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High Dynamics performances for the super twisting sliding mode controller for the asynchronous machine

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Abstract- *This paper proposes a super twisting sliding mode control technique for linear induction motors, taking into consideration the dynamic end effects. Comparing to the traditional first order SMC algorithms, super twisting guarantees the dynamic performance and serves to reduce simultaneously the chattering phenomenon. The control problem is formulated and each part of the controller is presented. The principal objective of this paper is to improve the control performance, robustness and stability, comparing to the twisting controller at very low speed. Therefore, the satisfactory performance of the super twisting controller is realized when our controller has been able to withstand in presence of load torque perturbations and parameters variations. Experimental results are presented in order to validate the dynamics performances of the new proposed technique to control an induction motor drive system.*

Keywords: Super twisting, Sliding mode control SMC, Induction motors, robustness, dynamic performance.

1. INTRODUCTION

In any formulation of a control problem, the mathematical model developed for the purpose of establishing the control law does not exactly reflect the actual process. These deficiencies can for example be due to unmodelled dynamics, to variations of the system parameters or to the direct approximation of complex process behaviors. Nevertheless, it must be ensured that, despite all these uncertainties, the resulting control law makes it possible to reach the predefined objectives. This has led to great deal of interest in the development of so-called robust controls methods (RCM) capable of overcoming this problem and giving a desired performance in presence of disturbances and uncertainties.

The first approach used by researches is the linear correctors, of the PID type, quickly showed its limits. Indeed, these are subject to the Bode law which wants amplitude effects and phase effects to be coupled and antagonistic. For example, any phase advance, which is the desired beneficial effect, goes hand in hand with an increase in the dynamic ratio. Therefore, the research then turned to nonlinear techniques, such as adaptive or absolute stability methods, and particularly the technique of sliding modes. The latter is part of the theory of systems with variable structure that emerged in the middle of this century in the Soviet Union. The sliding control laws are designed to drive and constrain the system to remain in the vicinity of a switching surface. There are two main advantages to such an approach: first, the resulting dynamic behaviour can be determined by choosing a suitable surface. Second, the closed-loop response of the system is totally insensitive to a particular class of uncertainties, making it a serious candidate for the development of robust controls.

The general theme of the presented work in this article is the control by sliding mode of higher order control, and in particular for a goal of stabilization. The approach was to favour control laws leading to converge in finite time and having robustness properties. In this work, one is compelled to design a robust controller-observer scheme, based on the super-twisting technique. In order to yield to a better performance of induction motors. Their structural properties were further studied to determine under what conditions they could be rejected. In addition, classes of systems representative of real processes have been taken into account in order to associate a practical dimension with our control laws. This led to the realization of experiments on a platform dedicated to the asynchronous machine controlled by super twisting and twisting control.

2. MATERIALS AND METHODS

2.1. Dynamic model of the induction motor

Before the implementation of the control law used in this paper, it's necessary to start by designing our system in the suitable structure utilized by the used control. Firstly, we introduce the dynamic equations of the induction motor of emphasizing the variables control such as flux and phases correspond to speed and torque. The mathematical model is described in a rotating field reference (d,q) by the following equation.

$$\begin{cases} \dot{\psi}_{dr} = -\frac{1}{\tau_r}\psi_{dr} + \omega_r\psi_{qr}\frac{L_m}{\tau_r}I_{ds} \\ \dot{\psi}_{qr} = -\omega_r\psi_{dr} - \frac{1}{\tau_r}\psi_{qr} + \frac{L_m}{\tau_r}I_{qs} \\ \dot{I}_{ds} = \frac{\alpha}{\tau_1 L_1}\psi_{dr} + \frac{\alpha}{L_1}\omega_m\psi_{qr} - \frac{1}{\tau_1}I_{ds} + \omega_s I_{qs} + \frac{1}{L_1}V_{ds} \\ \dot{I}_{qs} = -\frac{\alpha}{L_1}\omega_m\psi_{dr} + \frac{\alpha}{\tau_1 L_1}\psi_{qr} + \frac{1}{\tau_1}I_{qs} - \omega_s I_{ds} + \frac{1}{L_1}V_{qs} \\ \dot{\omega}_m = \frac{1}{J}\left[\frac{M}{L_r}\left(\psi_{dr}I_{qs} - \psi_{qr}I_{ds}\right) - T_m\right] \end{cases} \tag{1}$$

Where V_qs and V_ds are the stator voltage components. I_qs and I_ds are the stator current components. ψ_dr and ψ_qr are the rotor flux components.

And $\omega_r = \omega_s - p\omega_m$; $L_1 = L_s - \alpha L_m$; $\alpha = \frac{L_m}{L_r}$; $\tau_r = \frac{L_r}{R_r}$; $\tau_1 = \frac{L_1}{R_1}$; $R_1 = R_s + \alpha^2 R_r +$

Rr and Rs are respectively the rotor and stator resistances. Lr and Ls are respectively the rotor and stator inductances. Lm is the mutual inductance, p is the number of pairs of poles, ωs, ωr and ωm are respectively slip speed, electrical synchronous speed and rotor speed. Tm is a load torque and J is the inertia.

2.2. Problem description: second order of Sliding mode control

The control objective is to design a suitable control law that allows the system's control output to track the reference trajectory quickly and efficiently and estimate system parameters online. The designed control law consists of two parts: the equivalent control and the super-twisting sliding mode control; the super-twisting sliding mode control is used as a switching control to overcome external disturbances and uncertainties and improve the robustness of the system.

As soon as it appeared, the theory of sliding modes, used as first by Levant [1], came up against the problem of chattering, which proved to be a major drawback. In particular, it is difficult under such conditions to envisage developments for practical applications when their implementation involves relatively fast usage for process control elements. To overcome this obstacle, Russian researchers have proposed a new way of sliding. As will be described in this paper, it is then possible to reduce or even exclude any chattering phenomenon, while maintaining the properties of robustness and convergence in finite time. This shows, on the other hand, that for a system of relative degree strictly greater than one, it is not possible to obtain a convergence in finite time on a surface S by a sliding mode of order one. To obtain such a result, the use of a higher order control algorithm is then necessary. Using such a strategy, the command law u is then the output of a first-order dynamic system. The discontinuous algorithms are in fact applied to the derivative with respect to time ü, which becomes the new control variable of the system under consideration and leads to obtain a second order sliding regime on the surface S. In this way, the input u of the system is now continuous and avoids the phenomenon of chattering [2, 3]. In the second case, because of the uncertainties affecting the system under consideration and the partial knowledge (most of the time) of the state, a sliding-mode approach of order r, with r = 2, appears to be the method of most appropriate command. The application of a sliding algorithm of order p + 1 on ü is a solution to converge on S while avoiding the problems of chattering and remaining robust with respect to the uncertainties of the system.

The physical meaning of the equivalent command can be interpreted as follows. The discontinuous control law u consists of sum of a high frequency component (u_{hf}) and a low frequency component (Us): $u = u_{hf} + us$. u_{hf} is filtered by the system bandwidth and the speed on S is only affected by us, which can be seen as the output of the low-pass filter.

Let us consider the following nonlinear scalar system.

$$\dot{x} = f(t,x,u), S = S(t,x) \in \mathcal{R}, u = U(t,x) \in \mathcal{R} \tag{2}$$

Where x and f are functions, t is the time, u is a control function (discontinuous bounded function), S is a constraint function. The relative degree of the system is two so we say: $\frac{\partial}{\partial u}\ddot{S} \neq 0$

With these hypotheses, deriving S twice in relation to time,

$$\dot{S} = \frac{\partial}{\partial t}S(t,x) + \frac{\partial}{\partial x}S(t,x)f(t,x,u) \tag{3}$$

$$\ddot{S} = \frac{\partial}{\partial t}\dot{S}(t,x,u) + \frac{\partial}{\partial x}\dot{S}(t,x,u)f(t,x,u) + \frac{\partial}{\partial u}\dot{S}(t,x,u)\dot{u}(t) \tag{4}$$

2.3. Invariance condition of the sliding surface

The famous system of the sliding mode control applied to nonlinear system is designed by the following system, equation 5:

$$\begin{cases} s = 0 \\ \frac{\partial s}{\partial x}[f(x) + g(x)u_e] = 0 \end{cases} \tag{5}$$

The second equation is obtained by using $\dot{s} = 0$. u_e is called the equivalent command. Due to Utkin[4], the equivalent command is a means of determining the behavior of the system when it is restricted to the surface {s = 0}. It expresses by the following equation :

$$u_e(x) = -\left[\frac{\partial s}{\partial x} g(x)\right]^{-1} \frac{\partial s}{\partial x} f(x) \quad (6)$$

With regard to the first type, sliding mode of order r, one of the major problems for implementation is that the number of necessary information increases regularly with the order of the sliding regime. In general, if we use a sliding algorithm of order r with respect to s = 0, we will need the knowledge of s, s (1) ..., s (r-1). In particular, the 2nd order sliding mode controllers are used to zero the outputs with relative degree two or to avoid chattering while zeroing outputs with relative degree one. Among 2nd order algorithms one can find the sub-optimal controller, the terminal sliding mode controllers, the twisting controller and the super-twisting controller. In particular, the twisting algorithm forces the sliding variable S of relative degree two in to the 2-sliding set, requiring knowledge of S˙. The super-twisting algorithm does not require S˙, but the sliding variable has relative degree one. Therefore, the super-twisting algorithm is nowadays preferable over the classical siding mode, since it eliminates the chattering phenomenon.

2.3. Design of the twisting and super twisting control

**** Twisting Algorithm:***

Theorem (Levant, 1998)[5]: Consider the system (1) and the equation describing the sliding surface S. The Control law is defined as below:

$$u = \begin{cases} -\lambda_m . sign(S) & si\ S\dot{S} \leq 0 \\ -\lambda_M . sign(S) & si\ S\dot{S} > 0 \end{cases} \quad \textbf{(7)}$$

Where $\lambda_m, \lambda_M > 0$ and verified these conditions (Proof: see (Smaoui, 2004) [6]):

i. It's a two-order sliding mode algorithm compared to S.
ii. λ_m *and* λ_M are positive constants (Levant, 1993) [7] where the surface $S = \dot{S} = 0$ is rea ched in a finite time.

Trajectories, which describe a curve, wrapping infinitely on itself while converging in finite time towards the origin $S = \dot{S} = 0$ (figure 1). In the case where the sliding surface is chosen such that the system is of relative degree one, the new control law applied to the system is (Rolink, 2006) [8]:

$$u = \begin{cases} -u & & |u| > U_M \\ -\lambda_m sign(S) & si\ S\dot{S} \leq 0 & |u| \leq U_M \\ -\lambda_M sign(S) & si\ S\dot{S} > 0 & |u| \leq U_M \end{cases} \quad (8)$$

It leads to the same result, that is, the convergence in finite time to the set $S = \dot{S} = 0$.

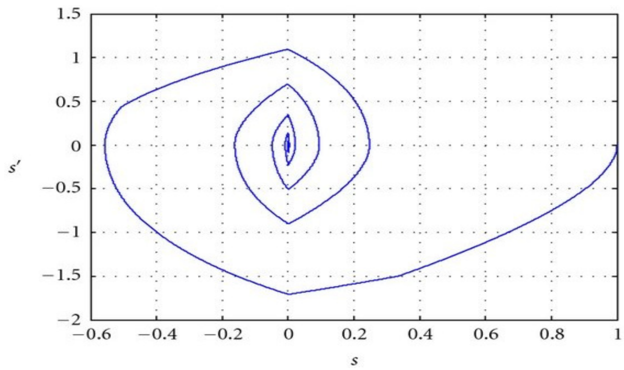


Figure 1 The convergence trajectory of twisting algorithm.

The second order of sliding mode control permits to lessen the chattering impact, while holding the same robustness as the traditional sliding mode control approach. But it requires knowledge of the derivative of the switching surface S, which is usually not available. For this, we present another version of this algorithm called Super-twisting algorithm.

- ***Super twisting Algorithm:***

This algorithm was proposed by Levant [9] and Utkin [10], and was developed for the control system of relative degree one in order to eliminate the phenomenon of reluctance. In this case, the control law is formulated by two terms: the first is defined by the time derivative of its discontinuity and the second is a continuous function of the sliding variable. The control algorithm is defined by [7] and as indicated in the following equation, eq.9:

$$u(t) = u_1(t) + u_2(t) \tag{9}$$

$$\dot{u_1}(t) = \begin{cases} -u & si\ |u| > U_M \\ -\alpha . sign(S) & si\ |u| \leq U_M \end{cases} \tag{10}$$

As,

$$u_2(t) = \begin{cases} -\lambda\ |s_0|^{\rho} . sign(s) & si\ |S| > s_0 \\ -\lambda\ |s|^{\rho} . sign(s) & si\ |S| \leq\ s_0 \end{cases} \tag{11}$$

Where α, λ, and ρ check the following inequalities [8]:

$$\begin{cases} \alpha > \frac{\emptyset}{K_m} \\ \lambda^2 \geq \frac{4\emptyset}{{K_m}^2} . \frac{K_m(\alpha+\emptyset)}{K_m(\alpha-\emptyset)} \\ 0 < \rho < 0.5 \end{cases} \tag{12}$$

This algorithmic program has the advantage of not requiring the knowledge of the star sign of the constraint derivative S. In fact, the measurement of the sign in real time is very difficult because of the noise.

This type of control is seen as a good property of robustness. Schematically, when a higher order SMC algorithm is used, the surface is reached more smoothly as shown in Figure 2.

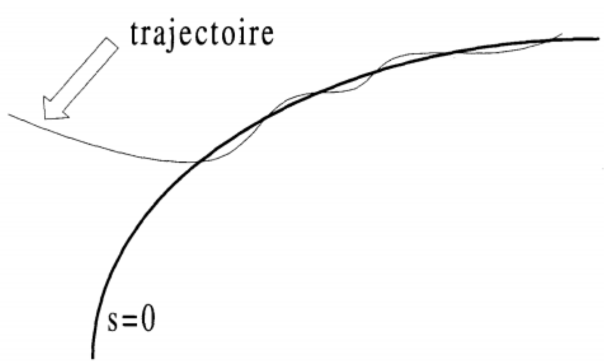


Figure 2 Curve of sliding regime for higher order

3. RESULT AND DISCUSSION:

3.1. Experimental setup

As it is indicated before, this paper serves to prove the performance of the super twisting control by using an experimental test bench installed in the laboratory of innovative technologies. The used experimental setup is based on dSpace DS1104 board in order to generate the controlled parameters to the induction machine. The latter is connected to a three-phases inverter by an adapter card in order to drive a 1.5kW induction motor. Yet, it is based on a TMS320F240 DSP as a microcontroller of the controller board; when its main function is the management of digital/analog input/output.

The controlled board serves to generate the desired speed and flux of the induction machine by using the two types of the second order of the sliding mode, twisting and super twisting control passing by a three phases inverter as showing in the figure 3. We define the given mechanical velocity of the motor as ωref. and the reference flux as ϕref. Therefore, the robustness of the controller is measured by the quality of the reached controlled variable. The first algorithm of the two-ways sliding mode command was verified by a practical implementation on the test bench as shown in the figure 4. The choice of motor parameters is the result of several validation tests, indicated in the table 1, followed by observations on the curves of speed, flux and control voltages.

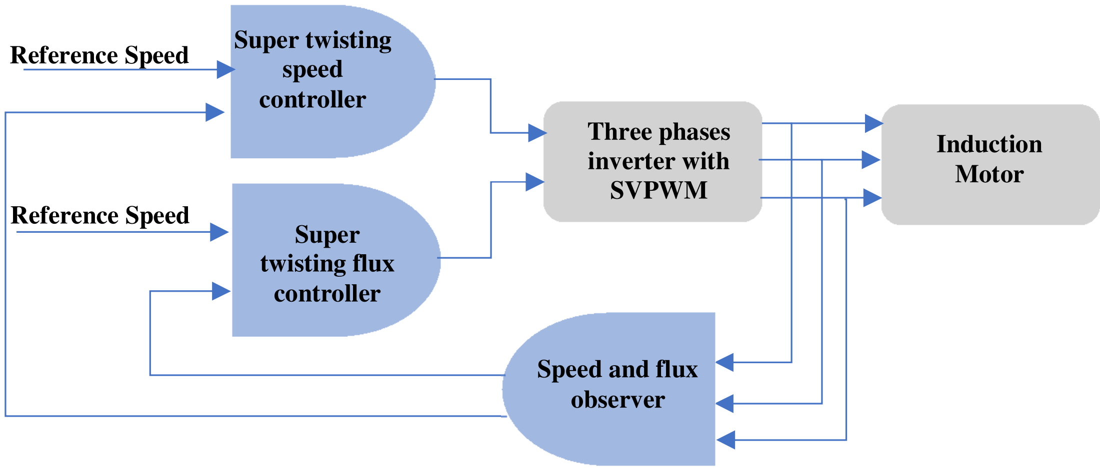


Figure 3 Induction motor vector control system based on the super-twisting control

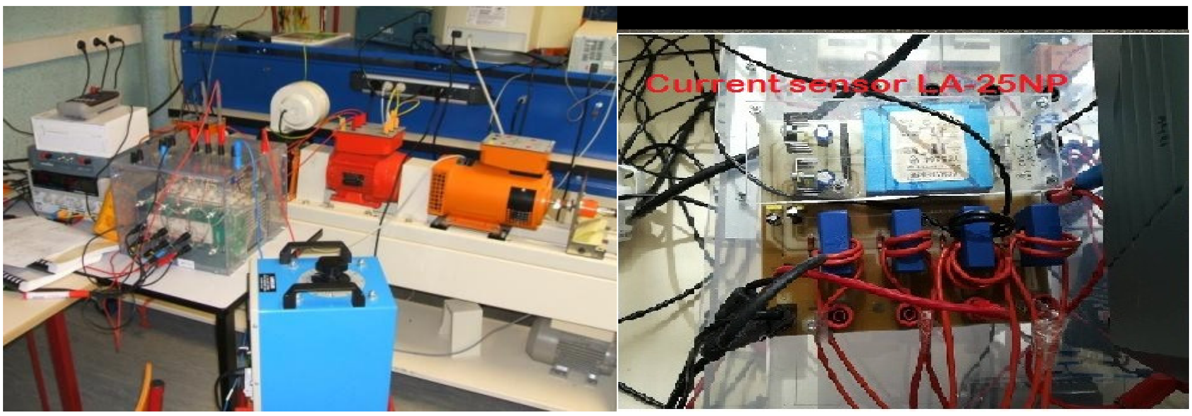


Figure 4 Test Bench used in the experiment test (LTI, Cuffies-Soissons, France laboratory)

TABLE 1 MOTOR PARAMETERS

Symbol	Quantity	Value
F	Frequency	50 Hz
Rr	Rotor resistance	4.2 Ω
Rs	Stator resistance	2.9Ω
Ls	Stator inductance	0.326 mH
Lr	Rotor resistance	0.288 mH
P	Pairs of poles number	2
Lm	Mutual inductance	0.288 mH

3.2. Results and Discussions :

The various experimental tests have been made in order to highlight the properties of the super-twisting controller and to improve its performance at very low speed in presence of load torque perturbations and parameters variations by comparison with the twisting algorithm. Figure 7 shows the responses of stator voltage by using the twisting and super-twisting algorithm during variation of load torque, respectively. Indeed, the quadratic stator voltage follows almost the same evolution as the motor speed for a super-twisting control. The reference velocity signal increases from 0 to 50 rad/s in the first 3 s and then remains constant, while the rotor flux modulus reference signal is directly taken from the calculated optimal flux, as shown in the two figures 5 and 6.

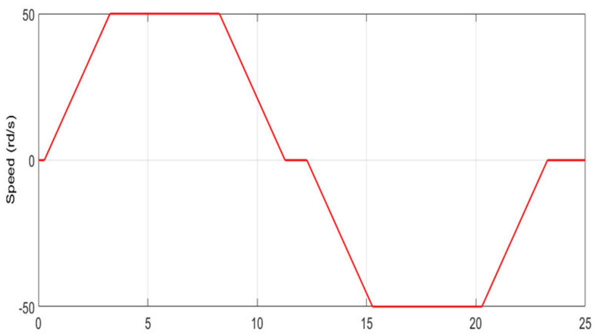


Figure 5. Reference speed curve

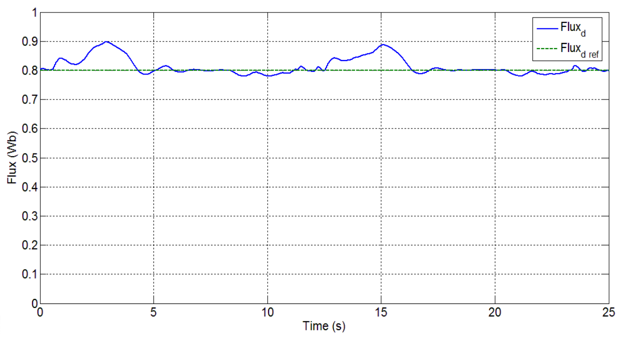
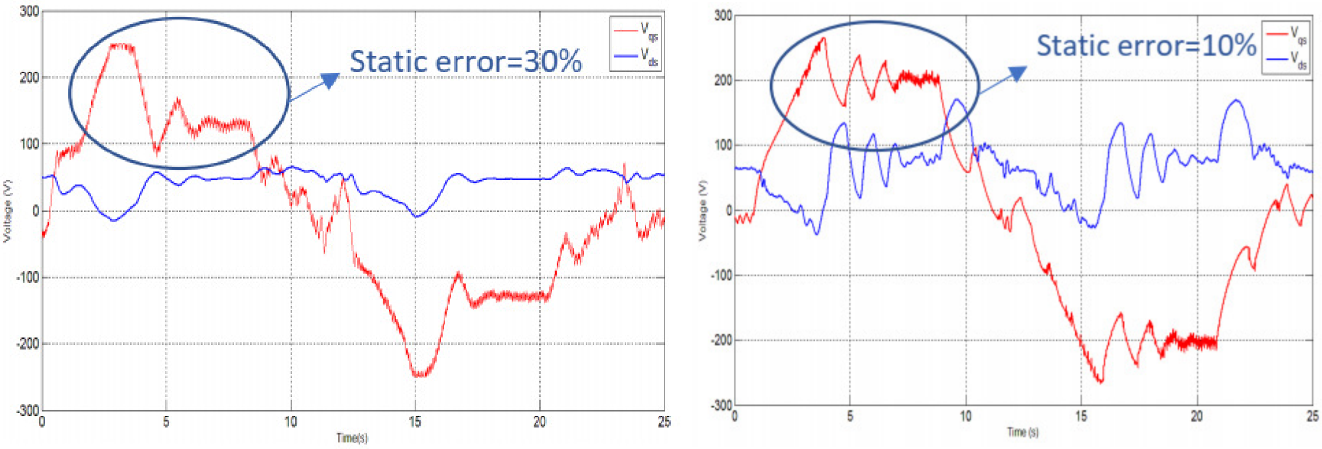


Figure 6. Flux curve of induction motor with twisting algorithm

From the experimental results shown in figure 8, we can observe that the motor speed ω_m tracked the reference speed ω_{ref} by using the super twisting better than using the twisting controller. With good performances, the overshoot of the rotor speed concerning the twisting algorithm curve is equal to 6.42 rd/s, while this parameter is equal to 2.48 rd/s for super twisting algorithm. Furthermore, The average of the error between the real motor speed and the reference one is almost zero. Besides the rise time of super-twisting curve is lower than speed evolution of twisting algorithm. In order to verify the robustness of such an algorithm, it is advantageous to excite the system by an external disturbance in order to know whether it maintains its equilibrium state or not. As mentioned in Figure 11, we applicate a load torque to the induction motor between the instance 8 and 13 seconds.



(a) (b)

Figure 7 Voltages curves Vds et Vqs : (a) twisting algorithm ; (b) Super-Twisting algorithm

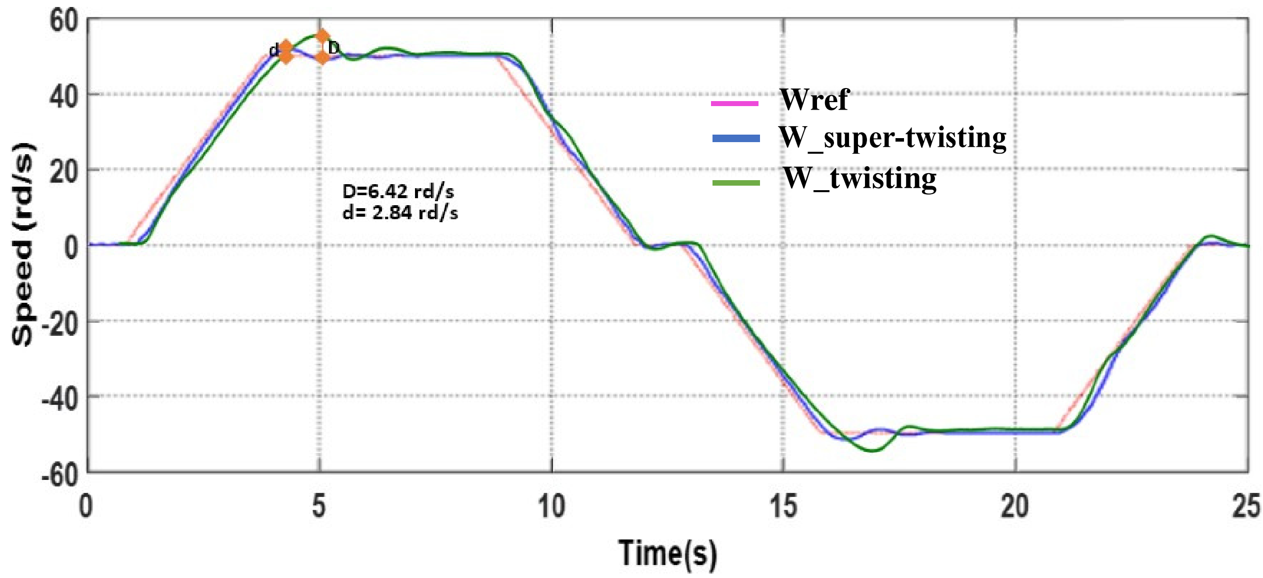
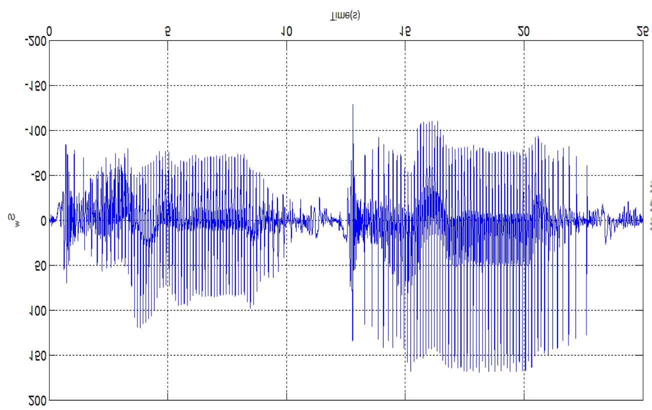


Figure 8 Reference and measured voltage curve with Super-twisting algorithm



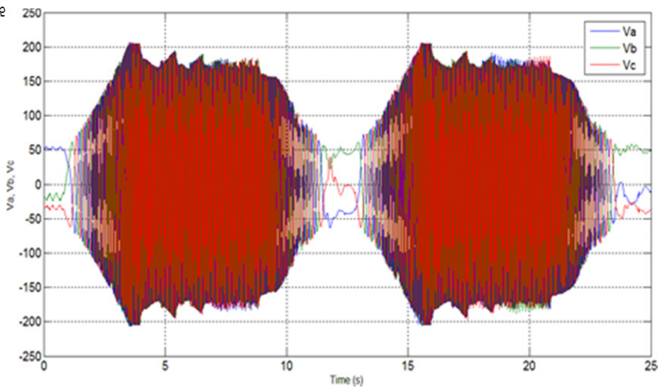


Figure 9 Sliding surface Sv (Algorithm of Twisting*)* Figure 10 Simple voltages Va ,Vb and Vc (Algorithm of super twisting controller)

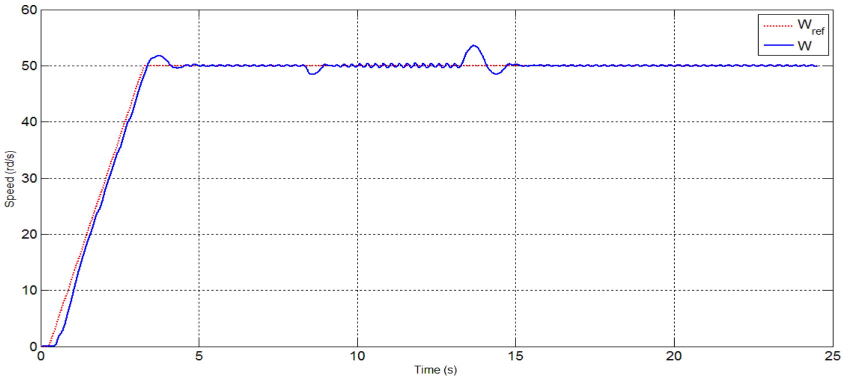


Figure 11 Robustness test (Super-Twisting)

A good tracking performance by the proposed controller, super twisting, can be appreciated in Table 2. From this table, we can observe a lower static error in the quadratic stator voltage by using super twisting controller. Super-twisting sliding mode control is a control scheme which suffers from the chattering effect without degrading the transient response, steady-state response and robustness. However, the twisting algorithm reduces the chattering phenomenon while retaining the robustness of the conventional sliding mode control approach.

Table2 : Comparaison between twisting and super twisting control

	Twisting Algorithm	**Super twisting Algorithm**
Static Error of Vqs	30%	10%
Vqs(in permanent regime)	120V	200V
Overshoot of rotor speed	6.42 rd/s	2.84 rd/s
Robustness test	Perturbed	Robust
Convergence time to permanent regime for rotor speed	6.5s	8.5s

6. CONCLUSIONS

As it was expected, the implementation of the super twisting showed a better performance of the torque and flux control measurement compared with measurement obtained from the twisting control of the second order of sliding mode. The combination of the super-twisting sliding mode controller and the high order sliding mode observer allowed us to control the torque and flux of the induction motor. From the experimental results showed in this paper, it was shown that the high-order sliding mode observer allowed us to estimate the altitude velocity and to estimate the disturbances that affect to the system's behavior. By using the information provided by the high-order sliding mode observer, the super-twisting sliding mode controller showed a satisfactory performance enabling the IMS to track a given reference. Finally, the extensive set of performed experiments allowed us to validate the proposed controller at different set points and under induced disturbances.

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