

# Comparison of the Performance Speed of the Induction Motor Drives by the Predictive Control and PI Regulator, Using Space Vector Modulation

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**Abstract.** The predictive control is born of a real need in the industry. A need for systems capable of regulating higher performance than conventional controllers (PID), while respecting the constraints of operation and producing even higher.

Many predictive control algorithms have been developed and their differences are based on the types of prediction model used to represent the process, the noise and the performance function to be minimized. In this paper the generalized predictive control (GPC) is used on the induction machine for speed control. The philosophy of this command is based on four main ideas reproducing the basic decision-making mechanisms of human behavior: Creating an anticipatory effect by exploiting the path to follow in the future definition of a numerical model prediction, minimizing of a quadratic criterion with finite horizon. We present in this paper a comparative study between two control strategy of electrical machines for controlling the speed The comparison is based on several criteria including: static and dynamic performance, structure and implementation complexity, Also, we present in this study the advantages and disadvantages of each control scheme, the best is the one that better meets the requirements.

**Keywords:** Induction Motor, Predictive control, synthesis of PI regulator, Space vector modulation (SVM).

## 1. Introduction

Predictive control is a technique of advanced control automation [1]. It aims to control complex industrial systems [2]. The principle of this technique is to use a dynamic model of the process inside the controller in real time to anticipate the future behavior of the process [3,4].

Predictive control is different from other control techniques that must be solved online [5]. It is to be optimized, based on inputs/outputs of a system, which predict the future behavior of the system under consideration [4]. The prediction is made from an internal model of the system on a finite interval of time called the prediction horizon [6,7].

The solution of the optimization problem is a control vector; the first input of the optimal sequence is injected into the system. The problem is solved again on the next time interval using the data system updates [7,8].

This control strategy has shown its efficiency, flexibility and success in industrial applications, even for systems with low sampling period [2,9]. The application of predictive control in the field of digital controls gave good results in terms of speed and accuracy.

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In this paper we present the 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 a PI controller. The control voltages can be generated by PI and imposed by SVM technique. In addition the estimate of the torque and flux are based on the model of the machine voltage. The simulation results are obtained by using Matlab/Simulink, compared with those obtained by the PI, show high dynamic performance.

## 2. Model of the Induction Machine

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 ( $V_{sd}$ ,  $V_{sq}$ ) 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 [10,11]:

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

In addition to these components of the stator flux and rotor 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 Inductance.

$(L_m, p)$ : mutual Inductance and Number of pole pairs.

$(\omega_s, \Omega)$ : electrical speed, mechanical rotor speed

## 3. The Philosophy of Predictive Control

The philosophy of predictive control model is to know the output of the controlled process 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) [6,7]. 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 [2]. As a result, the output of the process is different from the model.

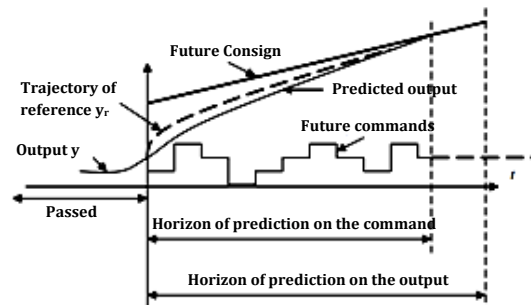


Fig.1 Time evolution of the finite horizon prediction

#### 4. The Principle and General Strategy of Predictive Control

The basic principle of predictive control is taken into account, at the current time, and of the future behavior, through explicit use of a numerical model of the system in order to predict the output on a finite horizon on the future, [4]. One of the advantages of predictive methods lies in the fact that for a precalculated 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:

- 1- Predict future process outputs in the prediction horizon is defined by using the prediction model. These outputs dependent on the output values of the input process known as control up to time  $t$ . [7].
- 2- Determine the sequence of control signal, by minimizing a performance criterion to conduct the process output to an output reference [8]. 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.
- 3- 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 beginning. [6,14].

#### 5. 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 multivariable [3].
- 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 both the control variables, and the internal variables of the process [3,7].

The 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 [3,8] including the generalized predictive control (GPC).

## 6. Generalized Predictive Control

The generalized predictive control (GPC) of Clarke [6], 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” [6]. For this, you must know at each iteration the system state is using a numerical tool. Temporal representation of generalized predictive control is given in (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.

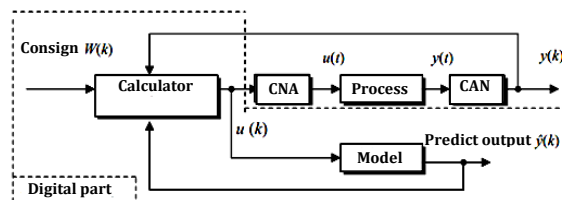


Fig. 2 Diagram of the GPC

## 7. 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 [9]. 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.

## 8. 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 [6][13]. This cost function is as follows:

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

With:

[1]

$w(t+j)$ : 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.

$\lambda$ : Weighting factor on the order.

$T_s$ : The period of sampling.

The criteria expression calls for several comments:

- When there are actually values of the set point in the future, all of these information 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  $\Delta u$  in the criteria.
- The coefficient  $\lambda$  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 [9].

## 9. Choice of the Parameters of Control

The definition of the quadratic criterion (1'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 automatically.

$N_1$ : minimum horizon of prediction is the pure delay system, if the delay is known or we should initialize to 1[6,7].

$N_2$ : maximum horizon is chosen so that the product  $N_2 T_s$  is limited by the value of the desired response time. Indeed moving beyond the prediction of the response time provides no additional information. In addition, the more  $N_2$  is larger; the fixed system is stable and slow [6,7].

$N_u$ : horizon of control, we should choose equal to 1 and not exceeding the value of two [13].

$\lambda$ : 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  $\lambda$  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 [6,7].

### 10.Regulating the Speed of the Induction Machine by Predictive Control

We will regulate the speed of the induction machine from 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 and of the mechanical equation can be represented in the ongoing plan by the following transfer:

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

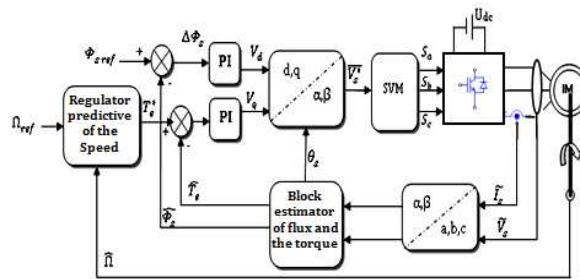


Fig. 3 Block diagram the speed control of the IM by the predictive control

### 11.Synthesis of Speed Regulator

The speed control is an essential need in the industry against undesirable variations in the load. In this closed loop, using a corrector type (PI) which combines proportional and integral action (Fig. 4).

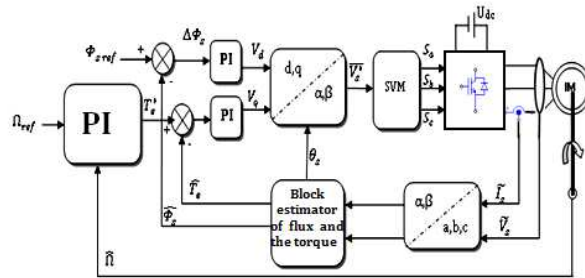


Fig. 4 Block diagram of the speed control of the IM by the PI regulator

The equation in the temporal pattern of this correction is given below:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \tag{7}$$

Where,  $e(t)$   $u(t)$   $K_p$  and  $K_i$ , denote respectively the error at time t, the command generated and gains of the corrector.

The corresponding transfer function is given by:

$$PI(s) = K_p + \frac{K_i}{s} = K_p(1 + \frac{1}{\tau s}) \quad (8)$$

Where 's' is the Laplace operator derived,  $\tau = \frac{K_p}{K_i}$  : Time-constant.

The (fig.5) shows the block diagram of the speed control where the mechanical time constant is dominant to the electric constant time.

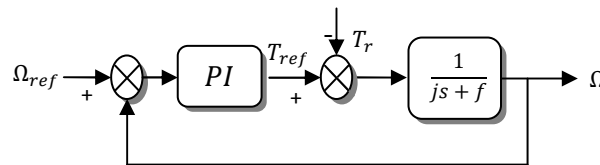


Fig.5 Conventional control speed

The transfer function in a closed loop is given by:

$$TFCL = \frac{PI(s) \cdot \frac{1}{js+f}}{1 + PI(s) \cdot \frac{1}{js+f}} \quad (9)$$

Substituting equation (8) into (9), and after simplification we get:  $T_r = 0$ .

$$TFCL = \frac{(1+\tau s)}{\frac{j}{K_i} s^2 + (\frac{f+K_p}{K_i}) s + 1} \quad (10)$$

To control the closed loop system, it is necessary to choose the coefficients, and in this case we use the method of the imposition of the poles.

The transfer function of a second order system closed loop is characterized by:

$$F(s) = \frac{K}{1 + \frac{2\xi}{\omega_n} s + \frac{1}{\omega_n^2} s^2} \quad (11)$$

The characteristic equation is:  $1 + \frac{2\xi}{\omega_n} s + \frac{1}{\omega_n^2} s^2$  where  $\xi$ : the damping coefficient and  $\omega_n$ : the natural angular frequency of the system. By identifying the relationship (10) we have the following system:

$$\begin{cases} \frac{1}{\omega_n^2} = \frac{j}{K_i} \Rightarrow K_i = j\omega_n^2 \\ \frac{2\xi}{\omega_n} = \frac{K_p+f}{K_i} \Rightarrow K_p = \frac{2\xi K_i}{\omega_n} - f \end{cases} \quad (12)$$

The Gains of the corrector are obtained to have a minimal response time while ensuring the absence of overshoot. This technique involves the imposition of values of damping and the pulsation  $\xi$  and  $\omega_n$  to determine the  $K_p$  and  $K_i$  coefficients.

## 12.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. 6).

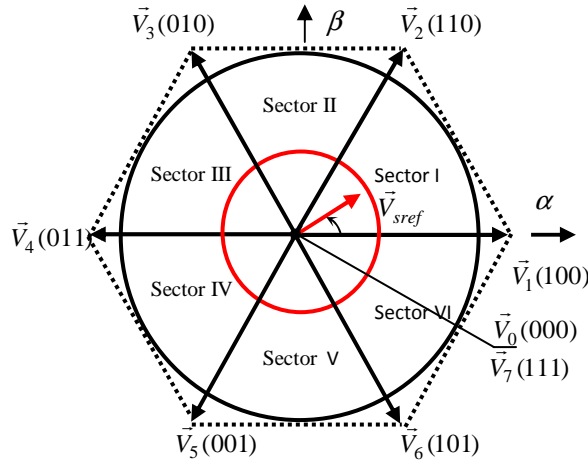


Fig. 6 The diagram of voltage space vectors

In every sector, the voltage vector is arbitrary synthesized by basic space voltage vector of the two sides of one sector and zero vectors [12]. For example (Fig.7), in the first sector,  $\vec{V}_{sref}$  is a synthesized voltage, space vector and its equation is given by:

$$\vec{V}_{sref} T_s = \vec{V}_0 T_0 + \vec{V}_1 T_1 + \vec{V}_2 T_2 \quad (13)$$

$$T_s = T_0 + T_1 + T_2 \quad (14)$$

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

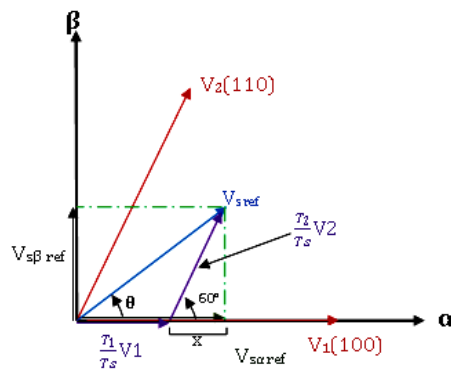


Fig. 7 Projection of the reference voltage vector

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

$$\begin{cases} V_{s\alpha ref} = \frac{T_1}{T_s} |\vec{V}_1| + x \\ V_{s\beta ref} = \frac{T_2}{T_s} |\vec{V}_2| \sin(\frac{\pi}{3}) \\ x = \frac{V_{s\beta ref}}{\text{tg}(\frac{\pi}{3})} \end{cases} \Rightarrow \begin{cases} T_1 = \frac{T_s}{2U_{dc}} (\sqrt{6}V_{s\alpha ref} - \sqrt{2}V_{s\beta ref}) \\ T_2 = \frac{T_s\sqrt{2}}{U_{dc}} V_{s\beta ref} \end{cases} \quad (15)$$



The rest of the period is in applying the null-vector. Switching duration is calculated for every sector [12]. The amount of times of the vector implementation can all be related to the following variables:

$$\begin{cases} X = \frac{T_S}{U_{dc}}(\sqrt{2}V_{s\beta ref}) \\ Y = \frac{T_S}{2U_{dc}}(\sqrt{6}V_{s\alpha ref} + \sqrt{2}V_{s\beta ref}) \\ Z = \frac{T_S}{2U_{dc}}(-\sqrt{6}V_{s\alpha ref} + \sqrt{2}V_{s\beta ref}) \end{cases} \quad (16)$$

The implementation of the durations sector boundary vectors are tabulated as follow:

Table 1. Durations of the sector boundary vectors.

Sector	1	2	3	4	5	6
T <sub>l</sub>	-Z	Y	X	Z	-Y	-X
T <sub>l+1</sub>	X	Z	-Y	-X	-Z	Y

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

$$\begin{cases} T_{aon} = \frac{T_S - T_i - T_{i+1}}{2} \\ T_{bon} = T_{aon} + T_i \\ T_{con} = T_{bon} + T_{i+1} \end{cases} \quad (17)$$

The last step is to assign the duty cycle (T<sub>xon</sub>) 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 <sub>a</sub>	T <sub>aon</sub>	T <sub>bon</sub>	T <sub>con</sub>	T <sub>con</sub>	T <sub>bon</sub>	T <sub>aon</sub>
S <sub>b</sub>	T <sub>bon</sub>	T <sub>aon</sub>	T <sub>aon</sub>	T <sub>bon</sub>	T <sub>con</sub>	T <sub>con</sub>
S <sub>c</sub>	T <sub>con</sub>	T <sub>con</sub>	T <sub>bon</sub>	T <sub>aon</sub>	T <sub>aon</sub>	T <sub>bon</sub>

### 13. 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 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 horizon of Prediction $N_2$

$N_2$  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  $N_2$ .

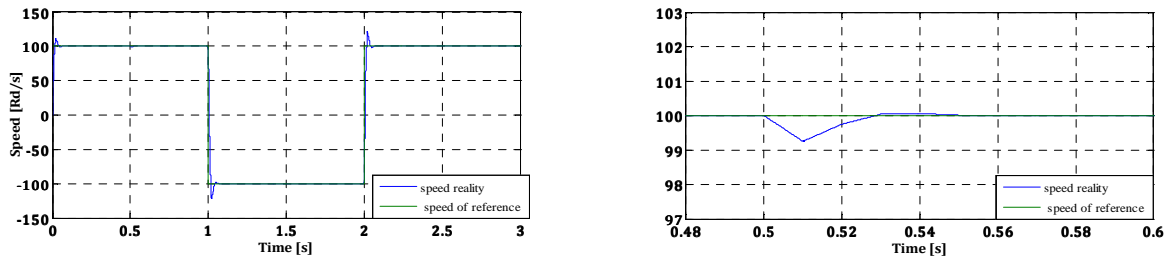


Fig. 8 Evolution of speed for  $N_1 = 1, N_2 = 1, N_u = 1, \lambda = 0.8$

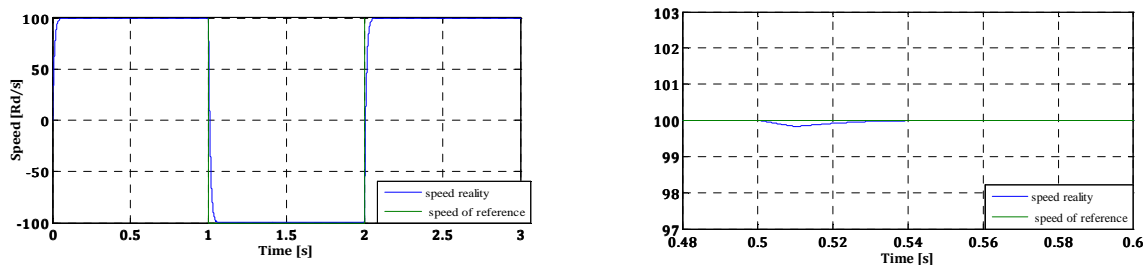


Fig. 9 Evolution of the speed  $N_1 = 1, N_2 = 2, N_u = 1, \lambda = 0.8$

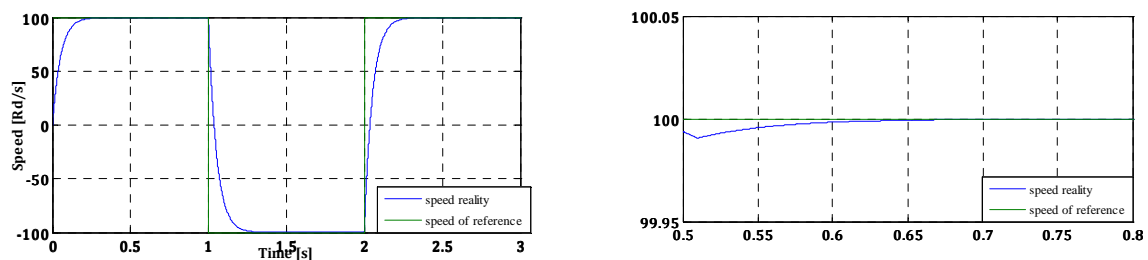


Fig. 10 Evolution of speed for  $N_1 = 1, N_2 = 8, N_u = 1, \lambda = 0.8$

### 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 Weighting Coefficient $\lambda$

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

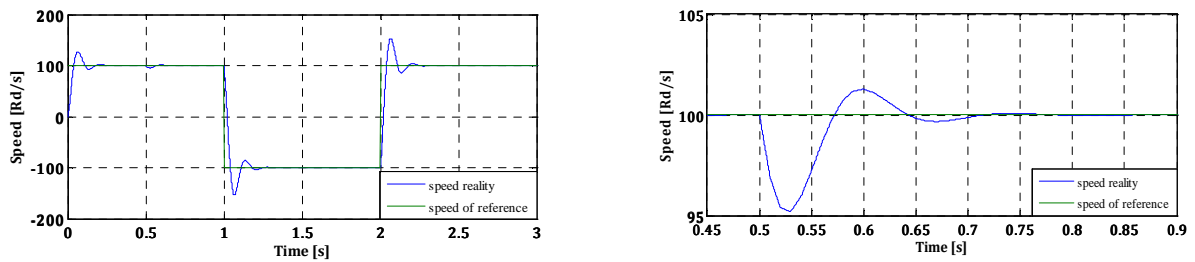


Fig. 11 Evolution of speed for  $N_1 = 1, N_2 = 2, N_u = 1, \lambda = 0.55$

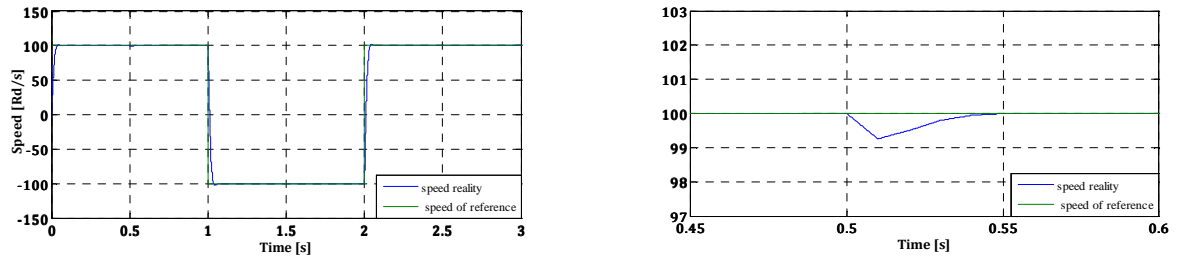


Fig. 12 Evolution of speed for  $N_1 = 1, N_2 = 2, N_u = 1, \lambda = 0.7$

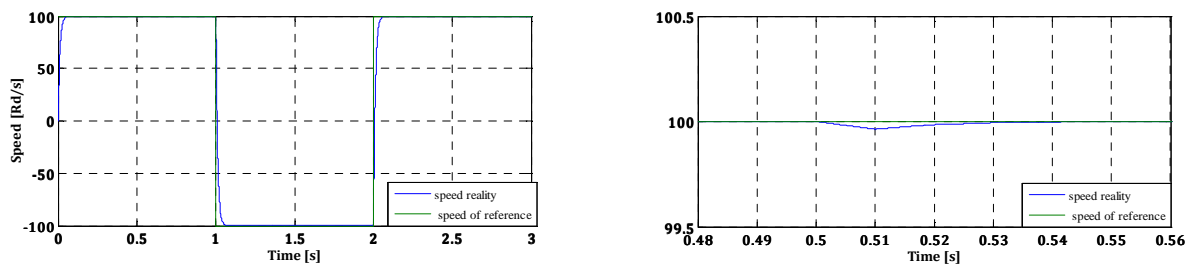


Fig.13 Evolution of speed for  $N_1 = 1, N_2 = 2, N_u = 1, \lambda = 0.9$

### Discussion of the Results

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

## 14. The Speed Control: Comparison of PI Regulator And Predictive Control

The simulation results from (Fig.14 and 15), shows efficiency of predictive control with respect to the results obtained, when regulating the speed of a conventional PI controller due to:

- The application of PI controller requires that the system is stable in open loop, as long as it compensates for the dominant pole, unlike the control Predictive that does not require restrictions, so it can be applied on any system.
- The PI is much easier to implement than predictive control, but the calculation time is less important compared to predictive control.
- We noted that the major drawback of predictive control is that the performance is greatly influenced by the choice of the synthesis parameters  $N_1, N_2,$  and  $N_u,$  and  $\lambda$  therefore, a judicious choice of these

parameters is necessary before the implementation of the simulation algorithm, to meet the desired performance.

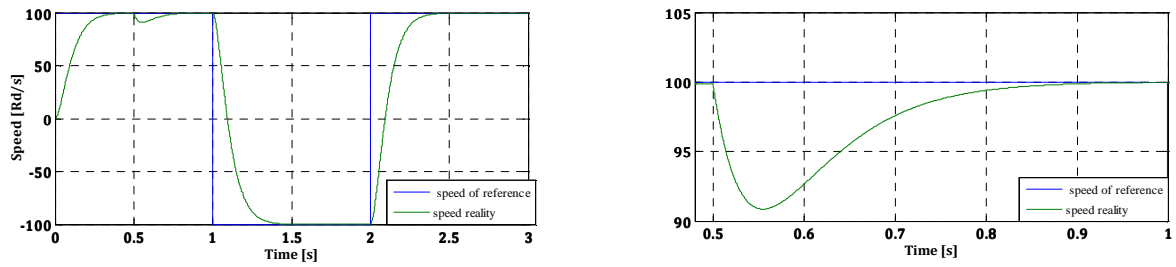


Fig. 14 Evolution of the speed by PI regulator

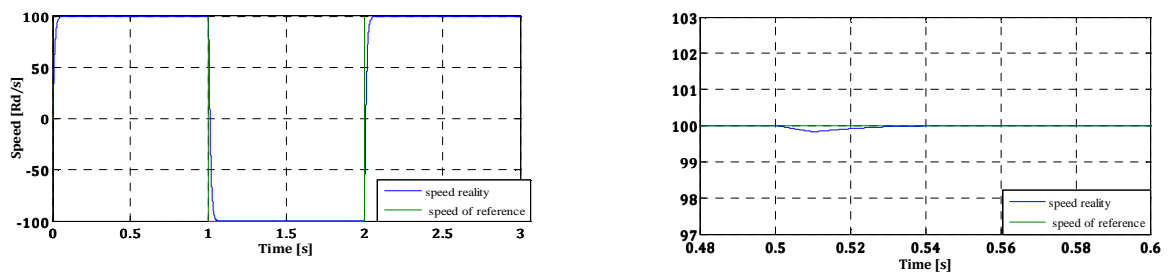


Fig. 15 Evolution of the speed by predictive control

## 15. Conclusion

In this article we have given a brief philosophy, 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, compared to the results obtained by the PI.

### Characteristics of the machine used for simulation:

<i>parameter</i>	<i>symbol</i>	<i>Value</i>
Number of pole pairs	p	2
Power	P <sub>u</sub>	3 KW
Line voltage	U <sub>n</sub>	380V
Line current	I <sub>n</sub>	6.3A
Nominal frequency	f	50Hz
Mechanical rotor speed	N <sub>n</sub>	1430 tr/mn
Electromagnetic torque	T <sub>e</sub>	20Nm
Stator Resistance	R <sub>s</sub>	3.36 Ω
Rotor Resistance	R <sub>r</sub>	1.09 Ω
Stator cyclic inductance	L <sub>s</sub>	0.256H
Mutual cyclic Inductance	L <sub>m</sub>	0.236H
Rotor cyclic inductance	L <sub>r</sub>	0.256H
Rotor inertia	j	4,5. 10 <sup>-2</sup> Kg. m
Viscosity coefficient	f	6,32.10 <sup>-4</sup> N. m.sec.

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