Robust Control Method for PMSM Based on Internal Model Control with Speed and Load Torque Estimator

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Abstract: A Robust controller designed by employing internal model control (IMC) is presented for permanent magnet synchronous motor (PMSM) drive with estimation of both the rotor speed and the load torque with a predictive state observer. It is to achieve accurate control performance in the presence of uncertainties and system parameters variation. The Experimental results prove that the IMC controller with the presence of the predictive state observer greatly improves the performances of the speed loop and simplifies the design procedure. The robustness of this scheme is analysed, and the bounds of control parameters that ensure the drive stability are obtained.

Keywords: Internal model control, permanent magnet synchronous motor, PI controller, speed estimator.

1. Introduction

During these last decades, the PMSM found a very great interest in many industrial applications, due to considerations of cost, size, low maintenance, speed capability and simplicity of design. However, the PMSM presents a coupled non-linear multi variable control structure which requires a complex nonlinear control in order to achieve good dynamic performances [1-5].

The machine drive systems with high performances must allow the development of control strategies which offer a strict follow-up in position and in speed. Moreover, these performances must be insensitive to the variations of the machine parameters, especially the mechanical parameters such as the inertia moment of the rotating mass.

Improved and robust control of these processes is becoming necessary due to increasing competition and environmental considerations. Also, the availability of advanced technology and inexpensive computing power are a consequent for design and implementation of advanced control strategies. Many control techniques have been proposed and analyzed for nonlinear processes, and a good review of these is available in literature [6-8]. Linear internal model control as a general structure that uses a model in parallel with the process has become very popular among practicing engineers [9-18].

IMC was widely used in the chemical industries, mostly in the form of proportional-integral-derivative (PID) controllers, in which a clear tradeoff between closed loop performance and robustness to model uncertainty is provided [12-14].

Besides its industrial importance, IMC also provides a convenient theoretical framework for understanding the performance limitations due to non minimum-phase behavior and model uncertainty [15-18].

In this work, an IMC strategy is proposed and applied to the PMSM speed control with estimating the rotor speed and load torque.

2. PMSM model

The stator *d-axis* and *q-axis* equations of the PMSM in the rotor rotating reference framework are as follows:

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$$u_{sd} = r_s i_{sd} + \frac{d}{dt}\phi_{sd} - \omega_r \phi_{sq} \quad (1)$$

$$u_{sq} = r_s i_{sq} + \frac{d}{dt}\phi_{sq} + \omega_r \phi_{sd} \quad (2)$$

and

$$\phi_{sd} = L_d i_{sd} + \phi_f \quad (3)$$

$$\phi_{sq} = L_q i_{sq} \quad (4)$$

$$\frac{d\theta}{dt} = \omega_r \quad (5)$$

The electromagnetic torque is as follows:

$$T_e = \frac{3}{2} p(\phi_f i_{sq} + (L_d - L_q) i_{sd} i_{sq}) \quad (6)$$

And the mechanical equation for the motor dynamics is as follows:

$$J \frac{d\omega_r}{dt} = T_e - T_L - f_c \omega_r \quad (7)$$

where, $u_{sd,}$and u_{sq} are d-axis and q-axis stator voltages, $i_{sd,}$ and i_{sq} are d-axis and q-axis stator currents, i_{sdref} is the stator direct reference current, ϕ_{sd} and ϕ_{sq} are the stator flux linkages in d-q frame, ω_r is the rotor speed, θ the rotor position, ϕ_f is the flux linkage produced by permanent magnet, T_e the electromagnetic torque, T_L the external load torque, p the number of pole pairs, r_s the stator resistance, L_d and L_q are d-axis and q-axis stator windings inductances, J moment of inertia, f_c viscous friction coefficient.

3. Configuration of the control structure

By analyzing the system of the previous equations (1 to 6), we can release that the model is nonlinear and is coupled. Indeed, the electromagnetic torque depends at the same time on i_{sd} and i_{sq}. If the coupling terms between the axes d and q are compensated, the voltage u_{sd} makes it possible to drive the current i_{sd} and the voltage u_{sq} makes it possible to drive i_{sq} and thus T_e. The PMSM behavior is in this case similar to the DC motor one. Physically, this strategy maintains the stator current in quadrature with the rotor flux, (i.e. to reduce the stator current to the only component i_{sq}). The control structure applied to the studied motor is represented by the diagram block of Figure 1.

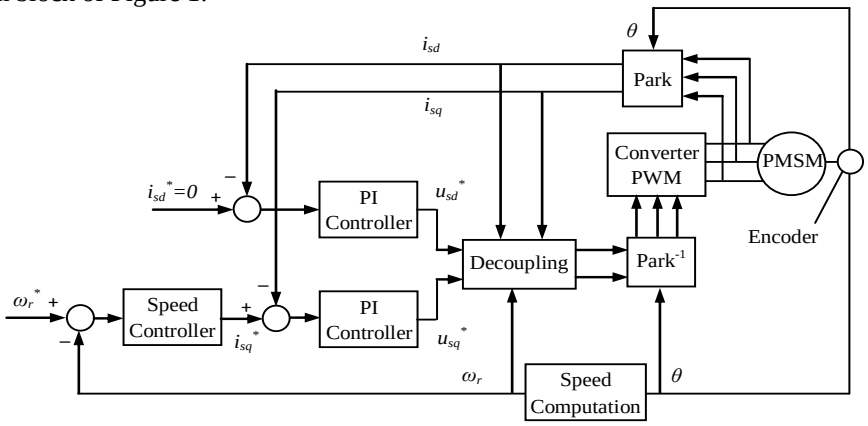

Figure 1. Block diagram of the control structure

4. The currents control loop

The stator currents are driven by proportional and integral (PI) controllers. The transfer function of a PI controller is as follows:

$$C(s) = K_{pi} + \frac{K_{ii}}{s} \tag{8}$$

where, K_{pi} and K_{ii} represent the proportional and integral gains of the controller.

To determine the controller parameters, the real pole of the current loop was compensated by the zero introduced by this controller. Therefore, the transfer function of the closed loop current dynamic is reduced in a first order. In that case, the controller parameters are given as below:

$$K_{pi} = K_{ii}.\tau_e \tag{9}$$

$$K_{ii} = \beta.\frac{r_s}{\tau_e} \tag{10}$$

Where τ_e represents the time constant of the electrical part of the PMSM and β characterizes the acceleration of the closed loop current with respect to that of the open loop current. In fact, the choice of the parameter β determines the dynamics of the desired current loop, therefore a good choice of this parameter allows to approximate the current loop to an unity gain, which makes the study of the speed loop more simple.

5. The IMC structure of speed loop.

A. IMC principle

The basic diagram of IMC structure is illustrated by Figure 2.

G(s) denotes the system, $\hat{G}(s)$ denotes the system model transfer function and *C(s)* denotes the controller. *r(t)*, *u(t)* and *d(t)* are respectively the reference, the command signal and the disturbance.

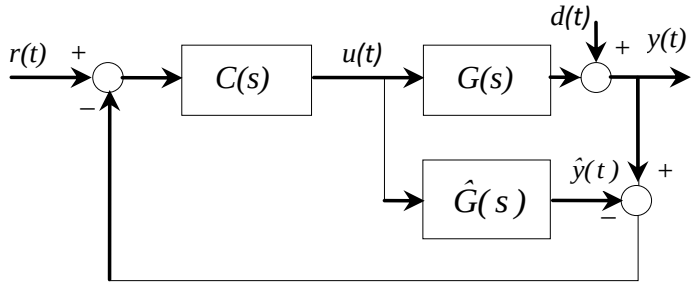

Figure 2. IMC structure

The difference between *y*, the plant measurement, and $\hat{y}$, the model output, is used for feedback. The IMC structure shown in Figure 2 can be transformed as a general feedback control structure shown in Figure 3. Then, the equivalent classic controller becomes:

$$Gc(s) = \frac{C}{1 - \hat{G}.C} \tag{11}$$

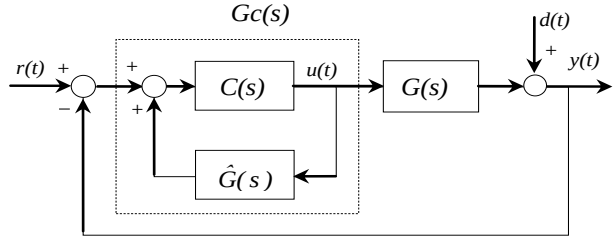

Figure 3. Classic control structure of speed-loop

The basic procedure for the IMC can be presented as follows:

When the model is perfect, i.e., $G(s) = \hat{G}(s)$, the stability of both controller $C(s)$ and plant is sufficient for overall system stability. That is, when $G(s) = \hat{G}(s)$, there is no signal feed through the feedback path. As a result, if the open-loop system is input-output stable, then the closed-loop system is also input-output stable.

If $G(s) = \hat{G}(s)$, and $\hat{G}(s)$ is invertible and the closed loop is stable, there is a controller such that $C(s) = \hat{G}^{-1}(s)$ and $C(0) = \hat{G}^{-1}(0)$, then the output *y(s)* equals the reference *r(s)* without offset. That is, the steady state controller gain is the inverse of the steady state model gain and the closed-loop system is stable. Then, the error will vanish asymptotically.

The above properties are based on ideal conditions. In practice, the perfect model assumption is rarely satisfied. There is a signal feeding through the feedback path. The closed-loop system is possibly unstable, although the open-loop system is stable. Further, the IMC structure can achieve perfect control. However, perfect control usually requires large control actions. This is undesirable in practice. To solve this problem, a filter $F(s)$ is used so that the controller comes $C(s) = \hat{G}^{-1}(s)F(s)$. The IMC filter, it must be chosen so that $C(s)$ is proper and $F(0) = 1$ in the case that the reference input is a step.

The simplest IMC filter is of the type:

$$F(s) = \frac{1}{(\alpha s + 1)^n} \tag{12}$$

where, α is the time filter constant. It is only a design and evaluation parameter for robust stability. The multiplier *n* must be chosen so that $C(s) = \hat{G}^{-1}(s)F(s)$ is proper.

Consider the performance of IMC from the input *u* and the disturbance *d* to the output *y*. The transfer function of IMC closed-loop is:

$$y = \frac{GC}{1 + C(G - \hat{G})} r + \frac{1 - \hat{G}C}{1 + C(G - \hat{G})} d \tag{13}$$

Assuming that $G(s) = \hat{G}(s)$ is stable and proper, then:

The closed-loop stability is characterized by stability of controller *C(s)*. *C(s)* denotes a free parameter of stabilized compensator.

The performance of the reference response ($r \to y$) and the disturbance response ($d \to y$) are linear functions of the free parameter *C(s)*.

In the case that a filter $F(s)$ is used, then the output can be given as follows:

$$y = Fr + (1 - F)d \tag{14}$$

From this relationship, the filter could reduce the disturbance effect on output. In addition, the filter could be used to limit the control action *u*.

Plant Model

Let $i_{sd} = 0$, $T_L = 0$, if the response time of the current controllers is neglected, and using (6) and (7) we deduce that the dynamic model is reduced to:

$$\hat{G}(s) = \frac{K_t}{Js + f_c} \tag{15}$$

where $K_t = p\phi_f$

In this case the plant model is a 1st order system, therefore, constructing the perfect inverse model of the plant model cannot be achieved. As a result, according the basic procedure for the

IMC described above, it must be used an IMC filter of the form $F(s)=\frac{1}{\alpha s+1}$. Then, the IMC controller can be of the following form:

$$C(s)=\hat{G}^{-1}(s)F(s)=\frac{Js+f_c}{K_t}\frac{1}{\alpha s+1} \tag{16}$$

The equivalent classic controller becomes:

$$G_c(s)=\frac{C}{1-\hat{G}.C}=\frac{Js+f_c}{K_t\alpha s} \tag{17}$$

A comparison with the standard PI controller that involves adjustment of two parameters, the tuning problem of the proposed controller $G_c(s)$ is reduced to the selection of one parameter only, the desired closed loop bandwidth α. This, not only simplifies the design procedure of the controllers, but also improves the performance of speed loop.

By using (14), the transfer function of IMC closed loop is given as follows:

$$y=\frac{1}{\alpha s+1}r+\frac{\alpha s}{\alpha s+1}d \tag{18}$$

It is clear that the IMC closed loop was reduced to a 1st order system.

This solution presents interesting properties with regard to its robustness and disturbances (resistive torque, variation of inertia) which can affect the mechanical part of the controlled system.

6. Experimental results

A. Speed and load torque estimation:

The PMSM studied in this work is equipped with an incremental encoder. Thus, the collection of information on the position goes to continuously perform the counting of pulses from the encoder. The speed that deduced by numerical derivation from position thus calculated contains, inevitably, noises. Therefore, the output of the speed controller provides a disturbed current picture, causing, in this case, oscillations around the desired operating points. One way to reduce disturbance is digital filtering. But it is interesting to recall that a filter with a cutoff frequency does not allow a total rejection of the introduced noises [6,8]. In contrast, a low cutoff frequency adds delays and causes possible instability of the system.

A solution to reduce efficiency the noise is to use a PI controller for the observation of load torque [3]. The structure of the observer is illustrated in Figure 4.

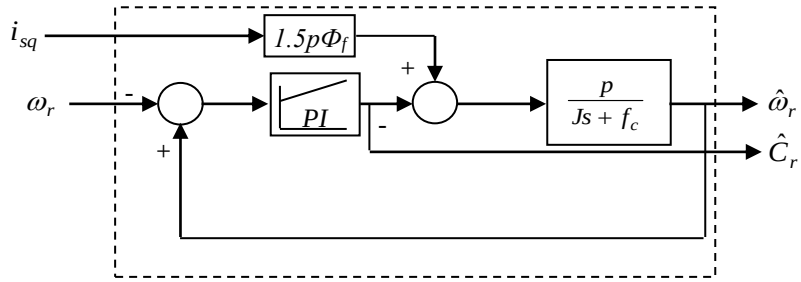

Figure 4. Speed and load torque estimator.

In this structure, the inputs are the measured speed and the q-axis current while the outputs represent the estimated speed and the estimated load torque. In fact, the estimated load torque is obtained from the PI controller output. The role of the controller is to cancel the difference between the measured speed and the estimated one. The result is the convergence of estimated load torque to the load torque applied to the motor.

B. IMC control validation

The experimental validation of this IMC control structure was carried out at the laboratory of automatic and computer engineering of the higher school of engineer of Poitiers, the test bench is composed of 2 identical PMSMs. One was used as a motor and the other one as a load. The parameters of the PMSM are given in Table 1. The motor is supplied by a 3-phase voltage-source PWM inverter, which is composed of 6-insulated gate bipolar transistors (IGBTs). A DC power supply is used to supply the inverter with maximum voltage of 500 V and a current of 5 A. The proposed control algorithm was carried out with MATLAB/Simulink software, and then compiled and established on DSPACE 1104 card. In the Simulink solver, the Euler's method with a sampling period of 0.1 ms was used for the control system discretization. Also, the chosen sampling period for the current loop is 0.1 ms and that's one for the speed loop is 0.3 ms. The PI controller parameters used in current loops are initialized as follows:

K_{pi} = 5.7, K_{ii} = 722.

These values were calculated by choosing the acceleration parameter β = 10.

The parameters of the estimator PI controller are initialized as follows:

K_{pob}= 0.0127 , K_{iob}= 0.104.

where, K_{pob} and K_{iop} represent the proportional and the integral gains of the PI controller of the estimator.

Table 1. Rating and motor parameters

Nominal voltage	220 V
Nominal current	3.5 A
r_s	0.56 Ω
L_d	4.0 mH
L_q	4.5 mH
p	2
Φ_f	0.074 wb
J	0.00208 kgm^2
f_c	0.0039 Nms/rad

Figures (6 to 11) illustrate the dynamic behavior of the PMSM for a speed control without load application. In these results the real speed of the motor was calculated starting from the position given by the encoder, and then filtered by a first order filter. Figure 6 denotes the reference speed and the estimated one. It shows that the overshoot is null and the time response is very short. This result is confirmed in Figure 7 which shows the error between the reference speed and the estimated one.

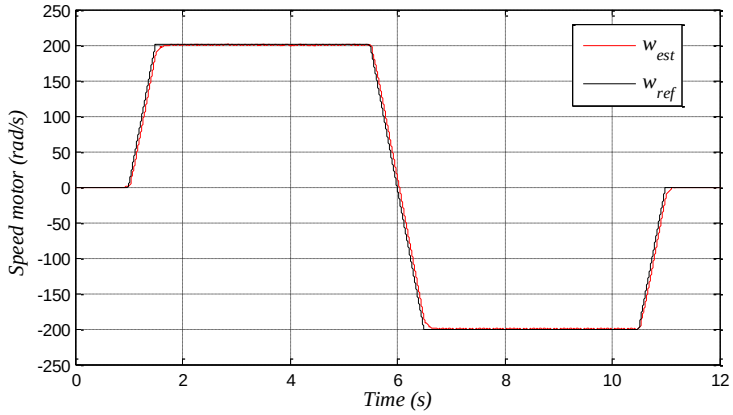

Figure 5. Speed response with IMC controller

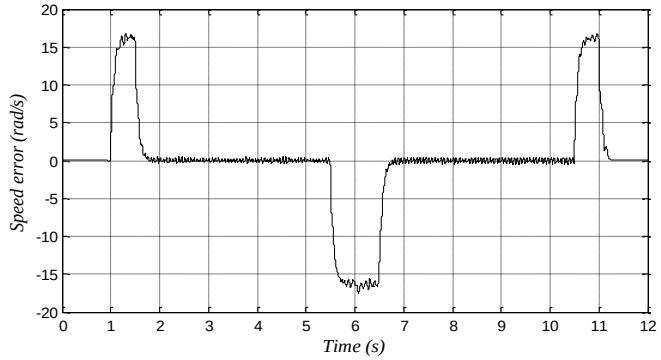

Figure 6. Speed error between the reference and estimated speed

To show the effectiveness of the algorithm studied in this work, it is presented at Figure 8 the progress of motor speed without load when the speed loop is controlled by a PI controller. In this case, the PI controller parameters were determined such that the dynamic of the closed loop, which is a second order, can have an optimal response, so the dumping coefficient is fixed at 0.707 and the natural pulsation at 15 rad/s.

Computations have given:

K_{pw} = 0.0604 and K_{iw} = 0.2340.

where K_{pw} and K_{iw} represent the proportional and the integral gains of the speed PI controller. This choice causes a transitory mode characterized by an overshoot and a significant time response compared to the previous case. This is shown in the Figure 9 which illustrates the error between the reference speed and the estimated one.

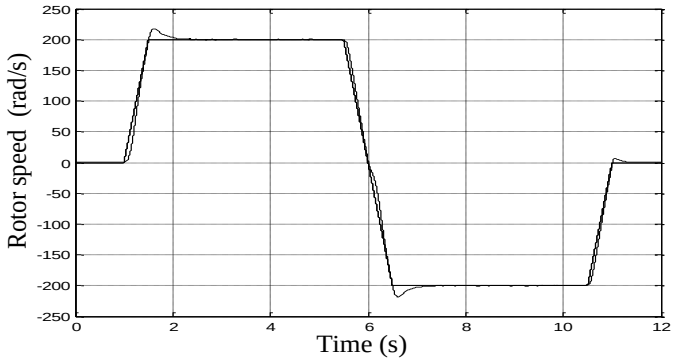

Figure 7. The speed motor with PI controller

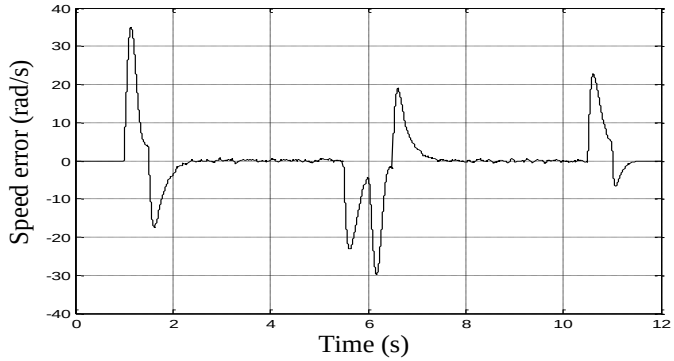

Figure 8. Speed error when PI controller is used for speed loop control

Figure 9 shows that the d-axis current always keeps a zero value which proves that the vector control technique with decoupling of d and q-axis is effective. Figures 10 and 11 show the effectiveness of the current controllers; the estimated current i_{sq} is perfectly confused on the reference current obtained on the output of the speed controller.

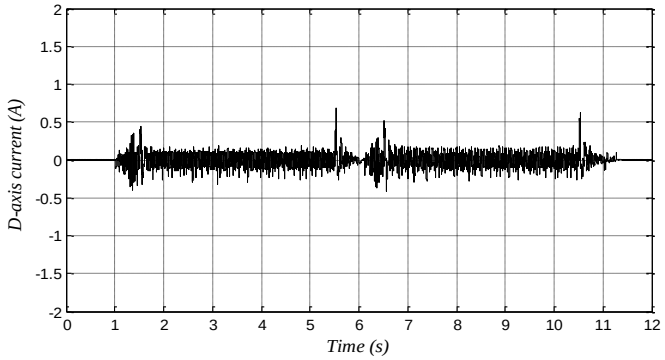

Figure 9. Evolution of d-axis stator current

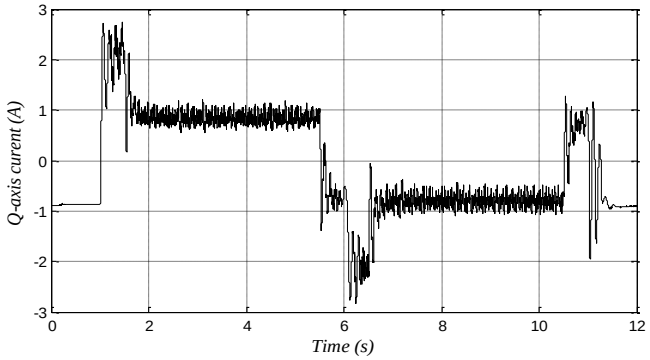

Figure 10. Measured q-axis stator current

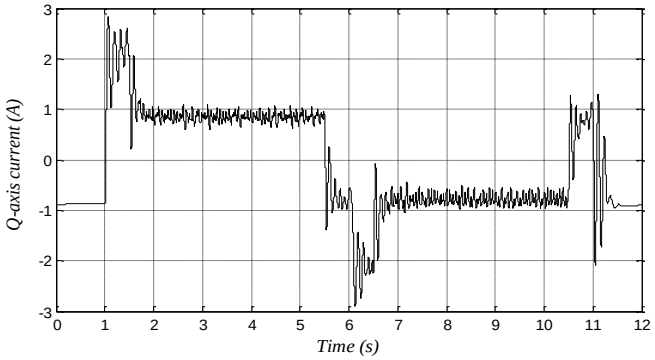

Figure 11. Reference q-axis stator current

The following Figure 12 shows the evolution of the phase current i_{s1}(t).

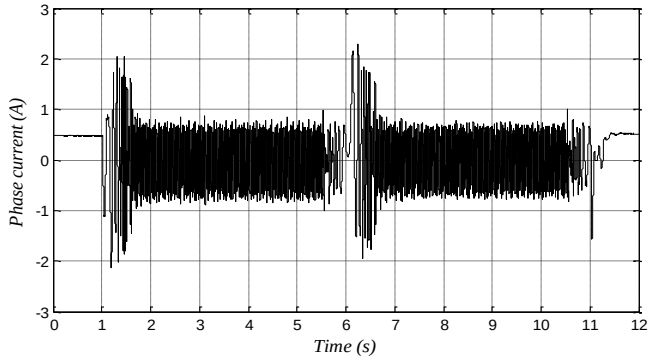

Figure 12. Stator phase current

C. PMSM parametric uncertainty influence

Generally, external disturbances, the measurement noise and errors due to inadequate description of physical systems are uncertainties. Thus, the problem of robustness can be described into two kinds: first, it is about the manner in which the unwanted or unexpected signals in the closed-loop system will be treat, that's the robustness in performance, and in other way, how maintain stable the closed-loop system despite changes in the behavior of the open loop system, that's the robustness in stability. To this end, the notion of robustness has no meaning unless it is associated with a property, such as stability or performance with respect to a disturbance, such as measurement error, external disturbances or uncertainties model parameters.

Depending on the place of occurrence, the uncertainties can be classified into two main categories; external uncertainty and internal uncertainty. Indeed, all the disturbances affecting the system from the outside, represents the external uncertainties. In this case, we can distinguish the external disturbances and measurement errors due to possible failures of sensors. As for the internal uncertainties, these origins can be multiple: lack of knowledge of some system parameters, dynamic poorly taken into account, linearization of physical equations.

In this work, only parametric uncertainties are taken into account because the parameters of the machine do not give rise to exact and final values. The origins of these variations are multiple. They correspond to the changing values during operation (increases or decreases) or the methods used in the identification phase of the machine parameters.

It should be noted that the robustness testing is not based on actual physical variations of the machine parameters, but we proceeded differently. In fact, instead of causing physical parameter variations, we designed rather the controller using, for each test, the varied value of the parameter in question, according to the adopted rate of change.

It is also interesting to note that the objective of this part of our study is to experimentally validate the robustness of the designed control laws by analyzing whether the control system maintains certain properties such as stability and different performances, namely transitory and permanent performances.

For the experimental tests, the trajectory of the reference speed used is that of Figure 19.

In this figure, it is clear that the measured speed in the different cases of parametric variations perfectly follows its benchmark. This allows to conclude that the control method used is robust against the parametric variations.

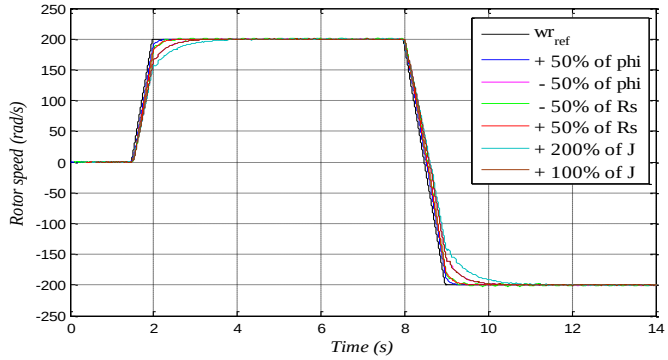

Figure 13. The rotor speed in different case of machine internal parameters variation

7. Conclusion

In this article, we have implemented the structure of the traditional vector control of the permanent magnet synchronous motor. This algorithm uses *PI* controllers in different loops which are two current loops and one speed loop.

During the controllers synthesis the two operating modes of the motor, the electrical mode and the mechanical mode, have been considered separates. The experimental results obtained by this structure are relatively satisfactory. they are characterized by an overshoot of 5%, of course, this is acceptable, but the transitory regime of speed response contain oscillations which can causes complications in some applications.

With the aim of improving the dynamic performances of the speed control, we have proposed a regulator based on the internal model control; this regulator fits well for the control of the permanent magnet synchronous machine driven by the vector control. The analysis of the different results obtained shows the capacities of the control by internal model to improvement the dynamics speed and its robustness in regard to the variations of the internal motor parameters. The insertion of the observation structure in the control loop allows to achieve a good estimation in a wide range of the speed and the load torque, also it reduces efficiently the noises in the speed response.

We can affirm that the control law based on the internal model control associated with state observer allows in general to give superior performances than the other correctors as well in nominal regime than in presence of internal parametric variations

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