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NEURO-GENETIC SENSORLESS SLIDING MODE CONTROL OF A PERMANENT MAGNET SYNCHRONOUS MOTOR USING LEUNBERGER OBSERVER

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ABSTRACT

The principal aim of this paper is a study and improves of sensorless vector control (VC) of a permanent magnet synchronous motor (PMSM). We interested mainly of the Luemberger observer. This method is based on a representation of the state of the dynamic model of the motor. In order to optimize the performance of the drive system, the genetic algorithm is proposed as an intelligent technique applied to the system of the observer to determine the values of its matrix gains to improve its dynamic performance. In a first stage we describe the modeling of PMSM and the principle of VC with a sliding mode controller. In the second stage, we insert the Luenberger observer with genetic algorithm in vector control block of PMSM.

Keywords: *Permanent Magnet Synchronous Motor (PMSM), Vector Control, Genetic Algorithm (GA), Observer Of Luenberger, Sliding Mode Controller.*

1. INTRODUCTION

The robustness, low cost, performance and ease of maintenance are of interest control in many industrial applications. Now the advances in power and digital electronics can address the variable speed control of machines in low power applications. The researchers have developed various approaches to control flux, torque and speed in real time for electrical machines.

The algorithms of the conventional control using proportional, integral and derivative (PID) controller can precisely control undisturbed linear processes which has constant parameters. If the controlled system is subjected to disturbances or changes in system parameters, automation adaptive solution by adjustment of controller parameters is mandatory to keeps in advance the fixed performance of the controlled system in the presence of disturbances and variations of parameters.

These last years the control sliding mode knew a big success, because of its simplicity of implementation, robustness with respect to uncertainties of system and external disturbances. It consists to bring the state trajectory to the sliding surface, and make it evolve over with some momentum to the balance point [1,2,9].

The Sensorless Control of synchronous machine is an axis of industrial research and development, because, it is a strategic purpose on business plan for most manufacturers of electric actuators. Therefore, the robustness to the sensorless control reinforces the idea of using the synchronous electromechanical actuator. Indeed, the sensorless control of synchronous machine has become one of the main interest fields of researches [3,4,5].

In this paper we propose the sensorless vector control method for PMSM by the sliding mode controller technique, and Leunberger observer based on genetic algorithm (LOGA). The values of matrix gains of Leunberger observer obtained by resolving the mathematical equation of PMSM are not exact and more suitable for PMSM drive. However we use a genetic algorithm to optimize the values of this matrix with the use of a fitness function designed to reduce the response time and overshoot.

The contents of this paper are organized as follows. In section 2, analytic model of PMSM is developed, the principal of VC is presented in section 3, the sliding mode control of the PMSM is detailed in Section 4, the Leunberger observer used

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in the control is addressed in sections 5, GA and Neuro selector are treated in sections 6 and 7, motor parameters and simulation results are given in sections 8. Finally section 9 concludes the paper.

The simulation method is designed with C Mex Files under Matlab/Simulink software.

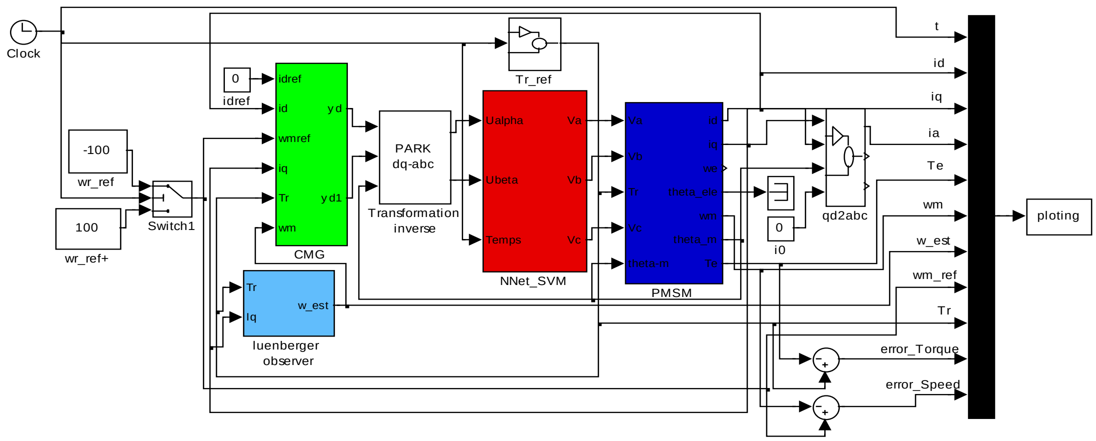

Figure 1. Simulation Scheme Of Sensorless Sliding Mode Control Of A Permanent Magnet Synchronous Motor

2. DYNAMIC MODEL OF PMSM:

We admit that the machine is symmetric, that its induction has a sinusoidal distribution in the air-gap and that it is not subjected to the saturation. In the reference axis connected to the rotating field, the electromechanical behavior of the PMSM in the (dq) frame is expressed by the following equations [6]:

$$U_d = Ri_d - \omega_r \lambda_q + \frac{d\lambda_d}{dt} \qquad (1)$$

$$U_q = Ri_q - \omega_r \lambda_d + \frac{d\lambda_q}{dt} \qquad (2)$$

$$\lambda_d = L_d i_d + \lambda_m \qquad (3)$$

$$\lambda_q = L_q i_q \qquad (4)$$

$$T_e = \frac{3}{2}\left(\lambda_m i_q + \left(L_d - L_q\right) i_d i_q\right) \qquad (5)$$

$$\frac{d\omega_r}{dt} = \frac{p}{J}\left(T_e - f_c \omega_r - T_r\right) \qquad (6)$$

Where

U_d : Direct -axis stator voltage;
U_q : Quadrature -axis stator voltage;
i_d : Direct -axis stator current;
i_q : Quadrature- axis stator current;
L_d : Direct- axis stator inductance;
L_q : Quadrature- axis stator inductance;
λ_d : Direct-axis stator flux;
λ_q : Quadrature-axis stator flux;
p : Number of poles;
R : Stator resistance;
λ_m : Rotor magnet flux linkage;
ω_r : Mechanical rotor speed;
f_c : Coefficient of viscous friction;
T_r : Resistive torque;

3. PRINCIPLE OF VECTOR CONTROL:

This technical consists to maintaining the reaction armature flux in quadrature with the rotor flux produced by the system of excitation like in case of the machine of DC. For an optimal working with a maximum torque, the simplest solution for a synchronous machine is to maintain the direct current equal to zero $i_d = 0$, and to control the speed by the quadrature current (i_d) with the voltage U_q [6][7][8]. By taking account of the equation (5) and by maintaining i_q constant and $i_d = 0$, the expression of the electromagnetic couple is written by:

$$T_e = \frac{3}{2} p \lambda_m i_q(t) \qquad (8)$$

By maintaining the conditions preceding, the equations of U_d and U_q are coupled, one is thus brought to establish a decoupling which consists the introduction of the compensation terms C_q and C_q. The tensions U_d and U_q depends respectively only by i_d and i_q (Fig 2).

We are defining the compensation terms by:

$$C_d = \omega_r L_q i_q(t) \qquad (9)$$

$$C_q = -\omega_r L_d i_q(t) + \omega_r \lambda_m$$

The fig.2 shows the decoupling of the system with the compensation terms.

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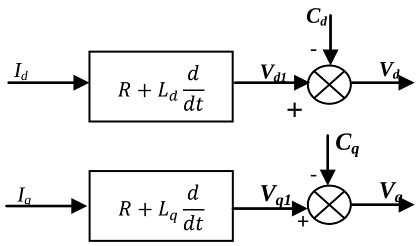

Figure 2. Decoupling Of The System

4. SLIDING MODE CONTROLLER:

4.1 Principle of sliding mode controller:

The sliding mode control is to bring the trajectory state and to evolve it on the sliding surface with a certain dynamic to the equilibrium point. As a result the sliding mode control is based on three steps [10][17][11]:

4.1.1 Choice of the switching surface:

For a nonlinear system presented in the following form:

$$\dot{X} = f(X,t) + g(X,t)U(X,t) \qquad (10)$$

$$X\epsilon\ IR^n, U\epsilon\ IR^n, rang\big(g(X,t)\big) = m$$

Where $f(X,t), g(X,t)$ are two continuous nonlinear functions:

To determine the sliding surface, we take the form of general equation given by J.J.E.Slotine [10]:

$$S(X) = \left(\frac{d}{dt} + \lambda\right)^{n-1} e(X) \qquad (11)$$

$$e(X) = X_{ref} - X$$

$e(X)$: denotes the error of the controlled greatness;

λ : Positive coefficient;

n : Order of the system;

X_{ref} : Reference greatness;

X : Variable of the controlled greatness. State;

4.1.2 The condition of convergence:

The condition of convergence is defined by the equation of Lyapunov [18], it make the surface attractive and invariant.

$$S(X)\dot{S}(X) \le 0 \qquad (12)$$

4.1.3 Control calculation:

The control algorithm is defined by the equation:

$$U = U_{eq} + U_n \qquad (13)$$

With:

U : Control variable.;

U_{eq} : Equivalent control variable;

U_n : Term of switch control variable. In order to reduce the chattering, the discontinuous function as exposed in equation (14) [20];

$$U_n = K_x sat\big(S(X)\big) \qquad (14)$$

Where:

$sat(S(X)\ /\ \delta)$: function of saturation;

δ : Width of the threshold of the saturation function;

K_x : Positive gain;

$$sat(S(X)/\delta) = \begin{cases} sign\big(S(X)\big) & if\ |S(X)| > \delta \\ S(X)/\delta & if\ |S(X)| < \delta \end{cases} \qquad (15)$$

4.2 Strategy of regulation of PMSM on three surfaces:

The figure (3) presents the diagram of the regulation by sliding mode using the principle of the method of regulation in cascade; the structure contains a control loop of speed which generates the reference i_q, which imposes the U_q. The control of U_d is imposed by the control of i_d current.

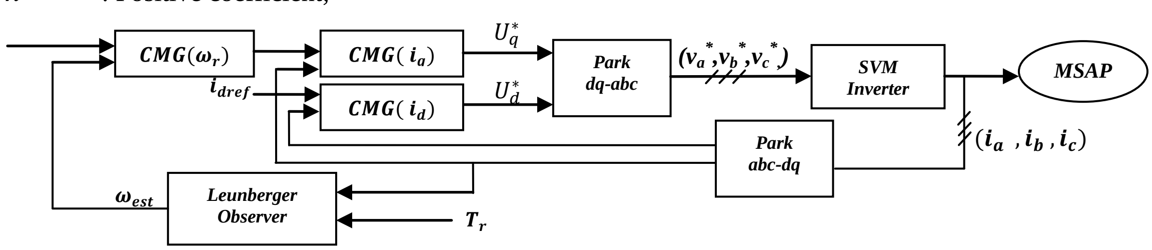

Figure 3. Schematic Global Of Sliding Mode Control With Strategy Of Three Surfaces

4.2.1 Control of speed:

The synthesis of control exploits the sliding modes technique, by using the principle of cascade adjustment method, which requires the choice of the surfaces that assure the objectives of control.

According to equations (5, 6), we notice that the relative degree of speed with i_q is equal 1. So, in equation (11) we replace n by 1, the surface selected for the control of speed error is:

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$$S(\omega_r) = \omega_{ref} - \omega_r \qquad (16)$$

The derivative of the equation (16) is:

$$\dot{S}(\omega_r) = \dot{\omega}_{ref} - \dot{\omega}_r \qquad (17)$$

The law of control is defined by:

$$I_{qref} = I_{qeq} + I_{qn} \qquad (18)$$

We replace respectively the equation (5) in (6) and the obtained equation in (17), we obtain the following equation:

$$\dot{S}(\omega_r) = \dot{\omega}_{rref} - \frac{3p}{2}\frac{(L_d - L_q)i_d + \lambda_m}{J} i_q + \frac{T_r}{J} + \frac{f_c}{J}\omega_r \qquad (19)$$

If we replace the equation (18) in (19) we obtain:

$$\dot{S}(\omega_r) = \dot{\omega}_{rref} - \frac{3p}{2}\frac{(L_d - L_q)i_d + \lambda_m}{J}(i_{qeq} + i_{qn}) + \frac{T_r}{J} + \frac{f_c}{J}\omega_r \qquad (20)$$

During the sliding mode we have:

$$S(\omega_r) = 0, \dot{S}(\omega_r) = 0, i_{qn} = 0 \qquad (21)$$

We deduce the expression of i_{qeq} from (22):

$$i_{qeq} = \frac{\dot{\omega}_{rref} + \frac{f_c}{J}\omega_r + \frac{T_r}{J}}{\frac{3p}{2}\left[\frac{(L_d - L_q)i_d + \lambda_m}{J}\right]} \qquad (22)$$

We replace equation (22) in (21) one obtains:

$$\dot{S}(\omega_r) = -\frac{3p}{2}\left[\frac{(L_d - L_q)i_d + \lambda_m}{J}\right] i_{qn} \qquad (23)$$

During the mode of convergence, the derivative of the equation of Lyapunov must be negative:

$$S(X)\dot{S}(X) \leq 0$$

According to the equation (15), the discontinuous function i_{qn} defined by:

$$i_{qn} = K_{\omega_r}.sat(S(\omega_r)) \qquad (24)$$

K_{ω_r}: Positive gain for speed regulator.

The control to the output controller of i_{qref} given by:

$$i_{qref} = \frac{\dot{\omega}_{rref} + \frac{f_c}{J}\omega_r + \frac{T_r}{J}}{\frac{3p}{2}\left[\frac{(L_d - L_q)i_d + \lambda_m}{J}\right]} + K_{\omega_r}.sat(S(\omega_r)) \qquad (25)$$

4.2.2 Control of id and iq currents:

The expression of i_d is given by the equation:

$$\frac{d}{dt}i_d = -\frac{R}{L_d}i_d + \frac{L_q}{L_d}\omega_r i_q + \frac{1}{L_d}U_d \qquad (26)$$

We note that the equation (26), show the relative degree of current i_d with U_d is equal to 1. Therefore the error variable e_d is given by:

$$e_d = i_{dref} - i_d$$

The sliding surface of this control is given by:

$$S(i_d) = i_{dref} - i_d$$

The derivative of the equation of $S(i_d)$ is:

$$\dot{S}(i_d) = \dot{i}_{dref} - \dot{i}_d \qquad (27)$$

If we replace the equation (26) in (27), the derivative of surface becomes:

$$\dot{S}(i_d) = \dot{i}_{dref} + \frac{R}{L_d}i_d - \frac{L_q}{L_d}\omega_r i_q - \frac{1}{L_d}U_d \qquad (28)$$

The low of control is defined by:

$$U_{dref} = U_{deq} + U_{dn} \qquad (29)$$

During the sliding mode we have:

$$S(i_d) = 0, \dot{S}(i_d) = 0, i_{dn} = 0$$

We deduce the expression of i_{qeq} from (30):

$$U_{deq} = \left(\dot{i}_{dref} + \frac{R}{L_d}i_d - \frac{L_q}{L_d}\omega_r i_q\right)L_d \qquad (30)$$

During the mode of convergence, the derivative of the equation of Lyapunov must be negative:

$$S(X)\dot{S}(X) \leq 0$$

Consequently, the command to the output controller of i_d becomes:

$$U_{dref} = \left(\dot{i}_{dref} + \frac{R}{L_d}i_d - \frac{L_q}{L_d}\omega_r i_q\right)L_d + K_d sat(S(i_d)) \qquad (31)$$

K_d : Positive gain for i_d current regulator.

In the same way to previous, by developing of the equation (32), the control to the output controller of i_q given by (33):

$$\frac{d}{dt}i_q = -\frac{R}{L_q}i_q + \frac{L_d}{L_q}\omega_r i_d - \frac{\lambda_m}{L_q}\omega_r + \frac{1}{L_q}U_q \qquad (32)$$

$$U_{qref} = \left(\dot{i}_{qref} + \frac{R}{L_q}i_q - \frac{L_d}{L_q}p\omega_r i_d + \frac{p\lambda_m}{L_q}\omega_r\right) + K_q sat\left(S(i_q)\right) \qquad (33)$$

K_q : Positive gain for regulator of i_q.

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5. OBSERVER OF LUENBERGER

5.1. Principle of the observer

The structure of an observer of state is illustrated by the figure (5), it is based on a model of the system, called the estimator or predictor, functioning in open loop. The complete structure of the observer includes a loop of corrective matrix gain, allowing correcting the error between the output of the system and that of the estimator [12] [13].

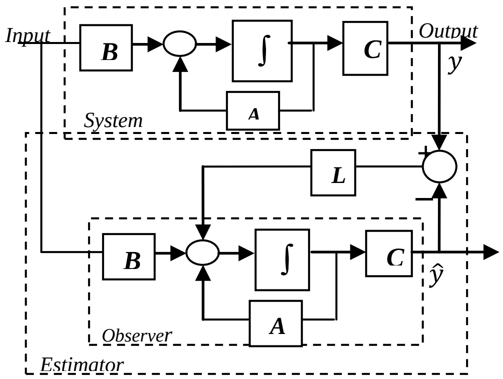

Figure 4. Structure Of An Observer Of State In Association With The System.

The dimensioning of corrective matrix gain L carried out to assure the convergence as soon as possible between the model of the estimator and the real system, Thus, by a wise choice of the matrix gain (L), we can modify the dynamics of the observer and consequently evolve the speed convergence of the error to zero, while preserving the condition on the matrix (A − LC) which must be a Hurwitz matrix [12], it means that its eigenvalues are with negative real parts in the continuous case, or have a module smaller than 1 in the discrete case.

5.2. Design of the observer of state:

The mathematical model of nonlinear states equations of PMSM is given by:

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \qquad (34)$$

With:

$$u = i_q$$

$$x = [\theta \quad \omega \quad T_r]$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \dfrac{-f_c}{J} & \dfrac{-1}{J} \\ 0 & 0 & 0 \end{bmatrix} \qquad (35)$$

$$B = \begin{bmatrix} 0 & \dfrac{p\lambda_m}{J} & 0 \end{bmatrix}^T$$

The state equation of luenberger observer is given by [19]:

$$\frac{d\hat{x}}{dt} = A\hat{x} + Bu + L(x - \hat{x}) \qquad (36)$$

With:

$$L = \begin{bmatrix} 0 & 0 & 0 \\ l_2 & l_1 & 0 \\ l_3 & 0 & 0 \end{bmatrix} \qquad (37)$$

The observer state can be described by the following system [13]:

$$\frac{d\hat{\theta}_r}{dt} = \hat{\omega}_r$$

$$\frac{d\hat{\omega}_r}{dt} = \frac{1}{J}\left(T_e - \hat{T}_r\right) - \frac{f_c}{J}\hat{\omega}_r + l_1(\omega_r - \hat{\omega}_r) + l_2\left(\theta_r - \hat{\theta}_r\right) \qquad (38)$$

$$\frac{d\hat{T}_r}{dt} = l_3\left(\theta_r - \hat{\theta}_r\right)$$

Figure 6 presents the functional diagram of luenberger observer. The estimated states are adjusted by the difference between the estimated $(\hat{\theta})$ and the calculated (θ) position from equation of motor.

In matrix gain (37), the variable l_2 determines the acceleration or the deceleration of the evolution of the variable estimated towards the real states. A greater gain will accelerate the process and a smaller gain will slow down it. The integral gains l_3 can reduce the static error to established regime of the observer [12].

The dynamics error of the observer is obtained from (34) and (36) by:

$$\dot{e} = (A - L)e \qquad (39)$$

With:

$$e = x - \hat{x}$$

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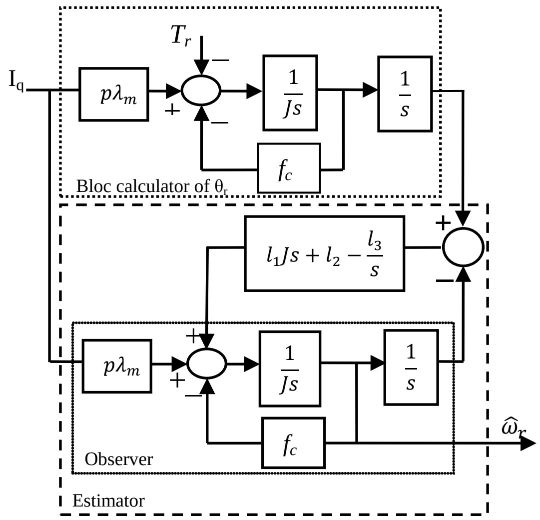

Figure 5. Structure Of The Luenberger Observer Of State.

The values of l_1, l_2 and l_3 obtained by resolving the system (38) which based on mathematical equation of PMSM, are not exact and more suitable for PMSM drive. However we use genetic algorithm to optimize l_1, l_2 and l_3.

6. NEURO SPACE VECTOR MODULATION

The Neural network (NN) is the most generic form of Artificial Intelligence (AI) for emulating the human thinking process, is particularly suitable for solving many important problems as SVM. The NN uses a dense interconnection of computing nodes to approximate nonlinear function [14]. Using a general flowchart for neural network and the parameters presented in table 2.

Table 1. Nn Parameters

Parameters	Value
Training Algorithm	Backpropagation
Input layer	3 neurons
Hidden layer	15 tansig neuron
Output layer	3 purelin neuron

The neural network voltage selector is illustrated by figure 7.

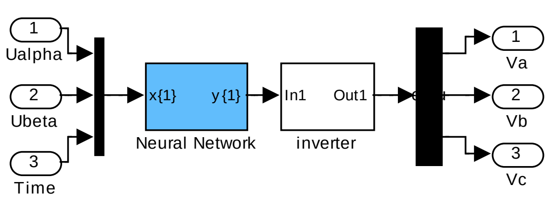

Figure 6. Neural Network Voltage Selector

7. GENETIC ALGORITHM:

Figure 6 shows the flowchart of GA [15]-[16].

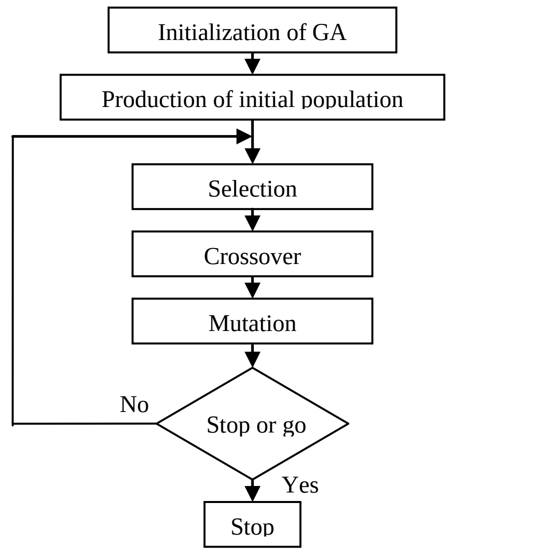

Figure 7. GA Flowchart

In order to the equation (45) with the system (19) a genetic algorithm is employed to optimize l_1, l_2 and l_3 of control process. The configuration of genetic algorithm parameters used in this paper is given in Table 1.

Table 2. Ga Parameters

Parameters	Value
Crossover probability	0,95
Mutation probability	0,001
Generation number Population	300
Population	200
Chromosome length	24 bit

The fitness function of each individual of this study is expressed by the equation (45):

$$fitness = \frac{1}{MO + 2ST + 1} \qquad (45)$$

Where:
MO: represents the overshot.
ST: represents the settling time.

8. RESULTS OF SIMULATION

5 parameters of PMSM:

The following table represents the parameters of PMSM:

Table 3. Parameters of PMSM

Parameter	**Value**	**Unit**
stator resistance.	***1.4***	Ω
d-axis inductance.	***6.6***	mH
q-axis inductance.	***5.8***	mH
magnetic flux constant	***0.1546***	Wb
Friction coefficient.	***0.00038***	$N \cdot m \cdot rad^{-1} \cdot s^{-1}$
Motor inertia.	***0.00176***	$Kg \cdot m^2$

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The matrix gains values of luenberger observer found by GA in this simulation is given by:

$$L = \begin{bmatrix} 0 & 0 & 0 \\ -9.7058e+03 & 1.9623e+04 & 0 \\ 7.2479e+03 & 0 & 0 \end{bmatrix}$$

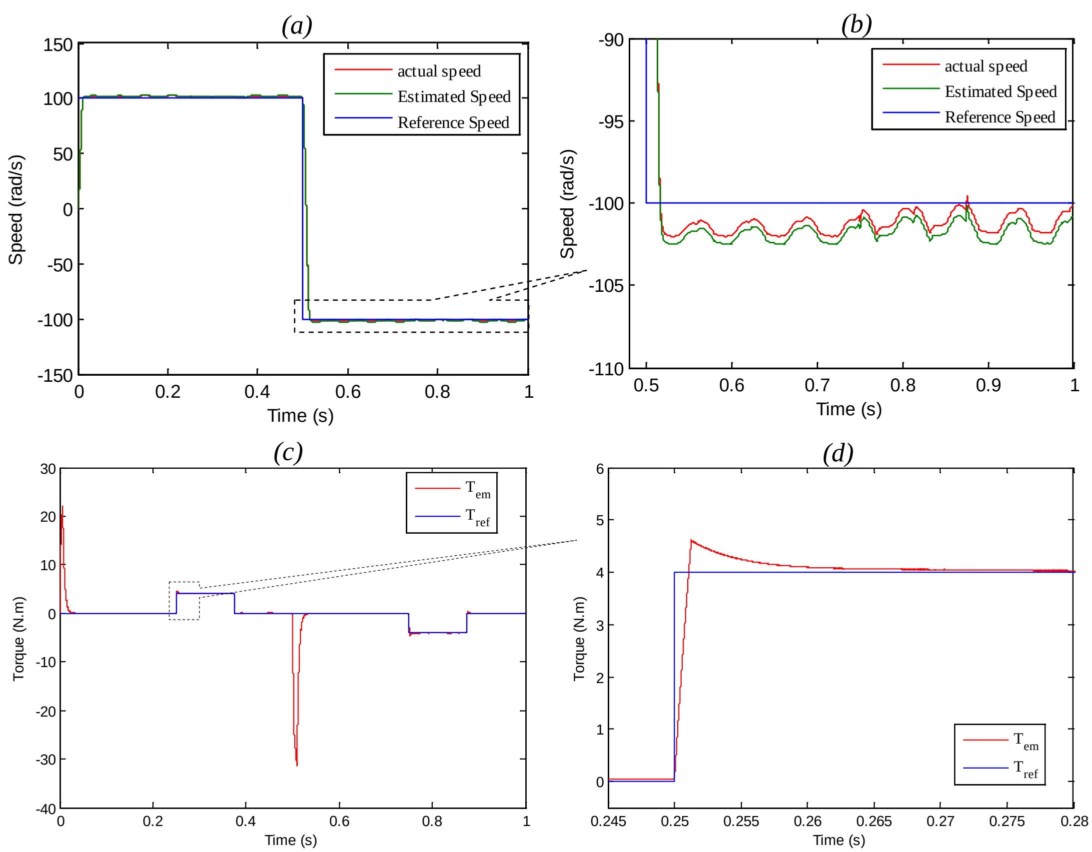
6 SIMULATION RESULT:

To illustrate the performances of the proposed method, we begin the simulation of PMSM without load, and at t= 0.5s we reverse the reference speed from $+100$ rad/s to -100rad/s.

The load is applied in two periods:

- ω_{ref}=+100rad/s, the load $(C_r = 4Nm)$ is applied at the moments $t = 0.25s$ and it elimination at $t = 0.375s$.
- ω_{ref}=–100rad/s, the load $(Cr = -4Nm)$ is applied at the moments $t = 0.75s$ and it elimination at $t = 0.875s$.

The fig.9 shows, that the speed and torque response reach the references quickly with rejection of harmonic ripples (fig.9-a, b, c and d). In other hand the current i_d is maintained null $(i_d = 0)$ and current i_q is limited in an acceptable maximum value (Fig.9-e), and the statics errors, between the reference and actual Torque, and between the reference and actual speed are negligible (Fig.9-g and h).



(e) (f)

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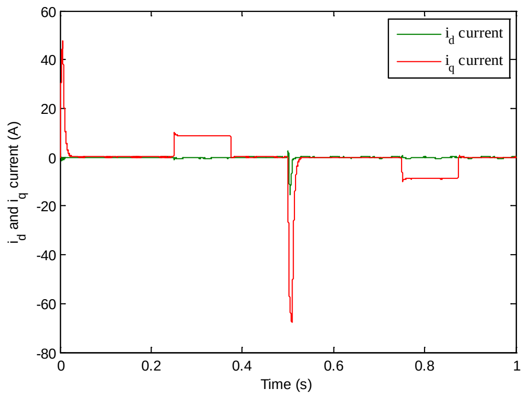
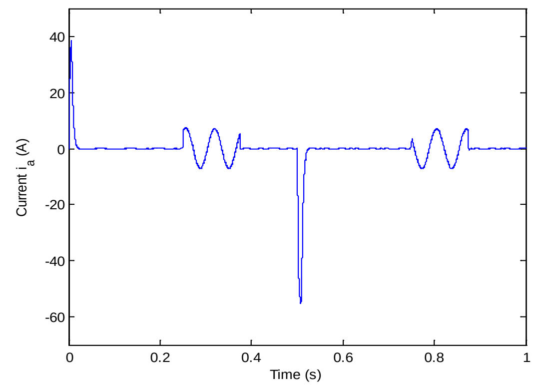
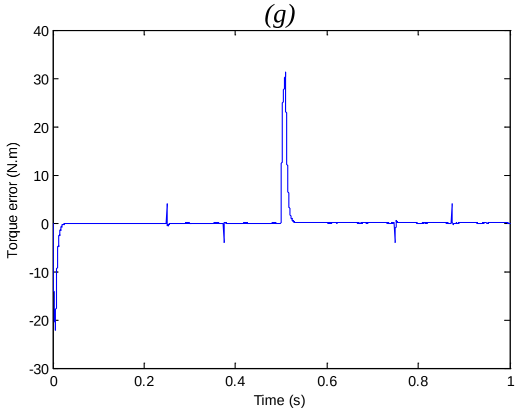




(g) *(h)*



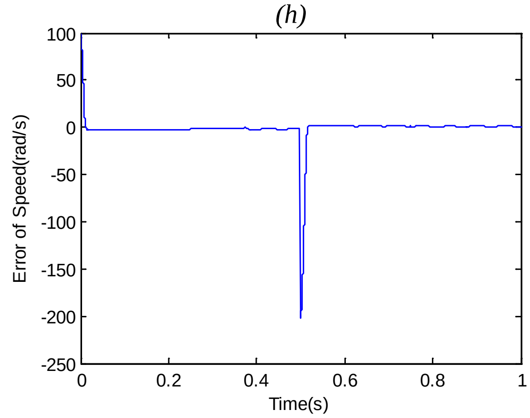


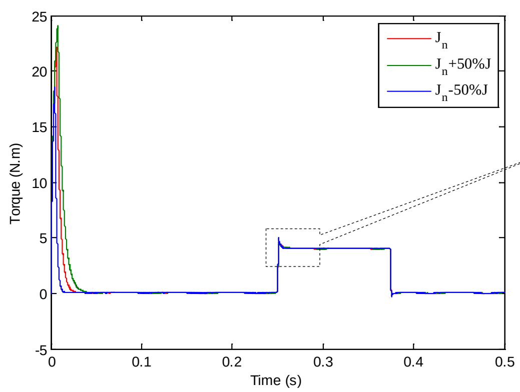
Figure 8. Simulated Speed (A), Zoom Of Speed (B), Torque (C), Zoom Of Torque (D), i_d And i_q(E) Currents i_a (F), Torque Error (G) And Speed Error (H) Responses Of The PMSM Drive With Neuro Genetic Sensorless Sliding Mode Control For A ±100 Speed Reference With A Fixed Charge Of ±4N.M

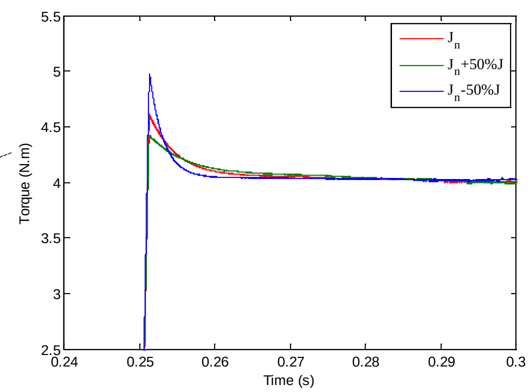
In order to test the robustness of the proposed control, we studied the influence of the variations parameters on the performances regulation of speed and torque.

Three cases are considered:

- A variation of ± 50% on inertia, (Fig.9)
- A variation of +50% on stator resistances, (Fig.10),
- A variation of + 20% on stator inductances. (Fig.11)

To illustrate the performances of the control, we applied $C_r = 4$Nm load torque at $t_1 = 0.25s$ and we eliminate it at $t_2 = 0.375s$, with level speed reference $+100\ rad/s$.





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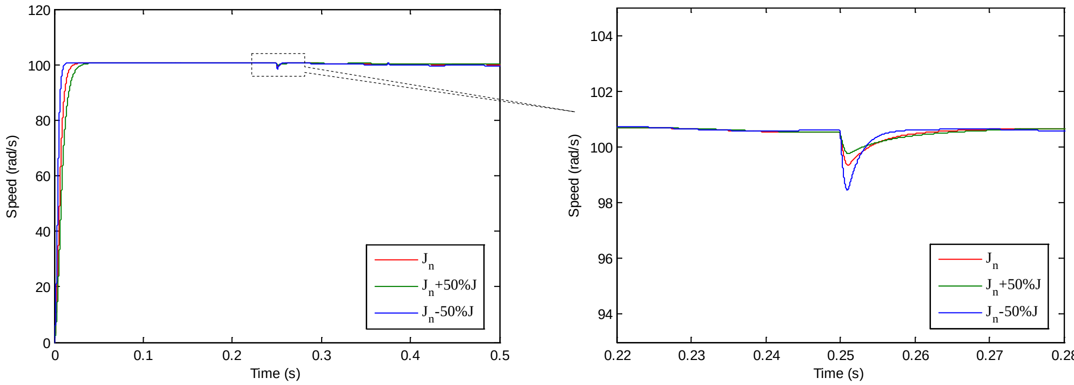


Figure 9. Test De Robustness Variation Of Inertia ±50%

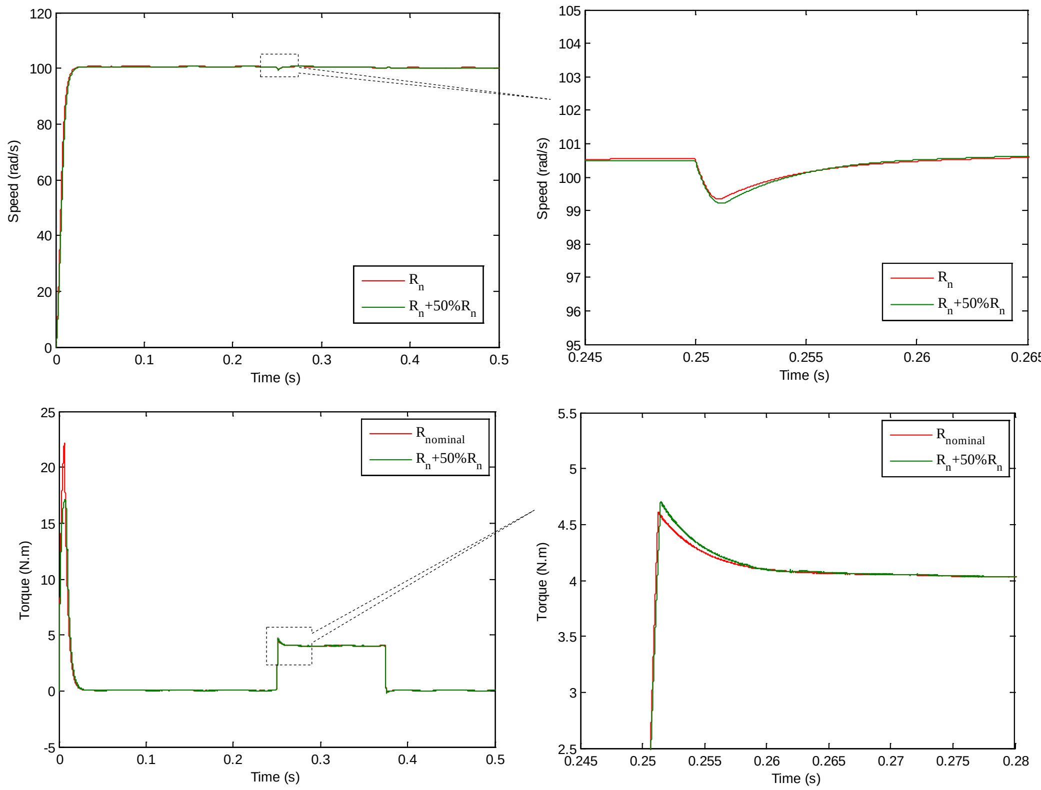
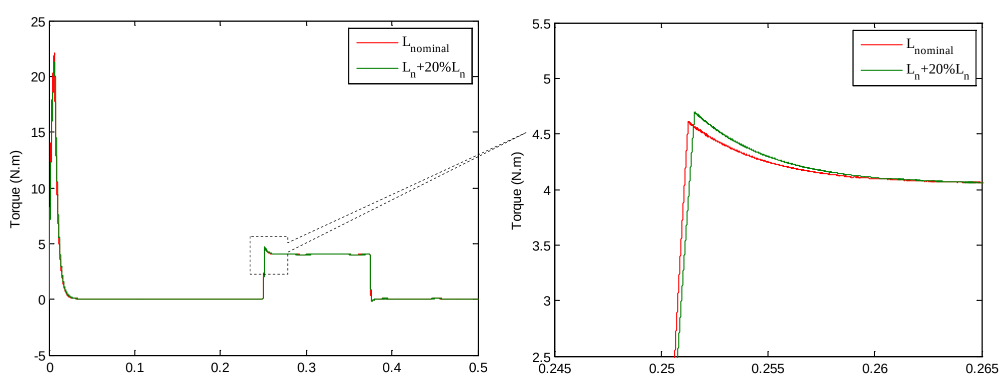


Figure 10. Test De Robustesse, Variation Des Résistances +50%



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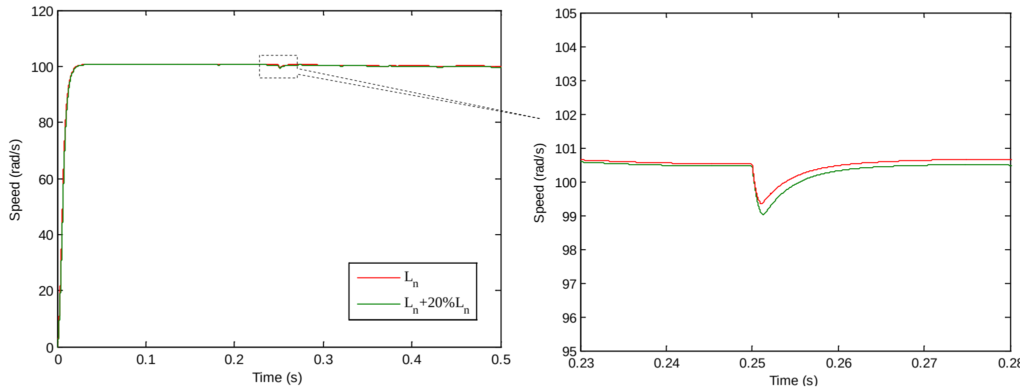

Figure 11. Test De Robustesse, Variation Des Inductances +20%

The simulation results presented in this part shows the robust of the Neuro-genetic sensorless VC with sliding mode controller of a permanent magnet synchronous motor using leunberger estimators, described in this papers, under stator resistance, moment of inertia and inductance variation. Figure 10 shows the stator resistance variation applied to examine our VC for PMSM drive by using novel estimator. In this case, the value of stator resistance was changed from the nominal value R_n to the $+1.5R_n$. Where, Figure 9 present the moment of inertia variation from J_n to $\pm 1.5J_n$, and the inductance variation from L_n to $+1.2L_n$, presented in Figure 11.

It's seen in figure (9, 10 and 11) that the proposed speed controller allows to achieve a faster response and reject the harmonic ripples (motor parameters variations), as with nominal motor parameters. Also, a faster motor torque response has been achieved with proposed technique compared to the simulation with nominal case; as shown in figure (9, 10 and 11). Indeed, combining speed sliding controller and the novel estimator allow VC for PMSM to reject stator resistance, inertia and inductance variation due to this sliding controller, which is shown in figure (9, 10 and 11).

In conclusion simulations results are presented in figure 9; 10 and 11 show that the proposed controller is adaptive and robust to the effects of the variation of motor parameters such as stator resistance, stator inductance and moment of inertia on speed estimations, over a wide speed range, have been studied. Hence, the observer is more robust to parameter detuning.

9. CONCLUSION

In this paper, the results of simulation enabled us to judge qualities of the proposed control based on sliding mode variable structure controller. Through the characteristics of the response obtained from simulation show that the control performances are very satisfactory. The dynamics of continuation is not affected during the variation of the load couple. The rejection of disturbance is very efficient. We notice, for speed, a fast starting with negligible overshoot and static error. The i_d current is maintained null and independent of the torque.

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