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# A Powerful Nonlinear Control Method Based on an Improved Adaptive Integral-Backstepping Technique for Optimal Speed Tracking of Induction Motors

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**Abstract:** *This paper describes an advanced control method of induction motors using an improved Integral-Backstepping version. The application of the conventional version of this technique has proven that it can cause bad behaviour during certain operating conditions because of its structure based on the integral action, which can cause strong vibrations accompanied by overcurrent before the final system stabilization. The adjustment presented in this work to improve the control and ensure its stability in the different operating zones is to incorporate the variable gains structure in the speed regulator. This modification generates a command composed of two distinct parts: the first guarantees optimal control around the equilibrium point by using high gains to ensure robustness in front of external disturbances. The second part is intended for transient regimes; it is characterized by relatively small gains with a total absence of the integral action to guarantee good convergence stability. The determination of each control law will be carried out based on Lyapunov's theorem, and the experimental validation will be performed using a dSAPCE-DS-1104 card. The experiments conducted show a high-efficiency real-time control with an interesting improvement in terms of robustness, stability, and good speed tracking capacity.*

**Keywords:** induction motor, vector control, variable gains Backstepping, Lyapunov stability, real-time control.

**Résumé :** *Cet article décrit une commande avancée des moteurs asynchrones en utilisant une version améliorée du Backstepping avec action intégrale. L'application de la version classique de cette méthode a prouvé qu'elle peut entrainer une mauvaise dynamique dans certaines conditions de fonctionnement, en raison de sa structure qui se base sur une action intégrale, cette dernière provoque de fortes vibrations accompagnées des surintensités du courant avant la stabilisation finale du système. L'optimisation présentée dans ce travail pour améliorer le contrôle et sa stabilité, est d'intégrer la structure des gains variables dans le régulateur de vitesse afin d'avoir une commande composée de deux parties distinctes : la première garantit un contrôle optimal autour du point d'équilibre par l'utilisation des gains élevés assurant la robustesse face aux perturbations extérieures, la deuxième partie est destinée aux régimes transitoires, elle se caractérise par des gains relativement faibles avec une absence totale de l'action intégrale pour garantir la bonne stabilité de convergence. La détermination de chaque loi de commande sera réalisée sur la base du théorème de Lyapunov, et la validation expérimentale sera réalisée à l'aide d'une carte dSAPCE-DS-1104. Les essais expérimentaux menées montrent un contrôle en temps réel avec des performances intéressantes en matière de poursuite, de stabilité et surtout de robustesse.*

**Mots-clés :** moteur asynchrone, commande vectorielle, Backstepping à gains variables, stabilité de Lyapunov, contrôle en temps réel.

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## 1. Introduction

Because of their economic and practical characteristics, induction motors (IM) are considered the most commonly used machines in the industrial field. Nevertheless, the variable speed applications based on this machine require the development of a good controller to ensure the ideal operation. At the beginning of the advancement in power electronics and digital processors, several techniques have been developed and applied to IM (Sun et al., 2019; Aichi, 2021). Indirect Field Oriented Control (IFOC) is one of the popular techniques in the field of variable speed drives because it eliminates a certain coupling between the electromagnetic torque and the rotor flux (Blaschke, 1972). Many researchers have adopted IFOC as a basic strategy to integrate the different regulation methods such as adaptive sliding mode control (Barambones & Alkorta, 2011), artificial intelligence (Gopal & Shivakumar, 2019), hybrid controllers (Aichi & Kendouci, 2020), etc. On the other hand, the association of the IFOC with the Backstepping method could offer very interesting results (Drid et al., 2017; Ben Regaya et al., 2018). Backstepping is a systematic method that can fragment a high-order global system into a series of first-order subsystems. Each control signal generated by one subsystem represents the reference for the next until the final command appears (Benaskeur, 2000). However, applying the classical version of Backstepping on the IM could offer only a modest performance, especially concerning the non-zero static error that appears in the presence of the system's unknown nonlinearity. Some researchers have preferred to integrate an external disturbances observer to compensate for this effect. Nevertheless, the integral version is the simplest and most practical way because it can offer a considerable improvement in terms of external disturbances rejection, according to Mehazzem & Reama (2017). On the other hand, saturation blocks are indispensable in all structures of AC drives for real applications. The operation of integrators with the limiting devices can lead to a phenomenon called Windup (Aichi, 2021, p.22). This phenomenon means that the information generated by the regulator does not exactly match the real command for the controlled system. In transient regimes, the integral action can continue to increase even if the control signal exceeds its limit value. Therefore, it is difficult to quickly weaken the real control signal before the final stabilization. During the saturation, the dynamic response may exhibit considerable overshoot accompanied by strong vibrations and starting overcurrent, which is unfavorable for the motor and its power supply.

The main contribution of this paper is improving Backstepping control without increasing its complexity. The proposed optimization incorporates the variable gains option into both speed and current controllers. The use of vector control as a basic strategy and the Backstepping principle for the design of control signals allow the development of a robust and simple technique for real-time execution. The control becomes adaptive, and two terms will control the speed: one to eliminate the overshoot and improve the transient regimes and another for the steady-state allows amplification of gains to ensure an optimal disturbances rejection. In this trend, our study will start with a brief description of the indirect field-oriented control (IFOC). In section 3, the synthesis of the Variable Gains Backstepping (VGB) and the design of the different nonlinear controllers have been detailed. After that, this advanced method was validated experimentally as the results are presented and extensively discussed in section 4. We finish with a conclusion that summarizes the key contributions of this work.

## 2. Mathematical model of IM controlled by IFOC

The fundamental idea of IFOC is to make the behavior of IM similar to that of a separately excited DC motor by acting on the rotor flux to eliminate the second term of the electromagnetic torque equation. In the synchronously rotating reference frame $(d, q)$, if the rotor flux vector « $\psi_r$ » and the direct axis '$d$' are superimposed, the quadrature flux component « $\psi_{qr}$ » will be eliminated. Consequently, we can act on the current « $i_{ds}$ » to keep the rotor flux module constant. At the same time, the electromagnetic torque equation becomes dependent directly on the current « $i_{qs}$ ». Therefore, we can say that the rotor flux and the electromagnetic torque will be controlled independently (Baghli, 1999).

The application of vector control makes it possible to simplify the dynamic equations of IM by removing some of the nonlinearities. The simplified model offered by this technique is very convenient for command applications where we can express it by equations (1) to (7) (Baghli, 1999; Aichi et al., 2020).

$$v_{ds} = R_s . i_{ds} + \delta . L_s . \frac{di_{ds}}{dt} - \omega_s . \delta . L_s . i_{qs} + \frac{M}{L_r} . \frac{d\psi_r}{dt} \quad (1)$$

$$v_{qs} = R_s . i_{qs} + \delta . L_s . \frac{di_{qs}}{dt} + \omega_s . \delta . L_s . i_{ds} + \omega_s . \frac{M}{L_r} . \psi_r \quad (2)$$

$$\psi_r + \Gamma_r . \frac{d\psi_r}{dt} = M . i_{ds} \quad (3)$$

$$0 = \frac{M}{\Gamma_r} . i_{qs} - \omega_{sl} . \psi_r \quad (4)$$

$$\frac{d\Omega_m}{dt} = \frac{1}{J} . \left( Te - T_L - B . \Omega_m \right) \quad (5)$$

$$Te = \Upsilon . \psi_r . i_{qs} \quad (6)$$

$$\forall\, \theta_s = \int \omega_s . dt , \qquad \omega_s = \omega_m + \omega_{sl} = p . \Omega_m + \frac{M}{\Gamma_r . \psi_r} . i_{qs} \quad (7)$$

*With:* $\alpha_1 = \beta . \left( R_s + \frac{M^2}{L_r . \Gamma_r} \right)$; $\alpha_2 = \beta . \frac{M}{L_r}$ ; $\beta = \frac{1}{\delta . L_s}$ ; $\delta = 1 - \left( \frac{M^2}{L_s . L_r} \right)$; $\Gamma_r = \frac{L_r}{R_r}$ ; $\Upsilon = \frac{3 . M . p}{2 . L_r}$

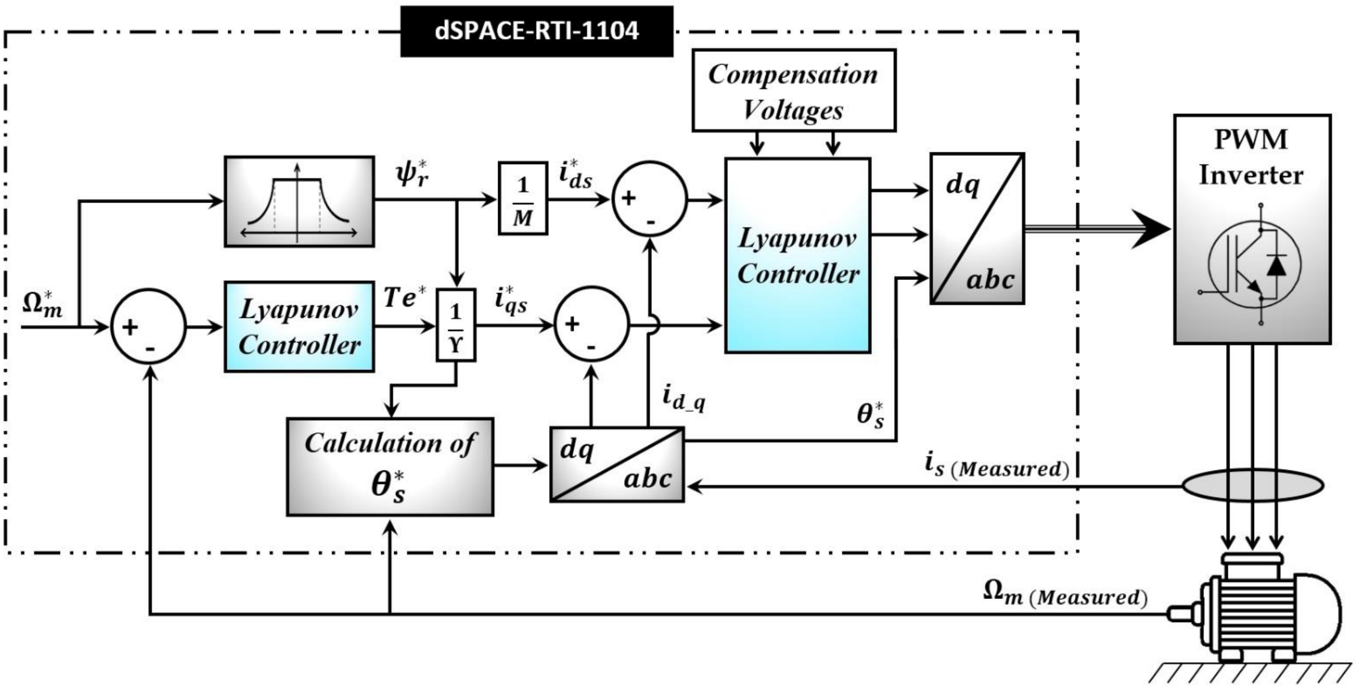
« $v_{ds}$ » and « $v_{qs}$ » are d-axis and q-axis stator voltages, « $i_{ds}$ » and « $i_{qs}$ » represent d-axis and q-axis stator currents. « $\forall\, \psi_{qr} = 0,\ \psi_r = \psi_{qr}$ » is the instantaneous rotor flux value. « $R_s$ » and « $R_r$ » are respectively stator and rotor resistance. « $L_s$ », « $L_r$ » and « $M$ » indicate stator, rotor, and mutual inductance, respectively. « $\omega_s$ », « $\omega_{sl}$ » and « $\omega_m$ » are respectively the synchronous angular velocity, slip angular velocity, and rotor angular velocity. « $\Omega_m$ » represents the instantaneous mechanical speed. « $Te$ » and « $T_L$ » respectively indicate the electromagnetic and load torque. « $\delta$ » is the leakage coefficient. « $J$ », « $B$ » and « $p$ » are respectively total inertia, friction coefficient, and pole-pairs number. « $\Gamma_r$ » is the rotor time constant, and « $\Upsilon$ » is a constant parameter.

## 3. Variable gains Backstepping control

Backstepping is a technique that consists in designing a control law based on the Lyapunov control function, which ensures a desired performance for the closed-loop system. It can be considered a systematic synthesis method for nonlinear systems class having a triangular form (Benaskeur, 2000). It consists of breaking down a high-order multivariable system into a set of first-order cascaded subsystems to establish successive causal relationships. Based on the second method of Lyapunov, the control law calculation is done recursively, starting from the inside of the control loop. A virtual control signal will be generated for each subsystem to reference the next subsystem until obtaining the final control for the global system (Kanellakopoulos et al., 1991). The overall stability can be ensured through the partial stability of each subsystem, meaning that each control variable can converge asymptotically towards its reference.

Figure (1) shows the general structure adopted for the IM control. The application of the VGB consists in determining the control voltages « $v_{ds}^*$ » and « $v_{qs}^*$ » in two main steps: the first guarantees the indirect rotor flux control and the speed regulation by a nonlinear variable gains regulator (NVGC), which delivers the reference torque « $Te^*$ » used to calculate the reference current « $i_{qs}^*$ ». The rotor flux « $\psi_r^*$ » will be imposed directly without regulation through a defluxing block, and the delivered information will be adopted to determine the reference current « $i_{ds}^*$ ». In the second step, both « $i_{ds}^*$ » and « $i_{qs}^*$ » outputs will be used to calculate the reference voltage module, while the control frequency will be estimated using equation (7). By this method, the control has a mechanism that ensures a uniform variation between the frequency and control voltages, guaranteeing the total control of IM throughout the range of speed variation.

**Figure (1): Block diagram of the structure adopted in speed control of three-phase induction motor**




### 3.1. First step: speed regulation

According to Aichi and Kendouci (2020), the load torque can be considered as an unknown external disturbance, so its value is limited by the maximum load torque supported by the motor. Therefore, this quantity can be neglected in order to simplify the regulator design, which can be developed by defining the auxiliary control variable « $\mathcal{Z}$ », where « $L_i$ » is a positive variable parameter that characterizes the integral action.

$$\forall\, e_\Omega = \Omega_m^* - \Omega_m\,, \qquad \mathcal{Z} = e_\Omega + L_i \cdot \int e_\Omega \, .dt \tag{8}$$

Using the dynamic equation (5), the time-derivative of the control variable « $\mathcal{Z}$ » is expressed by equation (9).

$$\frac{d\mathcal{Z}}{dt}=\frac{d\Omega_m^*}{dt}-\frac{\mathrm{Te}}{\mathrm{J}}+\frac{\mathrm{B}}{\mathrm{J}}.\Omega_m+\mathrm{L_i}.\mathrm{e}_\Omega+\frac{d\mathrm{L_i}}{dt}.\int \mathrm{e}_\Omega.dt \tag{9}$$

To ensure the asymptotic stability of the first subsystem, equation (10) is considered a good choice for determining the appropriate control law.

$$\forall\,\mathcal{Z}\neq 0\,,\qquad \mathcal{V}_\Omega=\frac{1}{2}.\mathcal{Z}^2 \tag{10}$$

The control law (11) ensures the asymptotic convergence of the mechanical speed towards its reference if and only if the gain « $\mathrm{k}_\Omega$ » is strictly positive. It should be noted that this parameter is a variable gain; its details will be presented in the remainder of the study.

$$\mathrm{Te}^*=\mathrm{J}.\left(\mathrm{k}_\Omega.\mathcal{Z}+\frac{d\Omega_m^*}{dt}+\frac{\mathrm{B}}{\mathrm{J}}.\Omega_m+\mathrm{L_i}.\mathrm{e}_\Omega+\frac{d\mathrm{L_i}}{dt}.\int \mathrm{e}_\Omega.dt\right) \tag{11}$$

***Proof :*** Based on dynamic equation (9), the time derivative of the Lyapunov function can be expressed by:

$$\frac{d\mathcal{V}_\Omega}{dt}=\mathcal{Z}.\left(\frac{d\Omega_m^*}{dt}-\frac{\mathrm{Te}}{\mathrm{J}}+\frac{\mathrm{B}}{\mathrm{J}}.\Omega_m+\mathrm{L_i}.\mathrm{e}_\Omega+\frac{d\mathrm{L_i}}{dt}.\int \mathrm{e}_\Omega.dt\right) \tag{12}$$

If we substitute the control law (11) in the derivative of the Lyapunov function « $\mathcal{V}_\Omega$ », we obtain:

$$\frac{d\mathcal{V}_\Omega}{dt}=-\,\mathrm{k}_\Omega.\mathcal{Z}^2\leq 0 \tag{13}$$

This mathematical inequality justifies that the Lyapunov function and its derivative have an opposite sign regardless of time. This condition confirms that the control law (11) guarantees the asymptotic convergence of speed error towards zero.

### 3.2. Implementation of the variable gains of the speed NVGC

The variable gains property in the speed regulation, makes the control adaptable to different operation zones, and robust against the various external disturbances. It has been proven by (Aichi et al., 2020) that conventional integral Backstepping can cause overshoot in transient regimes because of the integral term. However, this action is essential in the steady-state to compensate for uncertain nonlinearity, including applied load torque values. During the overtaking, strong vibrations can appear together with an overcurrent. This is likely due to the action associated with the gain « $\mathrm{k}_\Omega$ », which brutally forces the speed to converge towards its reference. This behavior can destabilize the overall system or even damage the control set. The bottom line is that the choice of the regulator gains must be judicious to respect maximum torque and current intensity and generate a control signal capable of ensuring fast dynamic response without overshoot with a good ability to reject external disturbances. The proposed solution is to create a slight delay in the speed reference; then, we define an equilibrated variation of gains based on a new parameter « $\Delta$ » that can be considered as a supervisor of transient regimes. This parameter can be determined by the absolute value of the difference between the final value of the reference « $\Omega_f^*$ » and the instantaneous one « $\Omega_m^*$ » as shown in equation (14).

$$\Delta=\left|\,\Omega_f^*-\Omega_m^*\,\right| \tag{14}$$

Based on this parameter, the variation of gains for the speed NVGC will be performed according to the following algorithm:

$if\left(\Omega_f^*=0\right)$ $\quad$ *% Stopping condition*

$\quad\mathrm{k}_\Omega=\sigma.\mathrm{k}_{\Omega\_Max}\quad;\quad \mathrm{L_i}=0\quad;$

*else* $\qquad$ *% Real − time operation condition*

$\quad$ *if* $(\Delta \leq \Delta_{\mathrm{Max}})$ $\qquad$ *% Gain amplification condition*

$$\mathrm{k}_{\Omega} = \mathrm{k}_{\Omega\_\mathrm{Max}} \cdot \left(1 - \frac{(1-\sigma)}{\Delta_{\mathrm{Max}}} . \Delta\right) \quad ; \quad \mathrm{L}_{\Omega} = \mathrm{L}_{\Omega\_\mathrm{Max}} \cdot \left(1 - \frac{1}{\Delta_{\mathrm{Max}}} . \Delta\right) \quad ;$$

$\quad$ *else* $\qquad$ *% Gain weakening condition*

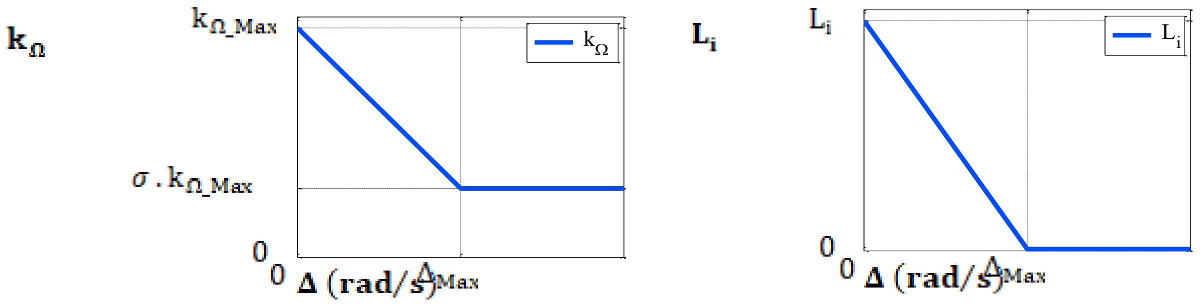
$$\mathrm{k}_{\Omega} = \sigma \, . \, \mathrm{k}_{\Omega\_\mathrm{Max}} \quad ; \quad \mathrm{L}_{\mathrm{i}} = 0 \quad ;$$

$\quad$ *end*

*end*

The index 'Max' refers to the maximum values. « $\Delta_{\mathrm{Max}}$ » represents the maximum value of « $\Delta$ » which can be determined experimentally. Figure (2) shows the graphical representation of each gain variation according to the parameter « $\Delta$ ».

**Figure (2): Graphical representation of the variation of the speed regulator coefficients**




Two different commands will carry out the speed regulation: one for the transient regime, which ensures the attractiveness of the speed without overshoot (similar to classic Backstepping without integral action), and another ensures the amplification of gains in the permanent regimes. This reduces the starting current, cancels the overshoot, and enhances robustness against various external disturbances.

### 3.3. Second step: current regulation

The current loops regulation has an indispensable role in most control techniques. They provide useful preservation to machines and their power supply and reinforce protection by applying saturation on the output voltages « $v_{ds}$ » and « $v_{qs}$ » in order to guarantee optimal current control even in the presence of anomalies in external control loops. However, identifying the current regulator gains is not so easy as in the case of speed regulation since its output represents the reference torque, in which its maximum value is the maximum load torque supported by the motor. Therefore, the gains must be chosen in order to respect this limitation. This is not the case in the current controller because the outputs are indeterminate. An effective technique will be presented to overcome this problem and applied the Backstepping principle in two steps: in the first place, it is assumed that the currents « $i_{ds}$» and « $i_{qs}$» will be filtered and then controlled by a simple PI in order to determine the approximate gains values of this regulator. The second step is to calculate the compensation voltages to satisfy the Lyapunov stability condition.

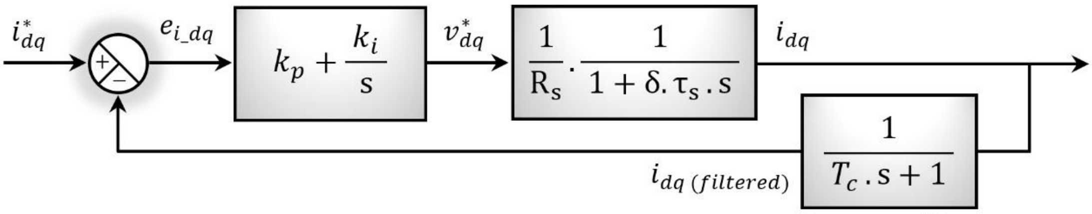
#### A. First step: calculation of the approximative regulator gains

By decoupling the two axes '$d$' and '$q$' concerning the stator voltages (equations (1) and (2)), two mono-variable linear systems can be obtained where the voltages have a first-order relationship with the currents. We note that 's' refers to the Laplace operator.

$$v_{(d,q)s} = (R_s + L_s.\delta.s).i_{(d,q)s} \tag{15}$$

Because of the fluctuations caused by the inverter and Park transformations, a simple first-order low-pass filter with a cut-off frequency « $f_c = 1/T_c$ » is used to minimize disturbances without influencing the regulation quality. Figure (3) shows the block diagram of the first regulation step.

**Figure (3): Currents regulation loop**




If « $k_p/k_i = \delta.\tau_s$ » for: « $\tau_s = L_s/R_s$ », the closed-loop transfer function « $H(s)$ » can be written as:

$$H(s) = \frac{\frac{k_i}{R_s.T_f}.(T_c.s+1)}{s^2 + \frac{1}{T_c}.s + \frac{k_i}{R_s.T_c}} \cong \frac{\omega_0^2}{s^2 + 2.\xi.\omega_0.s + \omega_0^2} \tag{16}$$

The quality of signals is not set as an objective in the current filter; it is used to eliminate high frequencies. If the cut-off frequency is relatively large, the zero of the transfer function (16) will be ineffective on the system response. The gain « $k_i$ » can be calculated according to the pole placement method. By taking a damping factor « $\xi = 1/\sqrt{2}$, the regulator gains are calculated as follows:

$$\begin{aligned} k_i &= R_s/(T_c.4.\xi^2) \\ k_p &= \tau_s.\delta.k_i \end{aligned} \tag{17}$$

### B. Second step: determination of the compensation voltages

This step's objective consists in determining the second part of the global control laws, which can ensure the asymptotic stability of the system in the sense of Lyapunov. In the work of Aichi et al. (2020), it has been verified that the system will be asymptotically stable if the compensation voltages are imposed as given in equations (18). These terms are obtained by applying the Backstepping principle, which can guarantee that zero represents an equilibrium point for all control variables.

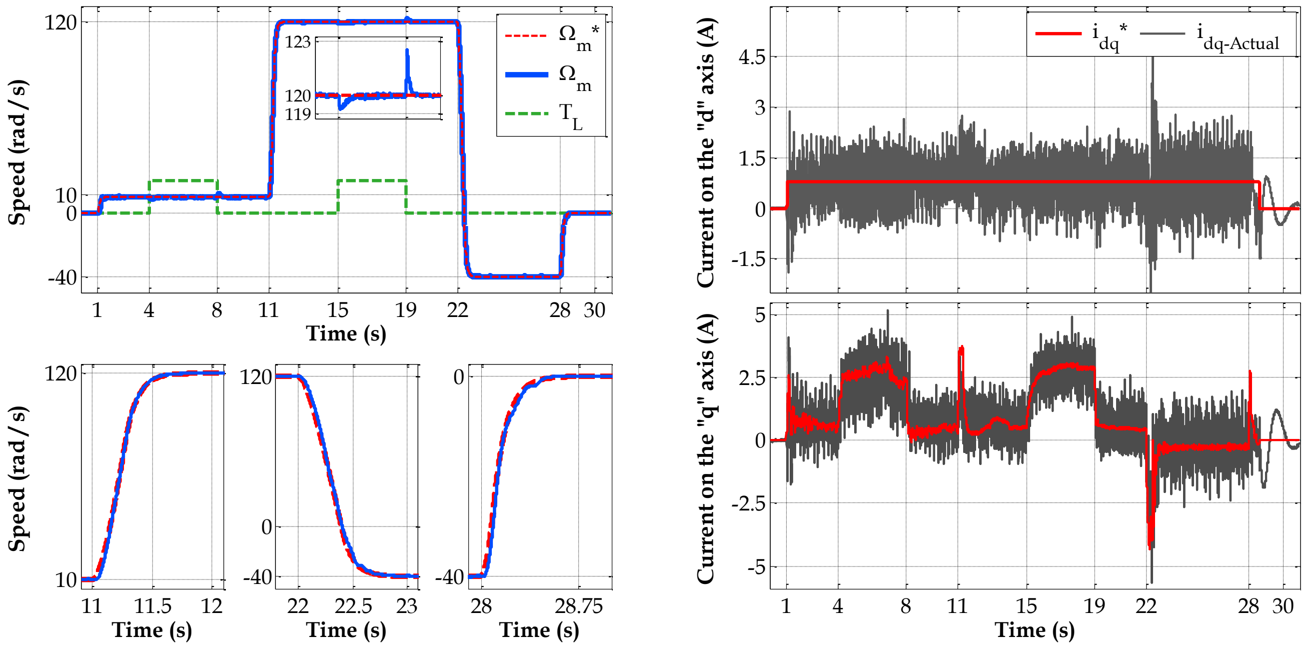
$$\begin{aligned} \mathcal{U}_d &= \frac{1}{\beta}.\left(\frac{di_{ds}^*}{dt} + \alpha_1.i_{ds} - \omega_s.i_{qs} - \frac{\alpha_2}{\tau_r}.\psi_r^*\right) \\ \mathcal{U}_q &= \frac{1}{\beta}.\left(\frac{di_{qs}^*}{dt} + \omega_s.i_{ds} + \alpha_1.i_{qs} + \alpha_2.\omega_m.\psi_r^* + \frac{\Upsilon.\psi_r^*}{J}.\mathcal{Z}\right) \end{aligned} \tag{18}$$

« $\alpha_1$ », « $\alpha_2$ » and « $\beta$ » are constants that depend on the IM parameters, and they are well detailed in work presented by Aichi et al. (2020). The authors proposed an advanced solution using variable gain property to solve obstacles related to very low-speed operations. The idea was inspired by equation (16): the amplification of the gain « $k_i$ » implies that the stabilization time is short, which means a fast regulation. Therefore, if this gain is small, the dynamic regulation will be slow but less sensitive to the current fluctuations that are considerable in low-frequency. The proposed solution is to abandon the fast-dynamic requirement at low speeds by varying the integral gain « $k_i$ » according to the final value of reference speed. The authors performed an intensive series of tests to determine each operating zone's optimal gain value. It is necessary to note that the effectiveness of this method cannot be verified only by practical validation.

## 4. Experimental results

To verify the performance of the proposed control, the VGB technique was practically implemented using a dSPACE-RTI-1104 card associated with a MATLAB/Simulink program. The experimental configuration illustrated in figure (5) consists of a 1kW induction motor whose parameters are presented in table (1). It is powered by a PWM inverter with a DC bus voltage of 550V and a switching frequency of 3kHz. The motor is equipped with an incremental encoder for speed measurement. Besides, it is coupled with a pneumatic brake that ensures the application of load torques. The dSPACE control board receives the information through the encoder and the current sensors to determine the switching times of the inverter's IGBTs in order to generate the appropriate voltages to the desired dynamics. The method of Euler (first-order differential equations) is chosen to solve the dynamic equations of the algorithm with a step size of 150µs. The ControlDesk software allows controlling and observing all system variables in real-time and makes it possible to adapt the algorithm parameters that drive the control performance.

**Figure (4): Experimental response of the IM controlled by the VGB technique**



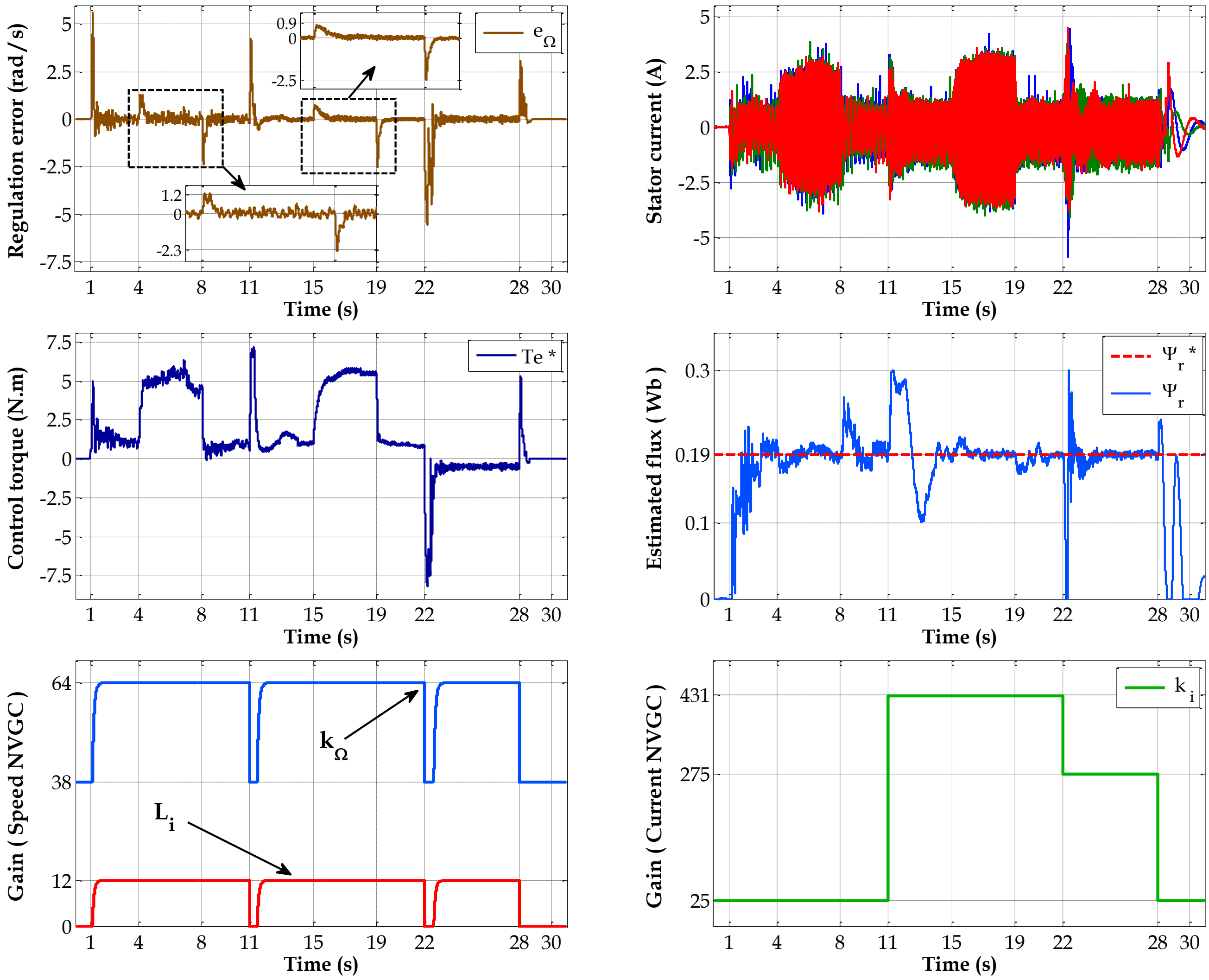
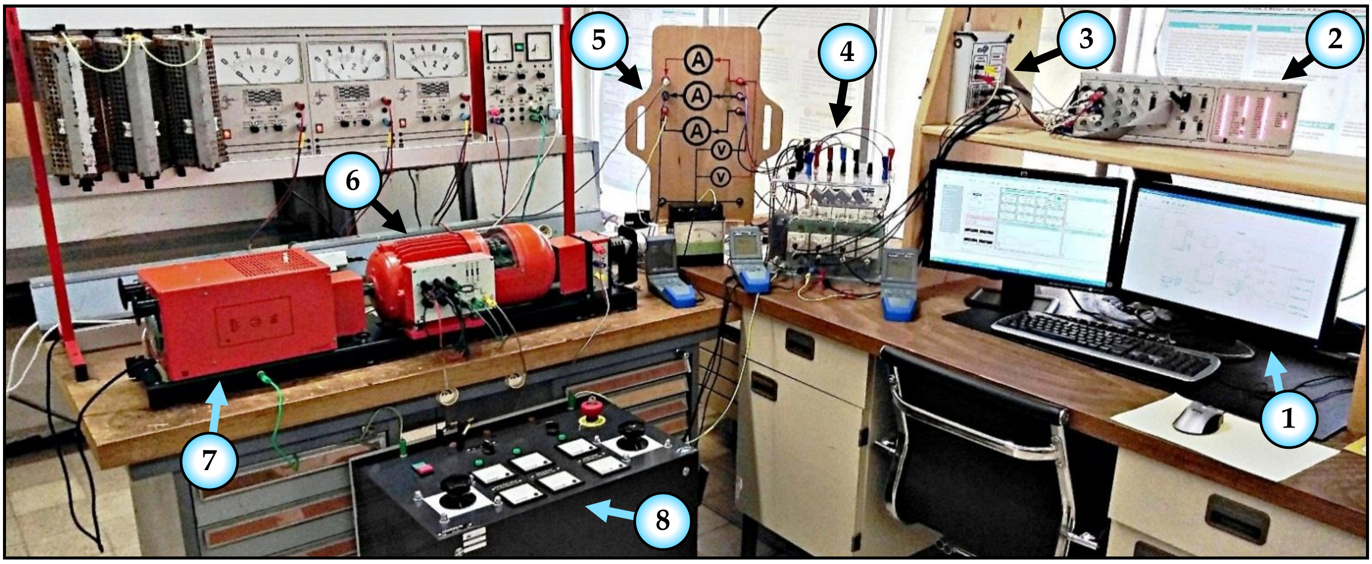



**Figure (5): Experimental test bench of the LDEE-USTO laboratory (Group of Control)**



| | | | |
|---|---|---|---|
| (1) – Control unit. | (2) – dSPACE-RTI-1104. | (3) – Control circuit of IGBT. | (4) – PWM Inverter. |
| (5) – Hall-effect sensors. | (6) – Three-phase IM. | (7) – Powder brake. | (8) – Auto-transformer. |

**Table (1): Parameters of the controlled induction motor**

| $\Omega_n\,(rad/s)$ | $V_n\,(V)$ | $I_n\,(A)$ | $f_n\,(Hz)$ | $R_s\,(\Omega)$ | $R_r\,(\Omega)$ |
|---|---|---|---|---|---|
| 145 | 220/380 | 2.5 / 4.32 | 50 | 8.79 | 0.65 |
| $L_s\,(H)$ | $L_r\,(H)$ | $M\,(H)$ | $J\,(kg.m^2)$ | $B\,(N.m.s/rad)$ | $p$ |
| 0.868 | 0.072 | 0.240 | 0.0157 | 0.0045 | 2 |

**Discussion**

The effectiveness of the VGB technique has been verified in various operating conditions, including low-speed performance tests. The experimental results show remarkable stability regarding the mechanical speed and the stator current. The mechanical speed converges well towards its reference with excellent precision without any overshoot. The load torque application causes a slight drop in speed which is quickly rejected; this robustness is mainly due to the large gains of the permanent regime. On the contrary, they are minimal in the transitional regime. That's why it does not cause overshoot or strong current.

Figure (4) shows Park's current regulation, reference torque, and stator currents. The reference quantities have very good stability throughout the operating range. The current regulation has been performed satisfactorily in the high-speeds and at low-speeds. The same figure shows the estimated value of rotor flux; since the « $i_{qs}$ » component follows its reference perfectly, as well as the rotor flux, this justifies the realization of the vector control principle. Concerning the value of gains of the different NVGC controllers, we can notice the equilibrate variation of speed NVGC gains during operation. Similarly, it is noted that the current NVGC integral gain decreases once the operation zone is near to low speeds. Therefore, it can say that thanks to the variable gains option, the overall control becomes adaptive for the different operating zones, less sensitive to harmonics presented in the supply voltage caused by the low frequencies operation, and very robust against external disturbances.

## 5. Conclusion

In this work, a modified version of Backstepping has been applied for robust speed and current control of a three-phase induction motor. The improvement presented in this paper introduces the property of variable gains in speed control for two main reasons: enhancing the dynamic response during transient regimes and ensuring large regulation coefficients in the steady-state to have optimal control against applied loads. All control signals are generated to achieve the asymptotic stability of the system based on the second Lyapunov theorem. It should be noted that the proposed method does not require information on the load torque and the rotor flux. This simplifies the control algorithm considerably and reduces dependency on the machine parameter. This strategy has been practically implemented for real-time control using a dSPACE-DS-1104 where empirical results demonstrated that the variable gain property could optimize speed control and ensure its robustness with remarkable stability in all operating regimes. In the future, we suggest using the present method in concrete applications such as electric vehicles control.

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