



A NOVEL LYAPUNOV BACKSTEPPING APPROACH TO CONTROLLING MECHANICAL POWER IN INDUCTION MOTORS

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ABSTRACT

In this work, a novel Lyapunov backstepping control law (LBC) is introduced, which allows for robust and stable regulation of the mechanical power produced by an induction motor (IM). The stator variables supply this induction motor through two converters. One, a motor converter (two-level inverter), allows for exact control and optimization of the energy flow during motor operation; the other, a mains converter (two-level rectifier), makes it easier to manage the direct current (DC) bus and increases the mains power factor. We demonstrated the modeling of our motor and its converters in the first section. The control structure that was suggested to regulate and maximize the mechanical energy produced by our motor (speed, torque) in order to attain optimal efficiency and transfer quality was presented in the second section. The outcomes of the numerical simulations show how well the new Lyapunov control system achieves these goals: electromagnetic torque below the nominal torque and mechanical speed side its references.



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I. INTRODUCTION

Induction machines play a key role in industry and are currently widely used for variable speed or positioning applications [1-3]. These machines have the advantage of being robust and inexpensive. However, despite these advantages, the control of induction machines is very complicated because their basic mathematical model is non-linear and their parameters are only approximately known and can vary over time. Current research is aimed at making the control of these machines simpler and more reliable [4-6]. The induction machine has several control techniques (scalar control, sliding mode control, vector control.). Each control technique poses a problem in terms of guaranteeing the stability of the system because its basic model is non-linear and highly coupled, which is the opposite of the simplicity of its structure. This model is also complicated by the fact that the parameters of the induction motor are only approximately known and can vary over time. In our work, we use a new control technique called BACKSTEPPING to improve the control of the machine [7] [8]. The backstepping technique is one of the new methods in this field. It provides a systematic method for designing a controller for nonlinear systems. The main advantage of this method is that it guarantees the stability of the control system [9] [10]. This paper develops a new Lyapunov control technique to control the mechanical power produced by the induction motor. This control technique guarantees the robustness and stability of our control system with a remarkable improvement in the convergence of the errors towards zero. The rest of this article is structured as follows: The next section presents the mathematical model of the induction motor and its converters. In section 2, we present the DPC control based on PI controllers. In section 3, we present simulation results that show the efficiency and robustness of the control developed to control the mechanical power generated by our induction motor. Finally, the paper will conclude with a conclusion.

II. MODELLING OF THE INDUCTION MOTOR AND ITS CONVERTERS

To simulate the behavior of the IM and develop a control technique for it, we need to model both the motor and its converters separately.

- The induction motor;

- The motor-side converter;
- The grid-side converter.

II.1 INDUCTION MOTOR MODEL

The induction machine is a very complex non-linear system, so applying our control to our machine requires more precise mathematical modelling to represent its behaviour in a satisfactory and realistic way [11-13].

$$\begin{cases} V_{s\alpha} = R_s i_{s\alpha} + \frac{d}{dt} \Phi_{s\alpha} \\ V_{s\beta} = R_s i_{s\beta} + \frac{d}{dt} \Phi_{s\beta} \\ V_{r\alpha} = 0 = R_r i_{r\alpha} + \frac{d}{dt} \Phi_{r\alpha} + \omega_r \Phi_{r\beta} \\ V_{r\beta} = 0 = R_r i_{r\beta} + \frac{d}{dt} \Phi_{r\beta} - \Phi_{r\alpha} \omega_r \end{cases} \quad (1)$$

$$C_{em} = \frac{PM}{L_r} (\Phi_{r\alpha} i_{s\beta} - \Phi_{r\beta} i_{s\alpha}) \quad (2)$$

$$J \frac{d}{dt} \Omega + f \Omega = C_{em} - C_r \quad (3)$$

The aim is to obtain a system of equations written as an equation of state. The model will have the form :

$$\dot{[X]} = [A][X] + [B][U] \quad (4)$$

With:

$$\begin{cases} [X] = [i_{s\alpha} \ i_{s\beta} \ \Phi_{r\alpha} \ \Phi_{r\beta}]^T \\ [V] = [V_{s\alpha} \ V_{s\beta}]^T \end{cases} \quad (5)$$

$$[A] = \begin{bmatrix} -(\frac{1}{\sigma T_s} + \frac{M^2}{l_r T_r}) & 0 & \frac{M}{\sigma l_s l_r T_r} & \frac{M}{\sigma l_s l_r} \omega_r \\ 0 & -(\frac{1}{\sigma T_s} + \frac{M^2}{l_r T_r}) & -\frac{M}{\sigma l_s l_r} \omega_r & \frac{M}{\sigma l_s l_r T_r} \\ \frac{M}{T_t} & 0 & -\frac{1}{T_r} & -\omega_r \\ 0 & \frac{M}{T_r} & \omega_r & -\frac{1}{T_r} \end{bmatrix} \quad (6)$$

$$[B] = \begin{bmatrix} \frac{1}{\sigma l_s} & 0 \\ 0 & \frac{1}{\sigma l_s} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (7)$$

II.2. MOTOR SIDE CONVERTER MODEL

The voltage inverter is a converter that makes it possible to obtain an AC voltage of fixed or adjustable frequency and RMS value from a DC voltage source. It consists of switching cells, generally transistors for high power [14] [15].

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{E}{6} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (8)$$

II.3. GRID SIDE CONVERTER MODEL

In addition to its bidirectional power flow capability, the grid-side converter has the advantage of maintaining a stable DC bus voltage and setting the reactive power reference to zero. This helps to maintain grid quality by maintaining a unity power factor [16] [17].

$$\frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} + \frac{1}{L} \begin{bmatrix} V_1 - V_{an} \\ V_2 - V_{bn} \\ V_3 - V_{cn} \end{bmatrix} \quad (9)$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \frac{U_C}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (10)$$

$$\frac{U_C}{i_s} = \frac{R_{Ch}}{1 + R_{Ch} \cdot C \cdot p} \quad (11)$$

This inverter can be cascade controlled, with two inner loops to control the phase currents and an outer loop to control the output voltage [18] [19].

$$\begin{cases} V_{pd} = V_d - R i_d - L \frac{di_d}{dt} + L\omega i_q \\ V_{pq} = V_q - R i_q - L \frac{di_q}{dt} - L\omega i_d \end{cases} \quad (12)$$

$$\begin{cases} P = \frac{3}{2} \cdot [V_d I_d + V_q I_q] \\ Q = \frac{3}{2} \cdot [V_q I_d - V_d I_q] \end{cases} \quad (13)$$

We pose:

$$P_{ref} = U_{cmes} I_{red_ref} \quad (14)$$

$$Q_{ref} = 0 \quad (15)$$

III. LYAPUNOV BACKSTEPPING CONTROL

Backstepping control for nonlinear systems enables the design of a control law that ensures stability throughout the process. By expressing the states in a purely parametric form, the process's subsystems become more apparent. For each subsystem, a control is derived using a Lyapunov function to achieve stability. This involves treating the preceding state as the controllable variable. The order of the subsystem is then incremented, and the procedure is repeated. Ultimately, this approach yields a control law for the entire process [20] [21].

III.1. PRINCIPLE OF OUR CONTROL

The main idea behind Backstepping is to calculate a control law to ensure that the derivative of a certain (Lyapunov) function is defined as positive and that this derivative is always negative. The system is broken down into a set of nested subsystems of decreasing order. The Lyapunov function is then calculated recursively from inside the loop [22] [23].

III.2. APPLICATION OF OUR ORDER TO OUR IM

The application of the backstepping control to the induction machine requires the use of its model in the (α, β) reference frame in order to avoid the use of Park transformations. This approach is based on three steps to determine the control law given by the machine's stator voltages; before starting the calculation of the various steps, we group together the electrical, magnetic and mechanical equations in the following system.

$$\begin{cases} \frac{d\Omega}{dt} = \frac{\mu}{J} (\Phi_{r\alpha} i_{s\beta} - \Phi_{r\beta} i_{s\alpha}) - \frac{C_r}{J} \\ \frac{di_{s\alpha}}{dt} = \alpha \beta \Phi_{r\alpha} + P \beta \Omega \Phi_{r\beta} - \eta i_{s\alpha} + \frac{1}{\sigma L_s} V_{s\alpha} \\ \frac{di_{s\beta}}{dt} = \alpha \beta \Phi_{r\beta} - P \beta \Omega \Phi_{r\alpha} - \eta i_{s\beta} + \frac{1}{\sigma L_s} V_{s\beta} \\ \frac{d\Phi_{r\alpha}}{dt} = -\alpha \Phi_{r\alpha} - P \Omega \Phi_{r\beta} + \alpha M i_{s\alpha} \\ \frac{d\Phi_{r\beta}}{dt} = -\alpha \Phi_{r\beta} + P \Omega \Phi_{r\alpha} + \alpha M i_{s\beta} \end{cases} \quad (16)$$

With:

$$\alpha = \frac{R_r}{L_r}, \quad \beta = \frac{M}{\sigma L_s L_r}, \quad \eta = \frac{M^2 \cdot R_r + L_r^2 \cdot R_s}{\sigma L_s L_r^2}, \quad \mu = \frac{PM}{L_r}$$

Rotor flux is given by:

$$\overline{\Phi_r} = \Phi_{r\alpha} + j \cdot \Phi_{r\beta} = \sqrt{\Phi_{r\alpha}^2 + \Phi_{r\beta}^2} \cdot \left[\frac{\Phi_{r\alpha}}{\sqrt{\Phi_{r\alpha}^2 + \Phi_{r\beta}^2}} + j \cdot \frac{\Phi_{r\beta}}{\sqrt{\Phi_{r\alpha}^2 + \Phi_{r\beta}^2}} \right] \quad (17)$$

$$\overline{\Phi_r} = \sqrt{\Phi_{r\alpha}^2 + \Phi_{r\beta}^2} \cdot [\cos(\theta_s) + j \cdot \sin(\theta_s)] \quad (18)$$

The modulus of the flow and its derivative are given by:

$$\phi_r = \Phi_r^2 \quad (19)$$

$$\dot{\phi}_r = 2(\dot{\Phi}_{r\alpha} \Phi_{r\alpha} + \Phi_{r\beta} \dot{\Phi}_{r\beta}) \quad (20)$$

Step 1

In this step we consider the errors "e1", "e2" between the speed " Ω " and its reference " Ω_{ref} " and the rotor flux " ϕ_r " and its reference " ϕ_{ref} ".

$$\begin{cases} e_1 = \Omega_{ref} - \Omega \\ e_2 = \phi_{ref} - \phi_r \end{cases} \quad (21)$$

So the derivative of "e1", "e2" is given by:

$$\begin{cases} \dot{e}_1 = \dot{\Omega}_{ref} - \dot{\Omega} = \dot{\Omega}_{ref} - \frac{\mu}{J} (\Phi_{r\alpha} i_s - \Phi_{r\beta} i_{s\alpha}) + \frac{C_r}{J} \\ \dot{e}_2 = \dot{\Phi}_{ref} - \dot{\Phi}_r = \dot{\Phi}_{ref} + 2\alpha\Phi_r - 2\alpha M(i_{s\alpha}\Phi_{r\alpha} + i_{s\beta}\Phi_{r\beta}) \end{cases} \quad (22)$$

The chosen Lyapunov function is defined as follows:

$$V_1 = \frac{1}{2}(e_1^2 + e_2^2) \quad (23)$$

Then the stabilisation functions are given by:

$$\begin{cases} i_{s\beta} = \frac{J}{\mu\Phi_{r\alpha}} \left(k_1 e_1 + \dot{\Omega}_{ref} + \frac{C_r}{J} \right) + \frac{\Phi_{r\beta}}{\Phi_{r\alpha}} i_{s\alpha} \\ i_{s\alpha} = -\frac{J}{\mu\Phi_{r\beta}} \left(k_1 e_1 + \dot{\Omega}_{ref} + \frac{C_r}{J} \right) + \frac{\Phi_{r\alpha}}{\Phi_{r\beta}} i_{s\beta} \end{cases} \quad (24)$$

To obtain a negative derivative of the Lyapunov function, the reference currents must be chosen as follows:

$$\begin{cases} (i_{s\alpha})_{ref} = -\frac{J \sin(\theta)}{\mu\Phi_r} \left(k_1 e_1 + \dot{\Omega}_{ref} + \frac{C_r}{J} \right) + \frac{\cos(\theta)}{2\alpha M\Phi_r} (K_2 e_2 + \dot{\Phi}_r + 2\alpha\Phi_r) \\ (i_{s\beta})_{ref} = \frac{J \cos(\theta)}{\mu\Phi_r} \left(k_1 e_1 + \dot{\Omega}_{ref} + \frac{C_r}{J} \right) + \frac{\sin(\theta)}{2\alpha M\Phi_r} (K_2 e_2 + \dot{\Phi}_r + 2\alpha\Phi_r) \end{cases} \quad (25)$$

The error dynamics must be chosen by:

$$\dot{e}_1 = -k_1 e_1 \text{ et } \dot{e}_2 = -k_2 e_2 \quad (26)$$

Then the derivative of the Lyapunov function with respect to time becomes:

$$\dot{V}_1 = -k_1 e_1^2 - k_2 e_2^2 < 0 \quad (27)$$

With: $k_1 > 0$ and $k_2 > 0$

Step 2

In this step, we consider the errors "e3", "e4" between the currents "isq" and "isqref" and the currents "isd" and "isdref".

$$e_3 = (i_{s\beta})_{ref} - i_{s\beta} \quad (28)$$

$$e_3 = \frac{J \cos(\theta)}{\mu\Phi_r} \left(k_1 e_1 + \dot{\Omega}_{ref} + \frac{C_r}{J} \right) + \frac{\sin(\theta)}{2\alpha M\Phi_r} (K_2 e_2 + \dot{\Phi}_r + 2\alpha\Phi_r) - i_{s\beta} \quad (29)$$

$$e_4 = (i_{s\alpha})_{ref} - i_{s\alpha} \quad (30)$$

$$e_4 = -\frac{J \sin(\theta)}{\mu\Phi_r} \left(k_1 e_1 + \dot{\Omega}_{ref} + \frac{C_r}{J} \right) + \frac{\cos(\theta)}{2\alpha M\Phi_r} (K_2 e_2 + \dot{\Phi}_r + 2\alpha\Phi_r) - i_{s\alpha} \quad (31)$$

Then the derivative of the errors "e1" and "e2" become:

$$\begin{cases} \dot{e}_1 = -k_1 e_1 - \frac{\mu}{J} \Phi_r (e_4 \sin(\theta) - e_3 \cos(\theta)) \\ \dot{e}_2 = -k_2 e_2 + 2\Phi_r \alpha M (e_4 \cos(\theta) - e_3 \sin(\theta)) \end{cases} \quad (32)$$

Then the derivative of the errors "e3", "e4" will be of the form:

$$\begin{cases} \dot{e}_3 = (i_{s\beta})_{ref} - i_{s\beta} = (i_{s\beta})_{ref} - \delta_2 - \frac{1}{\sigma L_s} V_{s\beta} \\ \dot{e}_4 = (i_{s\alpha})_{ref} - i_{s\alpha} = (i_{s\alpha})_{ref} - \delta_1 - \frac{1}{\sigma L_s} V_{s\alpha} \end{cases} \quad (33)$$

We pose

$$\begin{cases} \delta_1 = \alpha\beta\Phi_{r\beta} - P\beta\Omega\Phi_{r\alpha} - \eta i_{s\beta} \\ \delta_2 = \alpha\beta\Phi_{r\alpha} + P\beta\Omega\Phi_{r\beta} - \eta i_{s\alpha} \end{cases} \quad (34)$$

Step 3

To calculate the control laws (stator voltages), we choose the Lyapunov function dependent on all the previous errors. This function is given by:

$$V_2 = \frac{1}{2}(e_1^2 + e_2^2 + e_3^2 + e_4^2) \quad (35)$$

The derivative of this function is:

$$\dot{V}_2 = e_1 \dot{e}_1 + e_2 \dot{e}_2 + e_3 \dot{e}_3 + e_4 \dot{e}_4 \quad (36)$$

By replacing the derivatives of the errors by their respective values, we obtain:

$$\dot{V}_2 = -k_1 e_1^2 - k_2 e_2^2 + e_3 \left((i_{s\beta})_{ref} - \delta_2 - \frac{1}{\sigma L_s} V_{s\beta} + 2\alpha M\Phi_{r\beta} + \frac{\mu\Phi_{r\alpha}}{J} e_1 \right) + e_4 \left((i_{s\alpha})_{ref} - \delta_1 + 2\alpha M\Phi_{r\alpha} e_2 - \frac{1}{\sigma L_s} V_{s\alpha} - \frac{\mu\Phi_{r\beta}}{J} e_1 \right) \quad (37)$$

Finally, to obtain the derivative of the negative Lyapunov function, we choose the following control law

$$\begin{cases} V_{s\alpha} = \sigma L_s \left(k_4 e_4 + (i_{s\alpha})_{ref} - \delta_2 + 2\alpha M \Phi_{r\alpha} e_2 - \frac{\mu \Phi_{r\beta}}{J} e_1 \right) \\ V_{s\beta} = \sigma L_s \left(k_3 e_3 + (i_{s\beta})_{ref} - \delta_1 + 2\alpha M e_2 \Phi_{r\beta} - \frac{\mu \Phi_{r\alpha}}{J} e_1 \right) \end{cases} \quad (38)$$

With: $k_3 > 0$ and $k_4 > 0$

The derivatives of the errors "e3", "e4" will be as follows:

$$\begin{cases} \dot{e}_3 = -k_3 e_3 - 2\alpha M \Phi_{r\beta} - \frac{\mu \Phi_{r\alpha}}{J} e_1 \\ \dot{e}_4 = -k_4 e_4 - 2\alpha M \Phi_{r\alpha} e_2 + \frac{\mu \Phi_{r\beta}}{J} e_1 \end{cases} \quad (39)$$

So from equation (32), (39) we can write:

$$\dot{e} = A \cdot e \quad (40)$$

With:

$$A = \begin{bmatrix} -k_1 & 0 & \frac{\mu}{J} \Phi_r \cos(\theta) & -\frac{\mu}{J} \Phi_r \sin(\theta) \\ 0 & -k_2 & 2\alpha M \Phi_r \sin(\theta) & 2\alpha M \Phi_r \cos(\theta) \\ -\frac{\mu}{J \Phi_r} \cos(\theta) & -\frac{2\alpha M}{\Phi_r} \sin(\theta) & -k_3 & 0 \\ \frac{\mu}{J \Phi_r} \sin(\theta) & -\frac{2\alpha M}{\Phi_r} \cos(\theta) & 0 & -k_4 \end{bmatrix} \text{ and } e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix}$$

It can be seen that the elements of the matrix A contain variable terms $\cos(\theta)$ and $\sin(\theta)$ which can cause instability in the system. The following figure shows the block diagram of the backstepping control of the asynchronous machine in the (α, β) frame of reference.

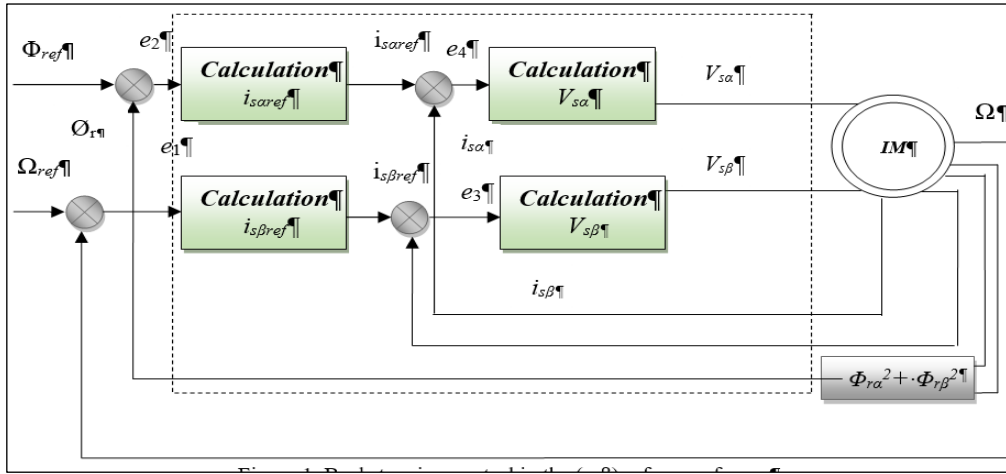


Figure 1: Backstepping control in the (α, β) reference frame.

Source: Authors, (2026).

III.3. SIMULATION RESULTS

These results obtained through simulating our motor within the MATLAB SIMULINK environment, using the new backstepping control developed. We carried out the test by implementing a resistive torque ($C_r = 6$ N.m) as an external variation of the instants ($t=2.5s$ and $t=3.5s$) and a speed setpoint equal to the nominal speed of the IM (157 Rad/s).

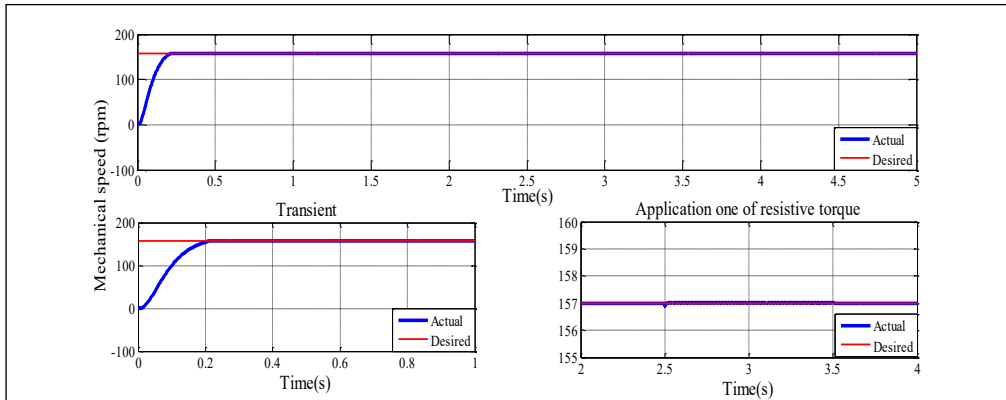


Figure 2: Mechanical speed produced for the new lyapunov backstepping control with a zoom (external variation).

Source: Authors, (2026).

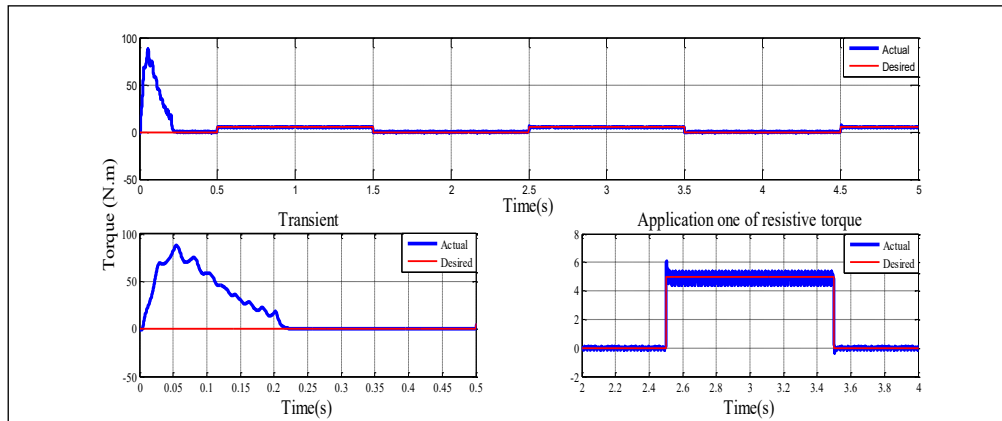


Figure 3: Torque produced for the new Lyapunov backstepping control with a zoom (external variation).

Source: Authors, (2026).

The simulation results show that the mechanical speed closely follows its reference with the developed control technique. The response time, the overshoot and the convergence of the exponential error to the steady state are all optimal, even when external variations (resistive torque) are applied and removed and the torque peaks at the first starting moment, then reaches the value of the resisting torque before and after the load is applied. This control technique demonstrates high efficiency and strong performance.

IV. CONCLUSION

In this study, we develop a control system based on Lyapunov stability theory, which is backstepping control. This method solves the parametric and external variation problems to obtain positive mechanical power output with error convergence to zero. It also guarantees the closed-loop stability of the induction machine at all times. The chosen model of the machine is in the (α, β) reference frame, which does not require a Park transformation. These excellent results obtained with the new Lyapunov backstepping control should be taught in academic circles and also applied in industrial environments.

V. AUTHOR'S CONTRIBUTION

Conceptualization: Chami Nouredine, Rouabhi Riyadh and Herizi Abdelghafour.

Methodology: Chami Nouredine, Rouabhi Riyadh and Herizi Abdelghafour.

Investigation: Chami Nouredine and Rouabhi Riyadh.

Discussion of results: Chami Nouredine, Rouabhi Riyadh and Herizi Abdelghafour.

Writing – Original Draft: Chami Nouredine and Rouabhi Riyadh.

Writing – Review and Editing: Chami Nouredine, Rouabhi Riyadh and Herizi Abdelghafour.

Resources: Chami Nouredine and Herizi Abdelghafour.

Supervision: Chami Nouredine, Rouabhi Riyadh and Herizi Abdelghafour.

Approval of the final text: Author One, Rouabhi Riyadh and Herizi Abdelghafour.

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