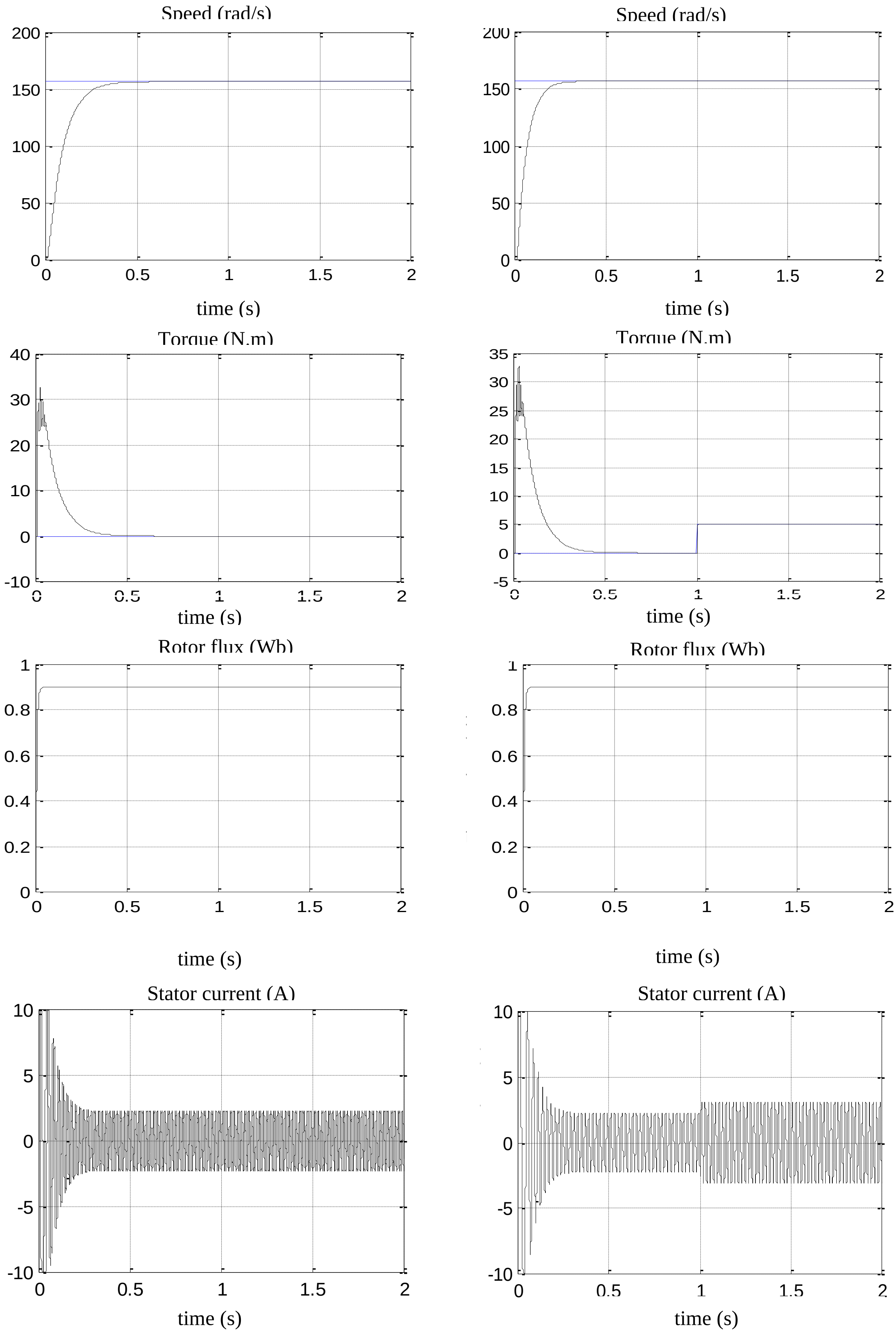
Speed (rad/s)
time (s)
Speed (rad/s)
time (s)
Torque (N.m)
time (s)
Torque (N.m)
time (s)
Rotor flux (Wb)
time (s)
Rotor flux (Wb)
time (s)
Stator current (A)
time (s)
Stator current (A)
time (s)

Figure 2. Simulation results of no load and load operation.

- **Robustness test for speed variation**

The tests are carried out under the conditions, operating under load (Cr = 5 N.m), the nominal rotor resistance (Rr = 1.8 Ω), are applied at the moment of starting

From the results illustrated in figure (4.9) we notice that the speed followed the desired reference values, the torque present significant peaks during speed variation.

Reduction of the flow at the moment of the overspeed variation, at the end of this variation it returns to its desired value. The current curve presents significant peaks at the time of speed variations.

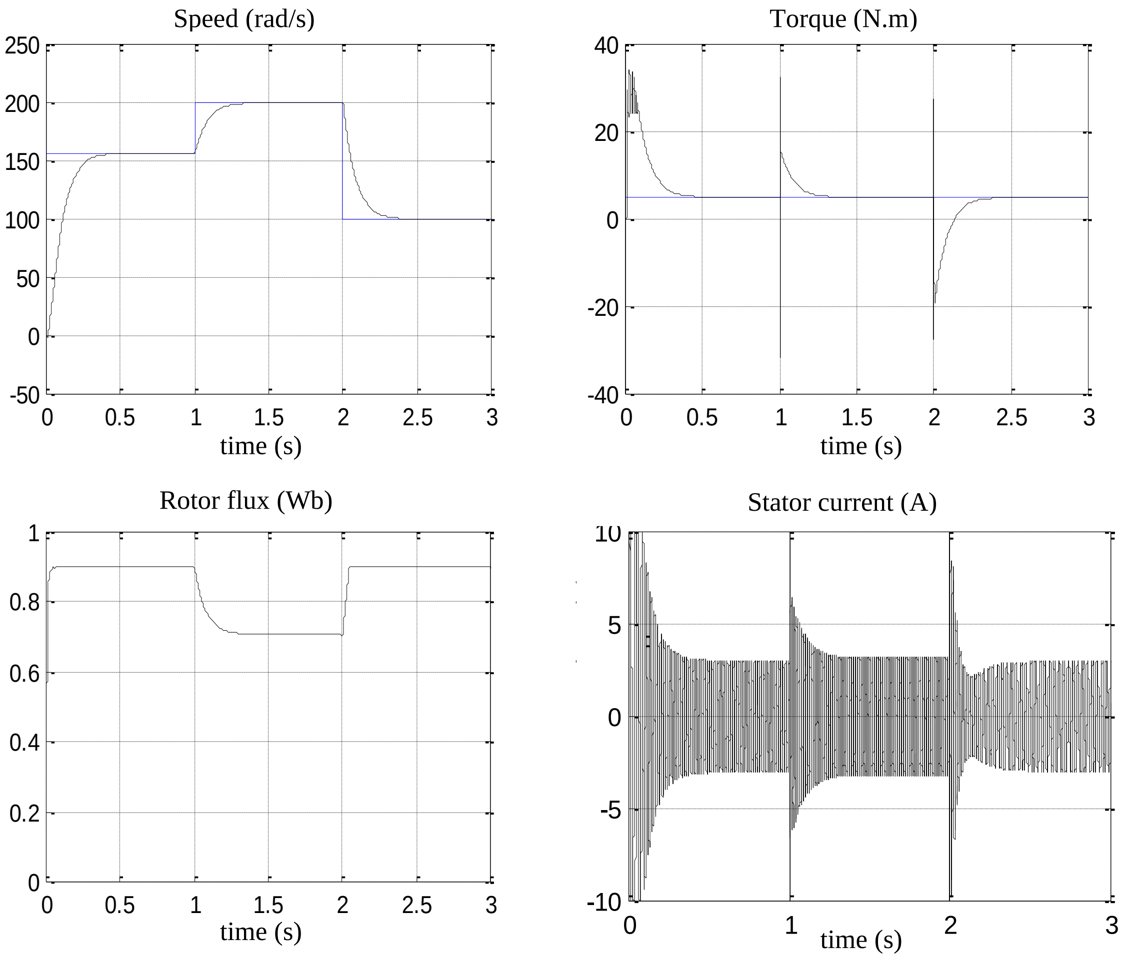

Figure 3. Robustness test results for speed variation.

- **Robustness test for speed inversion**

The tests carried out under the same conditions as the speed variation test. At the moment of the speed inversion, we notice that the speed followed the pace of the reference speed.

The torque presents a significant peak then stabilizes at the torque value imposed by the load on the motor shaft. The stator currents also show a significant peak with successive oscillations but they stabilize after a few alternations.

At the moment of speed variation. The flux decreases slightly then stabilizes at its value quickly, so the decoupling is still there.

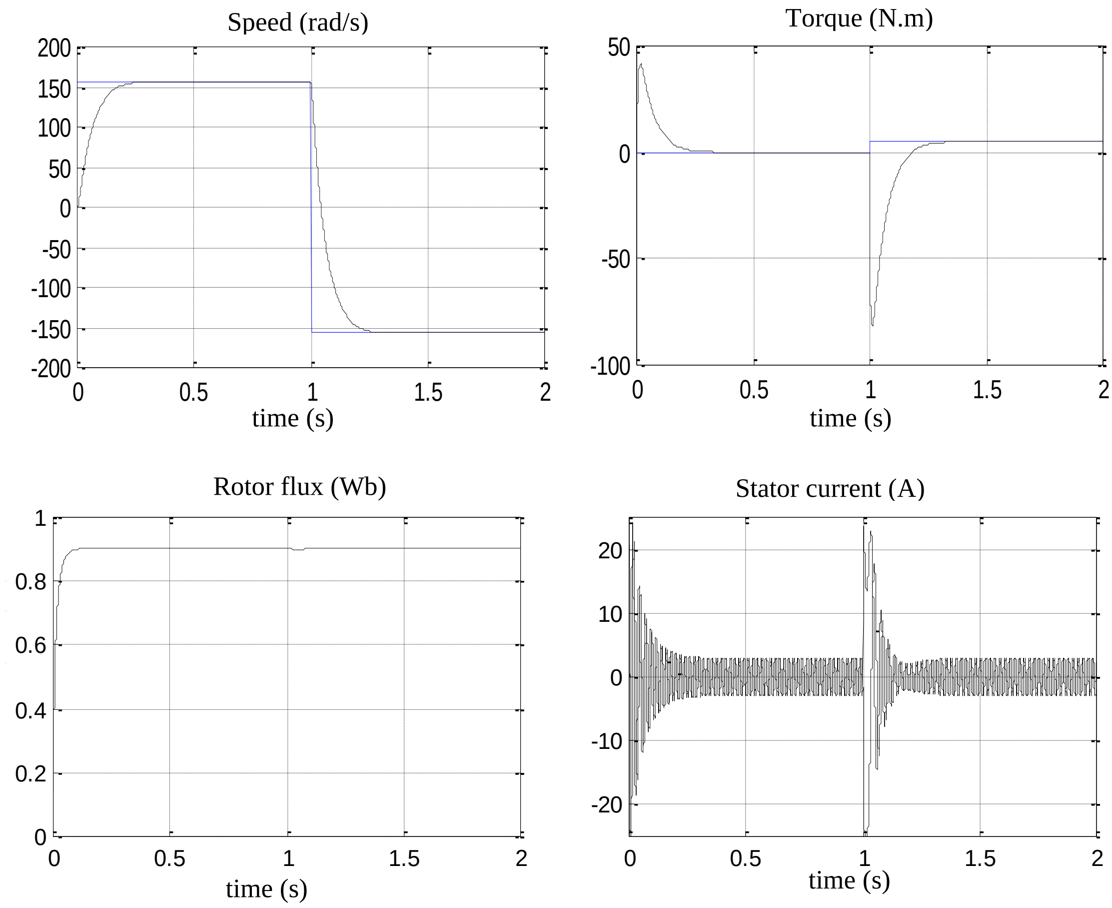

Figure 4. Robustness test results for speed reversal

V. Conclusion

The obtained results for the flux-speed control mode of the three-phase asynchronous machine (MAS) demonstrate that the application of nonlinear control ensures the decoupling of torque and flux quantities. Consequently, the asynchronous machine can be effectively controlled in a manner similar to a separately excited DC machine. It is worth noting that the MAS studied in this research exhibits parameter variations, such as resistances and inductances, and is subject to external disturbances, including load variations. Therefore, the primary objective of this study is to develop robust algorithms for efficient control of the asynchronous machine, considering these varying parameters and external disturbances.

By utilizing the properties of the nonlinear control technique known as linearization by state feedback, the need for additional algorithms for parametric identification is eliminated. The focus is on presenting the results obtained for speed control of the MAS using this type of control strategy. However, it is important to acknowledge a significant drawback associated with this control approach, which stems from the challenges in selecting appropriate regulator parameters. The placement of poles method, which is commonly used for regulator parameter determination, has proven difficult to apply in this context.

In summary, the research aims to design robust control algorithms for the efficient control of the three-phase asynchronous machine, considering parameter variations and external disturbances. The application of nonlinear control, specifically the linearization by state feedback approach, enables decoupling of torque and flux quantities, enhancing controllability. However, challenges arise in selecting regulator parameters, as the conventional method of pole placement faces difficulties in this control context.

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