



Full Length Research Article

HIGH PERFORMANCE SPEED OF THE INDUCTION MOTOR DRIVES BY THE PREDICTIVE CONTROL USING SPACE VECTOR MODULATION

***Lakhdar Djaghdali, Belkacem Sebti and Farid Naceri**

Department of Electrical Engineering, University of Batna Street Chahid Med El Hadi boukhrouf, Batna 05000, Algeria

ARTICLE INFO

Article History:

Received 21st March, 2015
Received in revised form
30th April, 2015
Accepted 06th May, 2015
Published online 28th June, 2015

Key words:

Induction Motor,
Predictive control,
Space vector modulation (SVM).

ABSTRACT

This paper investigates the application of the generalized predictive control (GPC), in order to control the speed of the induction motor. This application is based on four main ideas : reproducing decision basic mechanisms of human behaviour; the creation of an anticipatory effect by operation of the path to follow in the future; defining a numerical prediction model; minimization of a quadratic criterion with finite horizon and the principle of receding horizon. The results proved that the induction motor with the MPC speed controller has superior transient response, and good robustness in face of uncertainties including load disturbance. Moreover, accurate tracking performance has been achieved.

Copyright © 2015 Lakhdar Djaghdali et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

INTRODUCTION

AC induction motors have been widely used in industrial applications such as machine tools, steel mills and paper machines owing to their good performance provided by their solid architecture, low moment of inertia, low ripple of torque and high starting torque. Some control techniques have been developed to regulate these induction motor servo drives in high-performance applications. One of the most popular technique is the indirect field oriented control method (Egiguren *et al.*, 2008). The field-oriented technique guarantees the decoupling of torque and flux control commands of the induction motor, so that the induction motor can be controlled linearly as a separated excited d.c. motor. However, the control performance of the resulting linear system is still influenced by uncertainties, which are usually composed of unpredictable parameter variations, external load disturbances, measurement noise and unmodelled and nonlinear dynamics. Therefore, 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, adaptive control, neural control and predictive control (Egiguren *et al.*, 2008 and Marino *et al.*, 1998).

Since D. Clarke proposed in 1987 (Clarke *et al.*, 1987) the generalized predictive control design principles, a lot of authors have used this advanced technique in induction motors control. In the past decade, the generalized predictive control strategy has been focused on many studies and research for the control of the ac servo drive systems. The generalized predictive control lets to know the future sequence of the output and thus it is possible to calculate the optimal control signal for that output, when the reference is known a priori. In these sense, the system can react before the change has effectively been made, thus avoiding the effects of delay in the process response, (Egiguren *et al.*, 2008). Generally, for a greater number of the know future samples, the obtained control signal is better than the contrary case, but with the inconvenient of greater computation requirements for the controller, (Kennel *et al.*, 2001).

***Corresponding author: Lakhdar Djaghdali**

Department of Electrical Engineering, University of Batna Street Chahid Med El Hadi boukhrouf, Batna 05000, Algeria

However the gpc has other issues. on the one hand, it has the added difficulty of the existence of constraints, that is, the study of the control system taking account the limitations of the real system like saturation values, frequency and time limits, etc, (Egiguren *et al.*, 2008 and Rodríguez and Dumur, 2005). On the other hand, it has to be dealt with the presence of external disturbances (Camacho and Bordons, 2004) (known and unknown) and measurement of noise. Other important issue is the robustness of the gpc controller, (Egiguren *et al.*, 2008 and Rodríguez and Dumur, 2005).

In this paper, we present some brief philosophy of the principle and the interests of predictive control, we applied this command on the induction machine for speed control (fig. 3), where the torque and flux are regulated by pi controller (Belkacem, 2011 and Lai and Chen, 2001). The control voltages can be generated by pi and imposed by SVM technique (Zhou and Wang, 2002). In addition, the estimate of the torque and flux are based on the model of the machine voltage. The results of simulation show high dynamic performance.

MODEL OF THE MACHINE FOR THE CONTROL

Among the various types of models used to represent the induction machine, there is one that uses each of the stator currents, stator flux, and speed as state variables and voltages (Vsd, Vs_q) as control variables. This model is presented in reference (d, q), related to the rotating field. This model is expressed by the following system of equations (Carloss, 2000 and Grellet and Clerc, 2000):

$$\begin{cases} V_{ds} = R_s \cdot I_{ds} + \frac{d\Phi_{ds}}{dt} - \omega_s \cdot \Phi_{qs} \\ V_{qs} = R_s \cdot I_{qs} + \frac{d\Phi_{qs}}{dt} + \omega_s \cdot \Phi_{ds} \\ V_{dr} = 0 = R_r \cdot I_{dr} + \frac{d\Phi_{dr}}{dt} - (\omega_s - p\Omega) \cdot \Phi_{qr} \\ V_{qr} = 0 = R_r \cdot I_{qr} + \frac{d\Phi_{qr}}{dt} + (\omega_s - p\Omega) \cdot \Phi_{dr} \end{cases} \quad (1)$$

In addition, the components of the stator and rotor flux are expressed by:

$$\begin{cases} \Phi_{ds} = L_s \cdot I_{ds} + L_m \cdot I_{dr} \\ \Phi_{qs} = L_s \cdot I_{qs} + L_m \cdot I_{qr} \\ \Phi_{dr} = L_r \cdot I_{dr} + L_m \cdot I_{ds} \\ \Phi_{qr} = L_r \cdot I_{qr} + L_m \cdot I_{qs} \end{cases} \quad (2)$$

Moreover, the mechanical equation of the machine is given by:

$$j \frac{d\Omega}{dt} + f\Omega = T_e - T_r \quad (3)$$

The electromagnetic torque equation can be expressed in terms of stator currents and stator flux as follows:

$$T_e = p \cdot (\Phi_{ds} \cdot I_{qs} - \Phi_{qs} \cdot I_{ds}) \quad (4)$$

- Where $(I_{ds}, I_{qs}) ; (V_{ds}, V_{qs}) ; (\Phi_{ds}, \Phi_{qs}) ; (\Phi_{dr}, \Phi_{qr})$ are currents, voltages, and stator and rotor flux axis d-q.
- (R_s, R_r) : stator and rotor resistance.
- (L_s, L_r) : stator and rotor Cyclic Inductance.
- (L_m, p) : mutual Inductance and Number of pole pairs.
- (ω_s, Ω) : Stator pulsation and mechanical rotor speed.

THE PHILOSOPHY OF THE PREDICTIVE CONTROL

The philosophy of predictive control model knows the output of the process controlled to determine the command to make it join the set point according to a predefined path (reference trajectory) on the output of the process in accordance with (Fig.1) (Boucher and Dumur, 1996 and Camacho and Bordons, 2003). It is therefore to determine the sequence of future control applied to the input of the process to achieve the rallying. In reality, the process model called internal model predicts that the evolution of its own output, since the model adopted is flawed because of misidentification, is due to non considered disturbances and simplifications to use in real- time (Thomas and Hansson, 2010). As a result, the output of the process is different from the model.

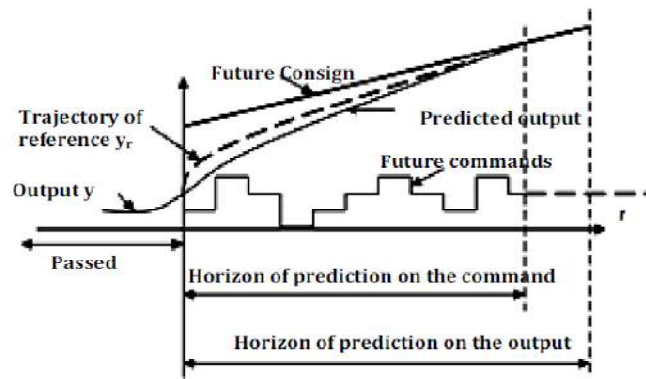


Fig.1. Time Evolution of the Finite Horizon Prediction

THE PRINCIPLE AND GENERAL STRATEGY OF PREDICTIVE CONTROL

The basic principle of predictive control is taken into account, at the current time of the future behavior, through explicit use of a numerical model of the system in order to predict the output on a finite horizon in the future, (Ahmed A. Zaki Diab *et al.*, 2013). One of the advantages of predictive methods lies in the fact that for a pre-calculated set on a horizon, it is possible to exploit the information of predefined trajectories located in the future, given that the aim is to match the output of system with this set on a finite horizon.

In general, the predictive control law is obtained from the following methodology:

Predict future process outputs the prediction horizon defined by using the prediction model. These outputs are dependent on the output values of the input process known to control up to time t (Camacho and Bordons, 2003). Determine the sequence of control signal, by minimizing a performance criterion to conduct the process output to an output reference (Garcia *et al.*, 1989). Usually the performance criterion to be minimized is a compromise between a quadratic function of the error between the predicted output and the desired future, and the cost of control effort. Moreover, the minimization of such a function can be subject to state constraints and more generally to constraints on the order. The control signal $u(t)$ is sent to the process while the other control signals are ignored at time $t+1$, we acquire the actual output $y(t+1)$ and again in the first (Papafotiou and Kley, 2009 and Camacho and Bordons, 2003).

INTERESTS OF THE PREDICTIVE CONTROL

Most industrial regulations are often made with analog PID controllers with remarkable efficiency and price/performance ratio with which it is difficult to compete. However, this type of controller does not cover all the needs and the performance suffers in a range of applications which we quote:

Difficult Process, especially nonlinear, unsteady, high pure delay and also multivariate (Karamanakos *et al.*, 2014). When performance is tensioned by the user, including: high attenuation of disturbances, following error zero tracking, minimum response time, which leads to function under constraints that affect on the control variables, and even the internal variables of the process (Camacho and Bordons, 2003 and Karamanakos *et al.*, 2014). Wealth of predictive control arises from the fact that it is not only capable of controlling simple processes of the first and second order, but also complex processes, including processes with time delay long enough, unstable loop process opened without the designer takes special precautions too. During the last years, different predictive controller structures have been developed (Garcia *et al.*, 1989), including the generalized predictive control (GPC).

GENERALIZED PREDICTIVE CONTROL

The generalized predictive control (GPC) of Clarke (Papafotiou and Kley, 2009), is considered as the most popular method of prediction, especially for industrial processes. This resolution is not repeated each time there is an optimal control problem: "how to get from the current state to a goal of optimally satisfying constraints" (Rawlings and Mayne, 2009). For this, you must know at each iteration the system state using a numerical tool. Temporal representation of generalized predictive control is given by (Fig.2), where there are controls $u(k)$ applied to the system for rallying around the set point $w(k)$. Numerical model is obtained by a discretization of the continuous transfer function of the model which is used to calculate the predicted output of a finite horizon.

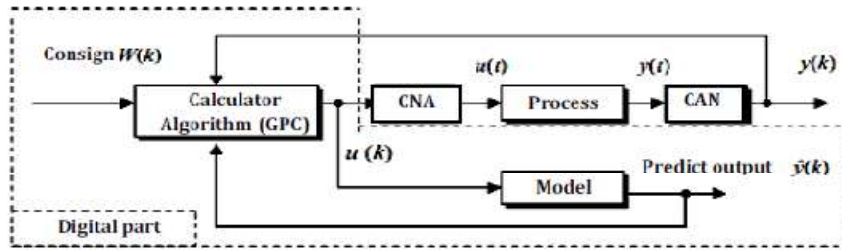


Fig. 2. Diagram block of the GPC

FORMULATION OF THE MODEL

All predictive control algorithms differ from each other by the model used to represent the process and the cost function to be minimized. The process model can take different representations (transfer function by state variables, impulse response...), for our formulation, the model is represented as a transfer function.

CRITERION OPTIMIZATION

We must find the future control sequence to apply the system to reach the desired set point by following the reference trajectory. To do this, we just minimize a cost function which differs according to the methods. But generally this function contains the squared errors between the reference trajectory, the predictions of the prediction horizon and the variation of the control (Boucher and Dumur, 1996). This cost function is as follows:

$$J = \sum_{j=N_1}^{N_2} [w(t+j) - \hat{y}(t+j)]^2 + \lambda \sum_{j=1}^{N_u} \Delta u(t+j-1)^2 \quad (5)$$

With:

$w(t+j)$: Set point applied at time $(t+j)$.

$\hat{y}(t+j)$: Output predicted time $(t+j)$.

$\Delta u(t+j-1)$: Increment of control at the moment $(t+j-1)$.

N_1 : Minimum prediction horizon on the output.

N_2 : maximum Prediction Horizon on the output with $N_2 \geq N_1$.

N_u : prediction Horizon on the order.

λ : Weighting factor on the order.

T_s : The period of sampling.

The criteria expression call for several comments:

When there are actually values of the set point in the future, all of these informations are used between horizons of N_1 and N_2 so as to converge the predicted output to this set point. There is the incremental aspect of the system by considering Δu in the criteria. The coefficient λ is used to give more or less weight to the control relative to the output, so as to ensure the convergence when the starting system is a risk of instability (Qin and Badgwell, 2003).

CHOICE OF THE PARAMETERS OF CONTROL

The definition of the quadratic criterion (l'eq-5) showed that the user must set four parameters. The choice of parameters is difficult because there is no empirical relationship to relate these parameters to conventional measures in automatically.

N_1 : minimum horizon of prediction is the pure delay system, if the delay is known or we should initialize to 1.

N_2 : maximum horizon is chosen so that the product $N_2 T_s$ is limited by the value of the desired response time. Indeed increase beyond the prediction of the response time provides no additional information. In addition, the more N_2 is larger, the system is stable and slow.

N_u : horizon of control, we should choose equal to 1 and not exceeding the value of two.

λ : weighting factor of the order, this is the most complicated to set parameter since it influences the stability of the closed loop system. Indeed, if λ is very high, it helps to balance the influence of the orders in the optimization, and thus can generate a correction more or less energetic; therefore more or less rapid.

REGULATING THE SPEED OF THE INDUCTION MACHINE BY PREDICTIVE CONTROL

We will regulate the speed of the induction machine by the laws of predictive control (Fig. 3). This figure comprises two loops one with two internal PI controllers is used to control the torque and flux and the other external to regulate the speed based on predictive control laws presented above. The transfer function of the torque-speed end of the mechanical equation can be represented in the ongoing plan by the following transfer:

$$\frac{\Omega(s)}{T_e^*(s)} = \frac{1}{js + f} \tag{6}$$

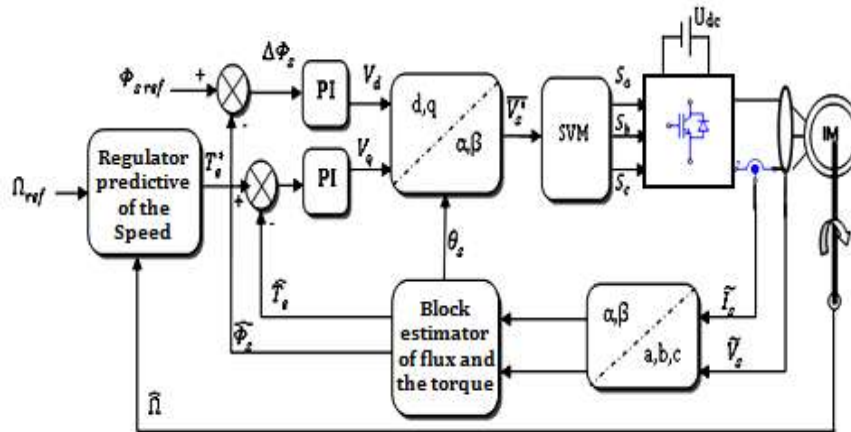


Fig. 3. Block diagram the speed control of the IM by the predictive control

SPACE VECTOR PULSE WIDTH MODULATION

The voltage vectors, produced by a 3-phase PWM inverter, divide the space vector plane into six sectors as shown in (Fig. 4).

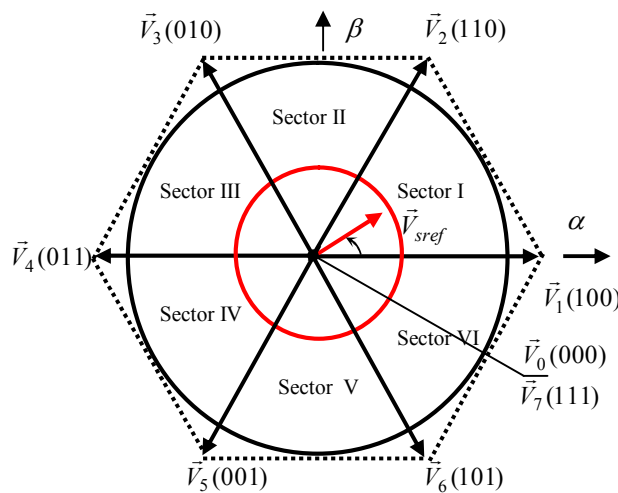


Fig. 4. The diagram of voltage space vectors

In every sector, the voltage vector is arbitrary synthesized by basic space voltage vector of the two sides of one sector and zero vectors. For example, in the first sector, \$V_{sref}\$ is a synthesized voltage, space vector and its equation is given by (Zhou and Wang, 2002).

$$\vec{V}_{sref} T_s = \vec{V}_0 T_0 + \vec{V}_1 T_1 + \vec{V}_2 T_2 \tag{7}$$

$$T_s = T_0 + T_1 + T_2 \tag{8}$$

Where, T_0 , T_1 and T_2 is the work time of basic space voltage vectors \bar{V}_0 , \bar{V}_1 and \bar{V}_2 respectively.

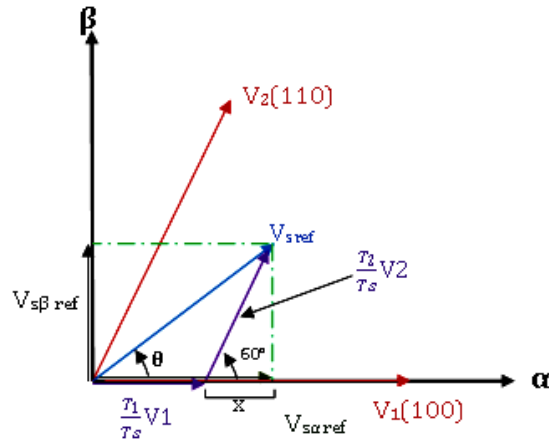


Fig. 5. Projection of the reference voltage vector

The determination of the amount of times T_1 and T_2 given by mere projections is:

$$\begin{cases} V_{s\alpha ref} = \frac{T_1}{T_s} |\bar{V}_1| + x \\ V_{s\beta ref} = \frac{T_2}{T_s} |\bar{V}_2| \sin(\frac{\pi}{3}) \\ x = \frac{V_{s\beta ref}}{\text{tg}(\frac{\pi}{3})} \end{cases} \Rightarrow \begin{cases} T_1 = \frac{T_s}{2U_{dc}} (\sqrt{6}V_{s\alpha ref} - \sqrt{2}V_{s\beta ref}) \\ T_2 = \frac{T_s\sqrt{2}}{U_{dc}} V_{s\beta ref} \end{cases} \quad (9)$$

The rest of the period is applying the null-vector. For every sector, switching duration is calculated. Amount of times the vector implementation can all be related to the Following variables:

$$\begin{cases} X = \frac{T_s}{U_{dc}} (\sqrt{2}V_{s\beta ref}) \\ Y = \frac{T_s}{2U_{dc}} (\sqrt{6}V_{s\alpha ref} + \sqrt{2}V_{s\beta ref}) \\ Z = \frac{T_s}{2U_{dc}} (-\sqrt{6}V_{s\alpha ref} + \sqrt{2}V_{s\beta ref}) \end{cases} \quad (10)$$

The implementation of the duration sector boundary vectors are tabulated as follows:

Table 1. Durations of the sector boundary vectors

Sector	1	2	3	4	5	6
T_i	-Z	Y	X	Z	-Y	-X
T_{i+1}	X	Z	-Y	-X	-Z	Y

The third step is to compute the duty cycles have three necessary times:

$$\begin{cases} T_{aon} = \frac{T_s - T_i - T_{i+1}}{2} \\ T_{bon} = T_{aon} + T_i \\ T_{con} = T_{bon} + T_{i+1} \end{cases} \quad (11)$$

The last step is to assign the duty cycle (T_{xon}) to the motor phase according to the sector.

Table 2. Assigned duty cycles to the PWM outputs

Sector	1	2	3	4	5	6
S _a	T _{aon}	T _{bon}	T _{con}	T _{con}	T _{bon}	T _{aon}
S _b	T _{bon}	T _{aon}	T _{aon}	T _{bon}	T _{con}	T _{con}
S _c	T _{con}	T _{con}	T _{bon}	T _{aon}	T _{aon}	T _{bon}

RESULTS OF SIMULATION

In the absence of general analytical rules leading to the choice of the synthesis parameters of a predictive control based on the type of process and required performance, the implementation practice always requires several simulation tests to finally arrive at an optimal choice. To test the effectiveness of the control strategy is going to make the choice to optimize the controller parameters by changing the parameters each one and see their effect on the performance of control, leading to a better choice of (speed, response time, overshoot, stability etc). To illustrate the performance of the predictive control applied to the speed control, the machine was simulated with a reference speed of 100 rd/s vacuum and then applying a nominal load of 20 Nm at t = 0.5 s to t = 1 s, then the motor is subjected to a target change speed 100 rd/s to -100rd/s.

a. INFLUENCE THE HORIZON OF PREDICTION N₂

N₂ is varied to see its effect on performance. The following figures show the evolution of the output (speed of induction machine) for different values of N₂.

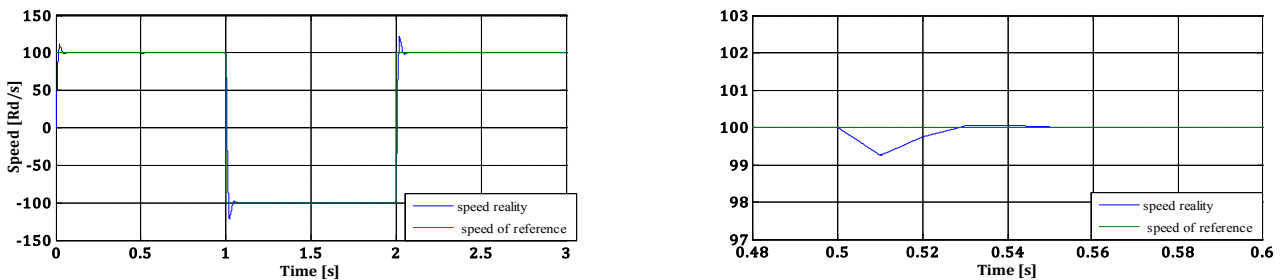


Fig. 6 Evolution of speed for N₁ = 1, N₂ = 1, N_u = 1, λ = 0.8

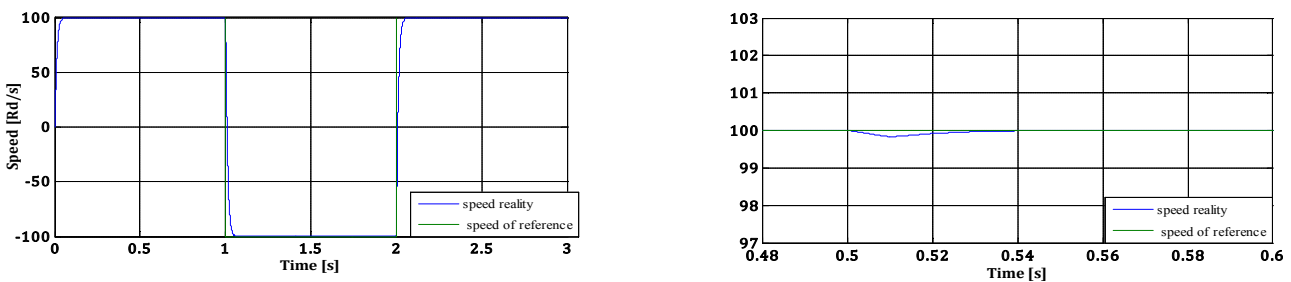


Fig. 7 Evolution of the speed N₁ = 1, N₂ = 2, N_u = 1, λ = 0.8

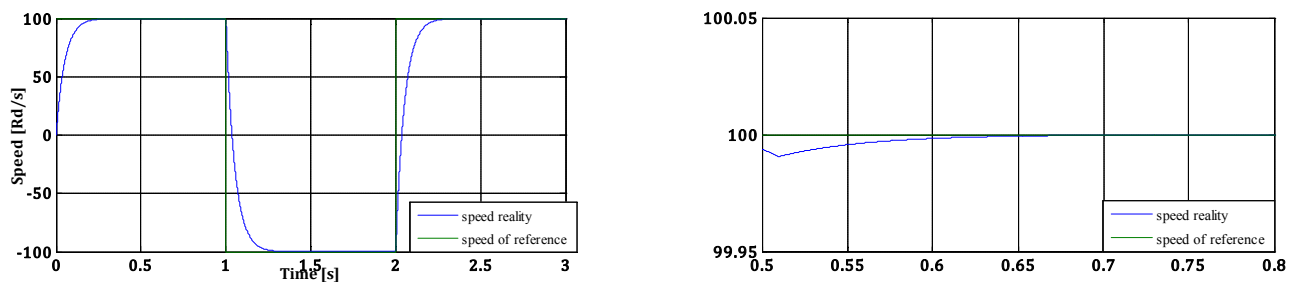


Fig. 8 Evolution of speed for N₁ = 1, N₂ = 8, N_u = 1, λ = 0.8

DISCUSSION OF THE RESULTS

It is remarkable that a significant increase in the prediction horizon (N_2) results in a slow response in the system while a too strong decrease results in a large overshoot of the set point. Time mounted increases with a positive variation of N_2 and decreases with a negative variation of N_2 .

b. INFLUENCE THE WEIGHTING COEFFICIENT λ

λ is varied to see its effect on performance. The following figures show the evolution of the output (speed of the machine) for deferent values of λ .

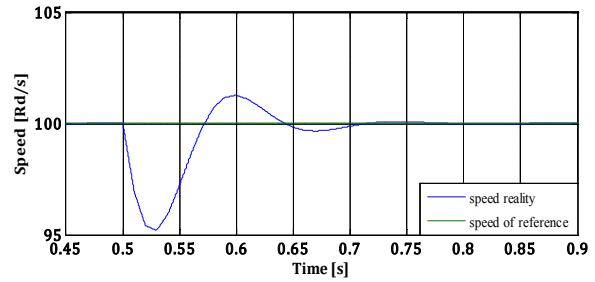
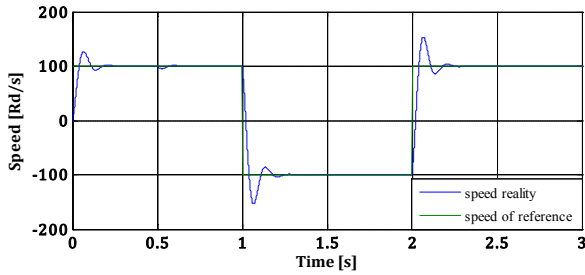


Fig. 9 Evolution of the speed $N_1 = 1, N_2 = 2, N_u = 1, \lambda = 0.55$

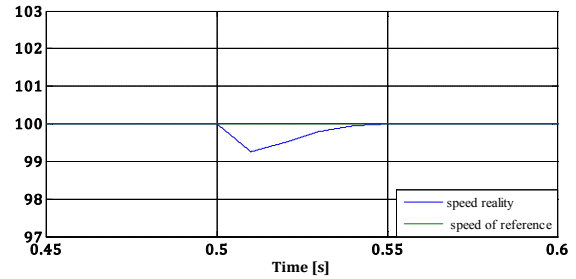
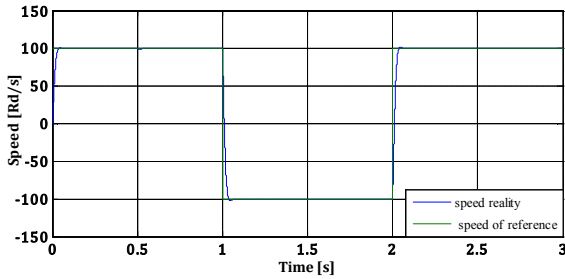


Fig.10 Evolution of speed for $N_1 = 1, N_2 = 2, N_u = 1, \lambda = 0.7$

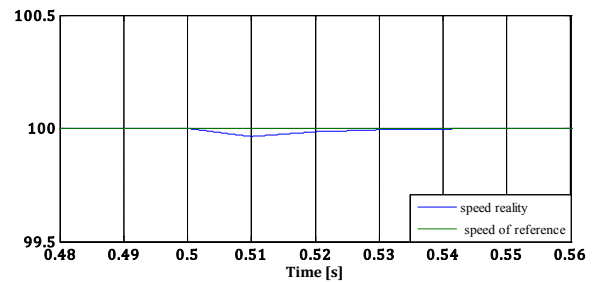
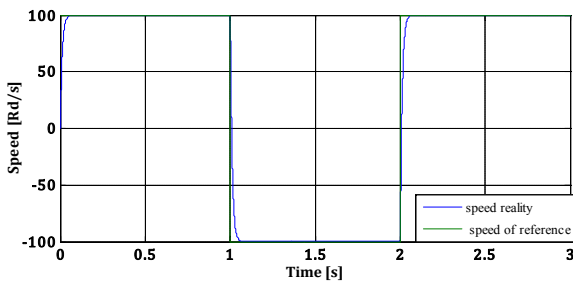


Fig.11 Evolution of speed for $N_1 = 1, N_2 = 2, N_u = 1, \lambda = 0.9$

DISCUSSION OF THE RESULTS

From the system response for deferent values of λ , we see an increase in weighting on the control (λ) results in a decrease in the response time of the system, resulting in a decrease exceeded set point.

CONCLUSION

In this article we have given a brief philosophy and the principle of predictive control. This command is a combination between the prediction of future behavior of the process and control feedback. We applied this command to the speed control of the induction machine, the simulation results show that predictive control gives very satisfactory performance especially in terms of response time and rejection of external disturbances of the machine.

We noted that the major drawback of predictive control is that the performance is greatly influenced by the choice of the synthesis parameters N_1 , N_2 , N_u , and λ therefore, a judicious choice of these parameters is necessary before the implementation of the simulation algorithm, to meet the desired performance.

CHARACTERISTICS OF THE MACHINE USED FOR SIMULATION

<i>parameter</i>	<i>symbol</i>	<i>Value</i>
Number of pole pairs	p	2
Power	P_u	3 KW
Line voltage	U_n	380V
Line current	I_n	6.3A
Nominal frequency	f	50Hz
Mechanical rotor speed	N_n	1430 tr/mn
Electromagnetic torque	T_e	20Nm
Stator Resistance	R_s	3.36 Ω
Rotor Resistance	R_r	1.09 Ω
Stator cyclic inductance	L_s	0.256H
Mutual cyclic Inductance	L_m	0.236H
Rotor cyclic inductance	L_r	0.256H
Rotor inertia	j	$4,5 \cdot 10^{-2} \text{Kg} \cdot \text{m}^2$
Viscosity coefficient	f	$6,32 \cdot 10^{-4} \text{N} \cdot \text{m} \cdot \text{sec}$

REFERENCES

- Ahmed A. Zaki Diab, Denis A. Kotin and Vladimir V. Pankratov, 2013. "Speed Control of Sensorless Induction Motor Drive Based On Model Predictive Control". XIV international conference on micro/nanotechnologies and electron devices, 978-1-4799-0762-5/13/\$31.00 © 2013 IEEE
- Belkacem, S. 2011. "High Performance Direct Torque Control of Induction Motor Drive Using SVPWM". 11th International Conference on Control, Automation and Systems Oct. 26-29, KINTEX, Gyeonggi-do, Korea.
- Boucher, P. and D. Dumur, 1996. "The Predictive Control" collection methods and practices of the engineer, central school of Lille.
- Camacho, E. F. and C. Bordons, 2004. "Control Predictivo: pasado, presente y futuro". ETSI, Universidad de Sevilla, CEA- IFAC, Sevilla, Spain.
- Camacho, E.F. and C. Bordons, 2003. "Model Predictive Control", Springer-Verlag London, 2eme edition.
- Carloss, C. 2000. "Modeling Vectorial Control et DTC". Edition Hermes Sciences Europe.
- Clarke, D. W., C. Mohtadi and P. S. Tuffs, 1987. "Generalized Predictive Control -Part I. The Basic Algorithm", Automatica, Vol. 23, NO. 2, pp. 137-148.
- Clarke, D. W., C. Mohtadi and P. S. Tuffs, 1987. "Generalized Predictive Control – Part II. Extensions and Interpretations", Automatica, Vol. 23, No. 2, pp. 149-160.
- Egiguren, P., O. Caramazana, A. Hernández and I. Garrido Hernández, 2008. "SVPWM Linear Generalized Predictive Control of Induction Motor Drives", university of the Basque Country. Avda de Otaola 29, 20600. Eibar (Spain) pp. 588-593. IEEE.
- Garcia, C. E., D. M. Prett and M. Morari, 1989. "Model Predictive Control: Theory and Practice – A Survey". Automatica, 25(3):335–348.
- Grellet, G. and G. Clerc, 2000. "Actionneurs Electriques, Principe, Modèles, Commande". Collection Electrotechnique. Edition Eyrolles.
- Karamanakos, P., P. Stolze, R. M. Kennel, S. Manias and H. Mouton, 2014. "Variable Switching Point Predictive Torque Control of Induction Machines". IEEE journal of emerging and selected topics in power electronics, vol. 2, no. 2.
- Kennel, R., Linder, A. and Linke, M. 2001. "Generalized Predictive Control (GPC)-Ready for use in drive applications". University of Wuppertal, Germany.
- Lai, Y. S. and J. H. Chen, 2001. "A New Approach to Direct Torque Control of Induction Motor Drives for Constant Inverter Switching Frequency and Torque Ripple Reduction", IEEE Trans. Energy Conv. 16.
- Marino, R., S. Peresada and P. Tomei, 1998. "Adaptive Output Feedback Control of Current-Fed Induction Motors with Uncertain Rotor Resistance and Load Torque.", Automatica, 34, pp. 617-624.
- Papafotiou, G., J. Kley, K. G. Papadopoulos, P. Bohren and M. Morari, 2009. "Model predictive direct torque control - part II: Implementation and experimental evaluation". IEEE Trans. Ind. Electron., 56(6):1906–1915.
- Qin S. J. and T. A. Badgwell, 2003. "A Survey of Industrial Model Predictive Control Technology". Control Engineering Practice, 11(7):733–764.
- Rawlings, J. B. and D. Q. Mayne, 2009. "Model predictive control: Theory and design". Nob Hill Publ.

- Rodríguez, P. and Dumur, D. 2005. "Generalized Predictive Control Robustification Under Frequency and Time Domain Constraints", IEEE Transactions on Control Systems Technology, Vol. 13, No. 4, pp. 577-587.
- Thomas, J. and A. Hansson, 2010. "Speed Tracking of Linear Induction Motor: An Analytical Nonlinear Model Predictive Controller". 2010 IEEE International Conference on Control Applications Part of 2010 IEEE Multi Conference on Systems and Control Yokohama, Japan, September 8-10.
- Zhou, K. and D. Wang, 2002. "Relationship Between Space-Vector Modulation and Three-Phase Carrier-Based PWM: A Comprehensive Analysis", IEEE transactions on industrial electronics, vol. 49, no. 1, pp. 186-196.
