Robust Adaptive Variable Structure Control of Induction Motor Drives

Patxi Alkorta Egiguren§, Oscar Barambones Caramazana§, Izaskun Garrido Hernández, Aitor J. Garrido Hernández
EUITI de Eibar§/Vitoria§/Bilbao, University of the Basque Country, Avda de Otaola 29, 20600. Eibar (Spain)
patxi.alkorta@ehu.es, oscar.barambones@ehu.es

Abstract- In this document a new proposal of speed vector control of induction motors based on robust adaptive VSC (Variable Structure Control) law and its experimental validation are presented. This control scheme uses the SVPWM (Space Vector Pulse Width Modulation) instead of the traditional current hysteresis comparator, because the space vector modulator eliminates the instability risk when the motor works with large loads and provides best quality of the stator currents, maintaining the main characteristics of the original adaptive VSC algorithm: fast response and good rejection to uncertainties and measurement noises. This algorithm has an adaptive sliding gain that reduces the chattering phenomenon that usually appears in the traditional control schemes. Thus, this regulator is compared with the non adaptive SVPWM-VSC and the PI (Proportional Integral) controller designed in the frequency domain, in order to prove the good performance of the proposed controller. The controllers have been tested using various simulation and real experiments, with and without load, and in the proposed case, taking into account the parameter uncertainties and measurement noise in the loop signal, in the rotor speed and in the stator current. This work shows that the robust adaptive VSC regulator is a good and usable controller, in both adverse conditions and suitable conditions.

I. INTRODUCTION

There is a great interest in industrial applications for the use of AC induction motors, because these machines have a good behaviour provided by their solid architecture, low moment of inertia, low ripple of torque and high initiated torque. Some control techniques have been developed to regulate these induction motors servo drives in high-performance applications. One of the most popular techniques is the indirect field oriented control method [1], [2]. With the field-oriented technique, the decoupling of torque and flux control commands of the induction motor is guaranteed, so that the induction motor can be controlled linearly as a separated excited D.C. motor. Nevertheless, the control performance of the resulting linear system is still influenced by uncertainties, which are usually composed of unpredictable parameter variations, external load disturbances, and unmodelled and nonlinear dynamics. For that reason, many studies have been made on the motor drives in order to preserve the performance under these parameter variations and external load disturbances, such as nonlinear control, optimal control, variable structure system control and adaptive control [3], [4].

During the last years in order to overcome the above system uncertainties, the variable structure control strategy using the sliding-mode has been the focus of many studies and research for the control of the AC servo drive systems [5], [6], [7]. The sliding-mode control offers many good properties, such as good performance against unmodelled dynamics, insensitivity to parameter variations, external disturbance rejection and fast dynamic response [8]. These advantages of the sliding-mode control may be employed in the position and speed control of an AC servo system.

Recently, it has been proposed [9] an induction motor speed control based on VSC algorithm that may eliminate the speed tracking error in spite of the presence of important uncertainties and measurement noises. Even so, its control scheme uses a current control based on a hysteresis-band which may cause instabilities if the induction motor load torque and hysteresis-band are large, and also undesirable harmonics generation. The authors of the present paper propose a SVPWM control that eliminates the instability risk when the system work with load torque, improves the quality of the stator currents and reduces the harmonics generation.

The organization of this document is as follows. The design of the PI speed controller is introduced in second section. The third section contains the adaptive structure robust speed control design. In the fourth section, the adaptive variable structure speed control with current PI controller is introduced. Next, in the fifth section, the induction motor speed control simulation and experimental results are presented. Finally, in the last section, some concluding remarks are stated.

II. PROPORTIONAL INTEGRAL SPEED CONTROLLER DESIGN

The PI control algorithm is one the best known control algorithm. Its great popularity and extended use in the industry are due to its simple design and good performance. Also, often the PI control is used as a reference in order to compare other controllers with it. We know that the closed loop stability of the motor with the PI controller is guaranteed if the $PM_{mo}$ margin phase has a positive, sufficiently high value. Thus, the gains of the PI controller may be calculated ussing the frequency domain [10].

The PI control for an induction motor and the function of the blocks can be seen in Fig.1. The $ABC \Rightarrow dq$ block get the $i_x$, space vector from the $i_x$, $i_y \in \mathcal{C}$ motor stator currents, using the Park’s transformation [2], while the $dq \Rightarrow ABC$ block makes the reverse Park’s transformation. It should be noted that this transformations make use of the rotor flux angular position, $\theta_r$. 

582
and therefore this angle should be calculated using an indirect method.

The design involves, on the one hand, calculating the PI controller parameters, $K_p$ and $K_i$, for the $\omega_m$, mechanical rotor speed loop, and on the other hand, calculating the PI controller parameters, $K_{pi}$ and $K_{ii}$ for the two current loops, $i_{sd}$ and $i_{sq}$ [10], [12].

$$K_p = \frac{\text{tg}(PM_m)K_i}{\omega_m}$$  \hspace{1cm} (1)

$$K_i = \frac{J_\omega \text{tg}^2}{\sqrt{1+\text{tg}(PM_m)^2}}$$  \hspace{1cm} (2)

$$\delta = \text{tg}\left(\text{tg}\left(\frac{PM_m}{2} + \text{arctg}\left(\frac{\omega_m L_\sigma}{\sigma}\right)\right)\right)$$  \hspace{1cm} (3)

$$K_{ii} = \frac{\omega_m \sqrt{R_L^2 + (\omega_m L_\sigma \sigma)^2}}{1 + \delta^2}$$  \hspace{1cm} (4)

$$K_{pi} = \frac{K_{ii} \delta}{\omega_m}$$  \hspace{1cm} (5)

when

$$\sigma = 1 - \frac{L_m^2}{L_i L_r}$$  \hspace{1cm} (6)

III. ADAPTIVE VARIABLE STRUCTURE SPEED CONTROLLER DESIGN

When the VSC uses the sliding mode is known to offer some good properties just as a good behaviour in the presence of unmodeled dynamics, load disturbances, parameter variations and measurement noises, and it also offers a fast dynamic response [8]. These properties can be used in the vector speed control of induction motor drives. The stability of the proposed motor controller is demonstrated using the Lyapunov stability theory.

From the motor electromagnetic torque equation (7)

$$T_e = \frac{3p L_m}{4 L_r} \Psi_{rd} i_{sq} = K_T i_{sq}$$  \hspace{1cm} (7)

where $K_T$ is the torque constant (8) and $\Psi_{rd}$ is the rotor flux command

$$K_T = \frac{3p L_m}{4 L_r} \Psi_{rd}$$  \hspace{1cm} (8)

and the mechanical equation (9)

$$J\ddot{\omega}_m + B\omega_m + T_L = T_e$$  \hspace{1cm} (9)

it is obtained

$$\dot{\omega}_m + a\omega_m + f = b i_{sq}$$  \hspace{1cm} (10)

where the parameters are defined as

$$a = \frac{B}{J}, b = \frac{K_T}{J}, f = \frac{T_L}{J}$$

Now, the previous mechanical equation (9) is considered, with $a, f$ and $b$ terms uncertainties ($\Delta a, \Delta f, \Delta c$).
The speed tracking error is defined as
\[ e(t) = \omega_m(t) - \omega_m^*(t) \]  \hspace{1cm} (12)
where \( \omega_m^* \) is the rotor speed command. Taking the derivative of the previous equation respect to time yields
\[ \dot{e}(t) = \dot{\omega}_m(t) - \dot{\omega}_m^*(t) = -ae(t) + u(t) + d(t) \]  \hspace{1cm} (13)
where
\[ u(t) = bi_{sq} - a\omega_m^* - f(t) - \omega_m^* \]  \hspace{1cm} (14)
and the uncertainty terms have been collected in the signal \( d(t) \)
\[ d(t) = -\Delta a\omega_m - \Delta f + \Delta bi_{sq} \]  \hspace{1cm} (15)
Next it is defined the sliding variable \( S(t) \) with an integral component as
\[ S(t) = e(t) + \int_0^t (k + a)e(\tau)d\tau \]  \hspace{1cm} (16)
Then the sliding surface is defined as: \( S(t) = 0 \). Now it is designed a variable structure speed controller, that incorporates an adaptive sliding gain, in order to control the induction motor drive
\[ u(t) = -ke(t) - \hat{\beta}(t)\gamma \text{sgn}(S) \]  \hspace{1cm} (17)
where \( \text{sgn}(\cdot) \) is the sign function, \( \hat{\beta} \) is the estimated switching gain, and \( \gamma \) is a positive constant. The switching gain, \( \dot{\hat{\beta}} \), is adapted according the following control law:
\[ \dot{\hat{\beta}} = \gamma |S| \quad \hat{\beta}(0) = 0 \]  \hspace{1cm} (18)
where \( \gamma \) is a positive constant that allow us to choose the adaptation speed for the sliding gain.
In order to obtain the speed trajectory tracking, the following assumptions should be formulated:  
(A1) The gain \( k \) must be chosen so that the term \((k+a)\) is strictly positive. Therefore the constant \( k \) should be \( k>-a \).  
(A2) The gain \( \beta \) must be chosen so that \( \beta \geq |d(t)| \) for all time.  
(A3) The \( \gamma \) constant must be chosen so that \( \gamma \geq 1 \)

Theorem 1. Consider the induction motor given by equation (11), and if assumptions (A1), (A2) and (A3) are verified, the control law (14) gives the rotor mechanical speed \( \omega_m(t) \) so that speed tracking error (12) tends to zero as the time tends to infinity.
This is demonstrated in [11], using for it the function candidate (19) and the Lyapunov stability theory,
\[ V(t) = \frac{1}{2}S(t)S(t) + \frac{1}{2}\hat{\beta}(t)\hat{\beta}(t) \]  \hspace{1cm} (19)
where the \( S(t) \) is the sliding variable defined previously, and
\[ \hat{\beta}(t) = \hat{\beta}(t) - \beta \]  \hspace{1cm} (20)
Finally it is concluded that \( S(t) \) tends to zero as the time \( t \) tends to infinity. Moreover, all trajectories starting off the sliding surface \( S(t)=0 \), must reach it and then remain on this surface. This system’s behaviour once on this sliding surface is called sliding mode [8]. When the sliding mode occurs on the sliding surface, then \( \dot{S}(t) = S(t) = 0 \), and therefore the dynamic behaviour of the tracking problem is equivalently governed by the following equation:
\[ \dot{S}(t) = 0 \Rightarrow \dot{e}(t) = -(a+k)e(t) \]  \hspace{1cm} (21)
Then, under assumption (A1), the tracking error \( e(t) \) converges to zero exponentially. Finally, the torque current command, \( i_{sq}^* \), can be obtained directly substituting (17) in (14):
\[ i_{sq}^*(t) = \frac{1}{b}\left[ -ke - \hat{\beta}\gamma \text{sgn}(S) + a\omega_m^* + \omega_m^* + f \right] \]  \hspace{1cm} (22)
We must know that in the previous version, non adaptive VSC, [9]
\[ u(t) = -ke(t) - \beta\text{sgn}(S) \]  \hspace{1cm} (23)
\[ i_{sq}^*(t) = \frac{1}{b}\left[ -ke - \beta\text{sgn}(S) + a\omega_m^* + \omega_m^* + f \right] \]  \hspace{1cm} (24)
where \( \beta \) is a positive constant.

IV. SVPWM ADAPTIVE VARIABLE STRUCTURE
It is well known that the highest efficiency on the induction machines is obtained when the stator currents are pure sinusoidal ones, and also that the current control based in the hysteresis-band it is not used in real implementations because this method produces a lot of harmonics in the stator currents of the induction motor. Thus, in this document it is proposed the replacement of hysteresis-band module [11] for the SVPWM modulator in order to eliminate the harmonics generated for the hysteresis-band current control, [12]. This modulator needs the stator voltage three-phase command but the VSC controller gives the current command, then this
problem is solved using two PI controllers: they convert the two current commands in two voltage commands and subsequently they can be converted through the \( dq \xrightarrow{ABC} \) block in the required three-phase voltage command, Fig. 3.

![Diagram of adaptive VSC speed control of induction motor with the PI current control and SVPWM.](image)

Fig. 3. Diagram of adaptive VSC speed control of induction motor with the PI current control and SVPWM.

V. SIMULATION AND REAL TESTS

The control platform used to verify these control algorithms for induction motors [12], incorporates a unit that let us test these algorithms when the induction motor has a load (load torque), Fig. 4. This unit has been implemented with a direct current machine functioning like a generator and connected by the shaft to the induction motor. Its control governs a dc/dc converter by means of a PWM unit that receives an equivalent load torque reference for the induction motor.

The direct current motor is a machine of 24kW and when it is connected to the induction machine, the moment of inertia \( J \) and the viscous friction coefficient \( B \) of the induction motor are incremented. In this sense, the induction motor, that is a machine of 7.5kW of squirrel-cage type, presents the following parameters:

- \( R_s, \) stator resistance, 0.57 \( \Omega \)
- \( R_r, \) rotor resistance, 0.81 \( \Omega \)
- \( L_m, \) magnetising inductance, 0.117774 mH
- \( L_s, \) stator inductance, 0.120416 mH
- \( L_r, \) rotor inductance, 0.121498 mH
- \( p, \) number of poles, 4
- \( J, \) moment of inertia, 0.2 kg m\(^2\)
- \( B, \) viscous friction coefficient, 0.1 Nm/(rad/s)

The rotor flux of the induction motor has been fixed to its nominal value of 1.01 Wb, keeping the flux current command, \( i_{sd}^*, \) to a constant value of 8.61 A. On the other hand, the electromagnetic torque current command \( i_{sq}^* \) has also been fixed to 20 A, to limit and to protect the over currents in the induction motor’s stator fed.

A. Speed tracking

Besides of the disadvantage that supposes to use the hysteresis band module in spite of the SVPWM modulator, due to the harmonics generation in the stator currents, there is another problem that appears when this module is used with the variable structure control and the motor has a load, Fig. 5. The system can convert to unstable if the load and the hysteresis band are large (20,5A, in this case), while if the SVPWM is used at the same conditions, it doesn’t occur, Fig. 6. If we compare the graphs of Fig. 5 and 6, we can verify that these two drawbacks are not present in this new proposal.

For the other hand, we will compare the new proposal adaptive VSC with the non adaptive VSC and the PI model. The following values have been chosen for the new proposed adaptive SVPWM-VSC: \( k = 14 \) and \( \gamma = 1.091 \) for the \( \omega_m \) rotor speed loop, and \( \omega_{ci} = 250 \text{ rad/s} \) and \( \text{PMi} = 70 \text{ rad/s} \) for the \( i_{sd} \) and \( i_{sq} \) current loops. For the non adaptive SVPWM-VSC: \( k = 14 \) and \( \beta = 600 \), and \( \omega_{ci} = 250 \text{ rad/s} \) and \( \text{PMi} = 70 \text{ rad/s} \). The uncertainties in the parameters have been fixed to \(+20\%\) for all tests in VSC controllers. About PI controller, they are the design parameters: for the rotor speed loop, \( \omega_i = 25 \text{ rad/s} \), \( \text{PM} = 45 \text{ rad/s} \), and for the currents loops, \( \omega_{ci} = 250 \text{ rad/s} \) and \( \text{PMi} = 70 \text{ rad/s} \). In all these cases a torque load of 12.5 Nm has been used.

Fig. 9 shows the graphs of the simulation test and real implementation for the new proposal, and the Fig. 7 shows for the non adaptive SVPWM-VSC proposal. Comparing the graphs of Fig. 7 and 9, it is possible to observe that the new proposed design offers the same effectiveness of control that the original one, and that in addition the chattering phenomenon doesn’t exist, and in the last of test, the speed error is much more smaller, concretely smaller or equal to 5 rpm (1% of the reference amplitude), both in the simulation as in the real implementation. Also, it is possible to see the evolution of the sliding gain: its value is increasing from zero to the last value, while the speed error is decreasing down to a very small value.
Fig. 5. Graphs of the simulation test of the adaptive VSC model with 24 Nm of the load (13 plus 11 starting from 3 s) and 20.5 A of hysteresis band: on the top speed reference and response, in middle $i_A$ stator current, and down, $S$ sliding variable.

Fig. 6. Graphs of the simulation and real tests of the proposed adaptive SVPWM-VSC with 24 Nm of the load (13 plus 11 starting from 3 s): on the top speed reference and response, in middle $i_A$ stator current, and down, $S$ sliding variable.

Fig. 7. Graphs of the simulation and real tests of the non adaptive SVPWM-VSC model with $\beta=600$ and 12.5 Nm of the load: on the top speed reference and response, in middle speed error, and down, electromagnetic and load torque.

Fig. 8. Graphs of the simulation and real test of the PI model with 12.5 Nm of the load: speed reference and response.

Fig. 9. Graphs of the simulation and real tests of the proposed adaptive SVPWM-VSC model with 12.5 Nm of the load: on the top speed reference and response, in middle, first speed error, and second electromagnetic and load torque, and down, $\beta$ adaptive sliding gain.

Fig. 10. Graphs of the simulation and real tests of the proposed adaptive SVPWM-VSC model with 12.5 Nm of the load: on the top speed reference and response, in middle, first speed error, and second electromagnetic and load torque, and down, $\beta$ adaptive sliding gain.

Fig. 8 shows the result of the PI controller. It can be seen that the induction motor response and the tracking error are very good. But the adaptive SVPWM-VSC gets the reference speed some time before. This detail can be important when the motor is working with a higher reference frequency, like it is shown in Fig. 10.
spite of everything, it may be observed that the real adaptive speed tracking is good in the adverse conditions. SVPWM-VSC controller works correctly and therefore the use of the two feedback signals. In all tests, the moment of inertia, when the controller is designed supposing that \( J^* = 0.1667 \text{ kg m}^2 \), and using different noise levels in the two feedback signals: \( \omega_m \) and \( i_A \). The graphs of the real tests for 300 rpm and 0.5 Hz square reference signal, and \( i_A \) stator current, using the adaptive SVPWM-VSC control.

B. Uncertainties and measurement noise rejection

The real tests have been made introducing the uncertainty in the moment of inertia, when the controller is designed supposing that \( J = 0.2 \text{ kg m}^2 \) and \( \omega_m \) and \( i_A \) without noise measurement, while the real tests have been done with \( J^* \) and a high level of noise in the measurement of the two feedback signals. In all tests, the moment of inertia is \( J = 0.2 \text{ kg m}^2 \) (+ 20% of \( J^* \)) and the load torque is 15 Nm. In spite of everything, it may be observed that the real adaptive SVPWM-VSC controller works correctly and therefore the speed tracking is good in the adverse conditions.

VI. CONCLUSIONS

This work presents and experimentally validates in real time a new adaptive SVPWM-VSC controller for speed control of induction motors. The main contribution of this work consists of the elimination of the chattering phenomenon from the electromagnetic torque, and also, the removal of the instability risk when the motor works with large loads. On the one hand, in order to eliminate the chattering phenomenon, the sliding gain is designed like a adaptive parameter instead of a constant. On the other hand, the current control based on the hysteresis comparator is replaced by the SVPVM modulation. This new control, adaptive SVPWM-VSC control scheme, has been compared with the non adaptive SVPWM-VSC control and the PI control, by means of some simulations and some real tests. The controllers have been compared both with load and without load conditions, and it is concluded that SVPWM-VSC control offers an answer better than the non adaptive version and PI control. Also, the new proposal has been tested in very adverse situations of measurement noise and uncertainties, and it is concluded that the adaptive SVPWM-VSC is a robust controller in real situations. The real experiments allow us to conclude that the control platform is a very efficient tool due to the great similarity existing between the results of the simulation tests and the experimental ones.

ACKNOWLEDGEMENT

The authors are very grateful to the MEC by the support of this work through the research project DPI2006-01677 and DPI2006-00714. They are also grateful to UPV/EHU and Basque Government by its support through EHU 06/88 and S-PE07UN04, respectively.

REFERENCES