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Second-Order Sliding-Mode Observer Based Speed Sensoless Robust Control of PMSM

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Abstract: This paper is given to the investigation of the exhibitions of a hearty speed sensorless nonlinear control of lasting magnet synchronous machine. In the initial segment, the controllers are outlined utilizing two techniques: the first utilizing the info yield input linearization control and the second is a nonlinear control in view of Lyapunov hypothesis joined with sliding mode control. This second arrangement demonstrates great heartiness as for parameter varieties, estimation mistakes and clamors. In the second part, the high request sliding mode speed eyewitness is utilized to beat the happening prattling wonders. The super contorting calculation is changed so as to plan a speed also, position eyewitness for PMSM. At last, reenactment comes about are given to show the adequacy and the great execution of the proposed control strategies.

Keywords: Lyapunov function, Permanents magnet synchronous motors, Sensorless control, Second-order sliding modes, Robust nonlinear control.

1 INTRODUCTION

The PMSM is ending up increasingly prominent in servo frameworks in light of the fact that of its powerful thickness, vast torque to latency proportion and high proficiency [1]- [2]. In any case, the PMSM show is nonlinear coupled and subject to parameter varieties. It is portrayed by a fifth-arrange nonlinear differential condition, where a piece of states are not effortlessly quantifiable, and regularly annoyed by an obscure stack torque. Established PI controller is a basic strategy used to control PMSM drives. However the primary disadvantages of PI controller are the affectability of its exhibitions to the framework parameter varieties and lacking dismissal of outside unsettling influences and load changes. So as to, conquer these issues, numerous arrangements have been proposed. In this way, expanded state eyewitnesses have been created for engine control applications to remunerate unmodeled flow what's more, aggravations [3, 4], and to empower the utilization of dynamic unsettling influence dismissal control in lack of involvement based plans [5]. Nonlinear control systems, for example, hearty control [6], versatile control [7, 8], Lyapunov based nonlinear control [9] what's more, sliding mode control have been connected. Additionally to, diminish cost and size of the drive, lessen upkeep prerequisite and increment the dependability and vigor of the framework,

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sensorless drives have gotten a wide consideration. The fundamental thought for sensorless drive is to assess engine speed and position through estimated stator terminal amounts [13 – 17]. To do that, diverse methodologies have been proposed, for example, demonstrate reference versatile framework (MRAS), high recurrence infusion technique [18, 19], onlooker based approach, for example, Extended Kalman Filter [20], nonlinear onlooker [21 – 24], versatile interconnected onlooker [25], sliding mode eyewitnesses [26 – 29], powerful correct differentiators [30 – 32], and high request sliding mode eyewitnesses [33 – 39]. In this work second-arrange sliding mode spectators are utilized to assess the rotor speed. These spectators are broadly utilized due to their, heartiness with regard to obscure sources of info, potential outcomes to utilize the estimations of the identical yield infusion for obscure sources of info recognizable proof and limited time union to the diminished request complex. To exhibit the adequacy and the great execution of the proposed control technique versus input yield criticism linearization control reenactment examinations are performed.

2 The PMSM Model

Its dynamic model expressed in the rotor reference frame is given by voltage equations:

$$v_d = R_s I_d + \frac{\mathrm{d}\Phi_d}{\mathrm{d}t} + p\Omega\Phi_q, \qquad v_q = R_s I_q + \frac{\mathrm{d}\Phi_q}{\mathrm{d}t} + p\Omega\Phi_d, \tag{1}$$

where the fluxes expressions are given by

$$\Phi_d = L_d I_d + \Phi_f, \quad \Phi_q = L_q I_q.$$

Considering d I and q I as states variables, (1) can be written as:

$$\frac{\mathrm{d}I_d}{\mathrm{d}t} = -\frac{R_s}{L_d}I_d + \frac{L_q}{L_d}p\Omega + \frac{v_d}{L_d}, \qquad \frac{\mathrm{d}I_q}{\mathrm{d}t} = -\frac{R_s}{L_q}I_q - \frac{L_d}{L_q}p\Omega I_d - \frac{\Phi_f}{L_q}p\Omega + \frac{v_q}{L_q}. \tag{2}$$

The electromagnetic torque is given by

$$T_e = \frac{3}{2}p\left[\left(L_d - L_q\right)I_d I_q + \Phi_f I_q\right] \tag{3}$$

and the associated equation of motion is

$$J_m\frac{\mathrm{d}\Omega}{\mathrm{d}t} = T_e - T_L - f_m\Omega. \tag{4}$$

From (2), (3) and (4), the state model is rewritten as:

$$u = U(t, x_4, x_3), \tag{5}$$

Where

$$f_r(x) = \begin{bmatrix} a_{11}x_1 + a_{12}x_1x_2 \\ a_{21}x_2 + a_{22}x_1x_3 + a_{23}x_3 \\ a_{31}x_1x_3 + a_{32}x_2 + a_{33}x_3 + a_{34}T_r \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix}, \quad g_d(x) = \begin{pmatrix} \lambda_d \\ 0 \\ 0 \end{pmatrix}, \quad g_q(x) = \begin{pmatrix} 0 \\ \lambda_q \\ 0 \end{pmatrix}; \tag{6}$$

$$v_s = \begin{bmatrix} v_d & v_q \end{bmatrix}^T, \quad \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix} = \begin{bmatrix} I_d & I_q & \Omega \end{bmatrix}^T,$$

$$a_{11} = -\frac{R_s}{L_d},\ a_{12} = \frac{L_q}{L_d}p,\ a_{21} = -\frac{R_s}{L_q},\ a_{22} = -\frac{L_d}{L_q}p,\ a_{23} = -\frac{\Phi_f}{L_q}p,$$

$$a_{31} = \frac{3p}{2J_m}(L_d - L_q),\ a_{32} = \frac{3p}{2J_m}\Phi_f,\ a_{33} = -\frac{f_m}{J_m},\ a_{34} = -\frac{1}{J_m}C_r,\ \lambda_q = 1/L_q,$$

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axes; d I and q I are the–where d v and q v are the stator voltages of the d q –q are flux linkages of the d q Φd andΦ axes, –stator currents of the d q f is the magnetic flux linkage, p is the number of poles pairs, TL is theΦaxes, load torque;Te is the electromagnetic torque, m J is the moment of inertia, mf is is the rotor speed.Ωthe viscous friction coefficient and

3 Input Output Feedback Linearization Control

Fig. 1 shows the control bloc diagram of a PMSM drive system using current and speed feedback control. The currents d I and q I can be calculated form i_a and i_b (which can be obtained from measurements) by Clarke and Park 2 Lh x f 2 are the first and second Lie) (and) (transformations. The terms Lh x f 1 derivatives.

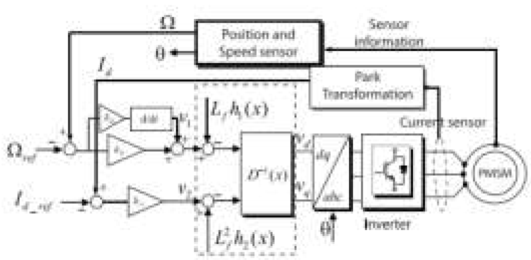

Fig. 1 – *Bloc diagram of* PMSM (IOC) *scheme.*

and the stator currentΩThe outputs to be controlled are the motor speed I_d . The function h (x) in (5) is defined as

$$h(x)=\begin{bmatrix} I_d \\ \Omega \end{bmatrix}. \tag{7}$$

The derivative of (7) is given by

$$\begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix}=\begin{bmatrix} L_f h_1(x) \\ L_f^2 h_2(x) \end{bmatrix}+D(x)\begin{bmatrix} v_d \\ v_q \end{bmatrix}. \tag{8}$$

The system has relative degree 1 for d I and 2 for decoupling matrix defined by

$$D(x)=\begin{bmatrix} \lambda_d & 0 \\ \lambda_d a_{31} x_2 & \lambda_q (a_{32}+a_{31}x_1) \end{bmatrix}, \tag{9}$$

And

$$L_f h_1(x)=a_{11}x_1+a_{12}x_2x_3\,, \tag{10}$$

$$L_f^2 h_2(x)=a_{31}x_2 f_1(x)+(a_{32}+a_{31}x_1)f_2(x)+a_{33}f_3(x)+a_{34}\dot{T}_L+a_{3}a_{34}T_L \tag{11}$$

Since

$|D(x)|=\lambda_d\lambda_q\left(a_{32}+a_{31}x_1\right)\neq 0$, then $D(x)$ is not singular (machine with permanents magnets) and the MIMO system is input-output linearizable.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix}=D^{-1}(x)\left[\begin{pmatrix} -L_f h_1(x) \\ -L_f^2 h_2(x) \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix}\right], \tag{12}$$

where $v=[v_1 \quad v_2]^T$ is the new input vector.

$$\begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix}=\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}=\begin{bmatrix} k_{11}\left(I_d-I_{d\_ref}\right) \\ k_{21}\left(\Omega-\Omega_{ref}\right)+k_{22}\left(\dot{\Omega}-\dot{\Omega}_{ref}\right) \end{bmatrix} \tag{13}$$

The downside of (12) is that it requires correct information of the engine parameters and any variety in the parameters or the heap torque will decay the controller exhibitions. So as to conquer this issue criticism nonlinear control in light of Lyapunov hypothesis is proposed.

4 Nonlinear Control Based on Lyapunov Theory for the PMSM

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The proposed PMSM control conspire is appeared in Fig. 2. We can see that just a single PI speed controller is utilized and the streams are criticism controlled in relationship with a sliding mode controller. We can likewise take note of the position of the estimator piece which assesses the input work 1f and 2f given by (6). To decide the control criticism, we rework (2) as take after:

$$\frac{\mathrm{d}\,I_d}{\mathrm{d}t} = \lambda_d v_d + f_1,$$
$$\frac{\mathrm{d}\,I_q}{\mathrm{d}t} = \lambda_q v_q + f_2. \tag{14}$$

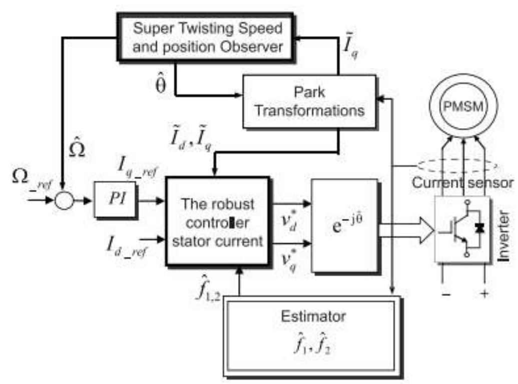

Fig. 2 – Bloc diagram of nonlinear control based on Lyapunov theory (NLC) with second-order sliding mode observer.

In a genuine circumstance, the nonlinear capacities fi engaged with the state-space demonstrate (14) are firmly influenced by the regular impacts of PMS engines, for example, temperature, immersion, skin impacts and clamor estimations. At that point the outline of a powerful control law needs the correct learning of fi capacities.

All inclusive, we can compose

$$K_{ii} \geq \beta_i, \tag{15}$$

where ˆ i f is the identified nonlinear feedback function, i f is the effective fi |∆fi are bounded (|∆fi is the error of fi. We assume that all ∆function and < i).β Substitution of (15) into (14) yields:

$$\frac{\mathrm{d}\,I_d}{\mathrm{d}t} = \lambda_d v_d + \hat{f}_1 + \Delta f_1,$$
$$\frac{\mathrm{d}\,I_q}{\mathrm{d}t} = \lambda_q v_q + \hat{f}_2 + \Delta f_2. \tag{16}$$

Let the candidate Lyapunov function related to the currents dynamics defined by:

$$V = \frac{1}{2}(I_d - I_{d\_ref})^2 + \frac{1}{2}(I_q - I_{q\_ref})^2 > 0. \tag{17}$$

This function is globally positive defined over the whole state space. Its derivative is given by

$$\dot{V} = (I_d - I_{d\_ref})(\dot{I}_d - \dot{I}_{d\_ref}) + (I_q - I_{q\_ref})(\dot{I}_q - \dot{I}_{q\_ref}). \tag{18}$$

Inserting (16) in (18) we obtain:

$$\dot{V} = (I_d - I_{d\_ref})(\lambda_d v_d + \hat{f}_1 + \Delta f_1 - \dot{I}_{d\_ref}) +$$
$$+(I_q - I_{q\_ref})(\lambda_q v_q + \hat{f}_2 + \Delta f_2 - \dot{I}_{q\_ref}). \tag{19}$$

Selecting the control law as

$$v_d = \frac{1}{\lambda_d}\left(-\hat{f}_1 + \dot{I}_{d\_ref} - K_1(I_d - I_{d\_ref}) - K_{11}\,\mathrm{sign}(I_d - I_{d\_ref})\right),$$
$$v_q = \frac{1}{\lambda_q}\left(-\hat{f}_2 + \dot{I}_{q\_ref} - K_2(I_q - I_{q\_ref}) - K_{22}\,\mathrm{sign}(I_q - I_{q\_ref})\right), \tag{20}$$

where $K_{ii} \geq \beta_i$, $K_i > 0$ and $i = 1,2$.

Inserting the control law (20) in (19), we obtain:

$$\dot{V}_1 = (I_d - I_{d\_ref})\left(\Delta f_1 - K_{11}\,\text{sign}(I_d - I_{d\_ref})\right) + \\ +(I_q - I_{q\_ref})\left(\Delta f_2 - K_{22}\,\text{sign}(I_q - I_{q\_ref})\right) + \dot{V} < 0, \tag{21}$$

where V is given by

$$\dot{V} = -K_1(I_d - I_{d\_ref})^2 - K_2(I_q - I_{q\_ref})^2 < 0. \tag{22}$$

Hence the Δf_i variations can be absorbed if we take

$$K_{11} > |\Delta f_1|, \quad K_{22} > |\Delta f_2|. \tag{23}$$

These inequalities are satisfied since $K_i > 0$ and $|\Delta f_i| < \beta_i < K_{ii}$ Finally, we can write

$$\dot{V}_1 < \dot{V} < 0. \tag{24}$$

Hence, using Lyapunov theorem [2], we conclude that

$$\lim_{t\to\infty}(I_d - I_{d\_ref}) = 0, \\ \lim_{t\to\infty}(I_q - I_{q\_ref}) = 0. \tag{25}$$

5 Observer Design

The proposed observer is based on a second-order sliding mode approach knowing to be robust versus parametric uncertainties, modeling errors and disturbances. The structure is identical to Fig. 2 except the sensor information which is replaced by the super twisting speed and position observer. The observer is based on the so-called broken super twisting algorithm presented in [33].

Using (3) and (4) we obtain the following form:

$$\dot{x}_4 = x_3, \\ \dot{x}_3 = f_O(t, x_4, x_3, u) + \xi(t, x_4, x_3, u). \tag{26}$$

where 4 x and 3 x are respectively is theξ , u is the torque and Ω and θ uncertainties.

$$\dot{\theta} = \Omega, \\ \ddot{\theta} = \dot{\Omega} = -\frac{f_m}{J_m}\Omega - \frac{1}{J_m}T_L + \frac{3}{2}p\Phi_f i_q + \xi. \tag{27}$$

The super twisting second order sliding mode observer is designed as follows:

$$\dot{\hat{\theta}} = \hat{\Omega} + z_1, \\ \ddot{\hat{\theta}} = \dot{\hat{\Omega}} = -\frac{f_m}{J_m}\hat{\Omega} - \frac{1}{J_m}T_L + \frac{3}{2}p\Phi_f i_q + z_2, \tag{28}$$

where ˆ θ and ˆ$\Omega$are the states estimations and the correction variables 1z and 2 z are output injections of the form:

$$z_1 = \lambda\,|\Omega - \hat{\Omega}|^{1/2}\,\text{sign}(\Omega - \hat{\Omega}), \\ z_2 = \alpha\,\text{sign}(\Omega - \hat{\Omega}). \tag{29}$$

We consider initially that ˆ θ = θ andd ˆ Ω =0Taking into accountθ–θ= θˆ e and , we obtain the following error equations

$$\dot{e}_\theta = e_\Omega - \lambda\,|e_\Omega|^{1/2}\,\text{sign}(e_\Omega), \\ \dot{e}_\Omega = -\frac{f_m}{J_m}e_\Omega - \alpha\,\text{sign}(e_\Omega). \tag{30}$$

We assume that:

$$\left| -\frac{f_m}{J_m}e_\Omega + \xi \right| < f^+ \tag{31}$$

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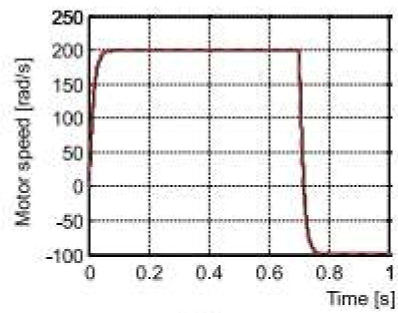
.Ω ≤ Ω and ˆ sup | | 2sup | | Ω θholds for any possible , , t The use of this super twisting algorithm ensures the finite time convergence of ˆ ˆ .Ω→Ω and θ→θ

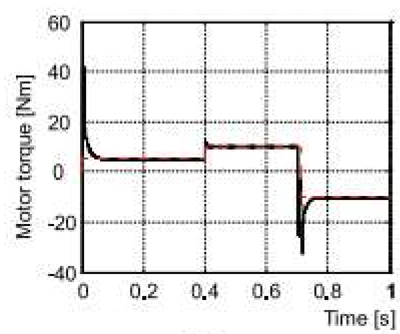
6 Simulation Results

To demonstrate the efficiency of the proposed composite control method, simulations on a PMSM servo system have been performed. Three control methods have been applied: input output feedback linearization Control (IOC), nonlinear control based on Lyapunov theory (NLC), and speed sensorless control of PMSM based on second-order sliding mode observer (super Twisting algorithm observer). The parameters of the PMSM used in the simulation are:

rated voltage	$V = 511$ V
number of poles	$p = 3$
armature resistance	$R_s = 1.4\ \Omega$
stator inductances	$L_d = 0.0066$ H $L_q = 0.0058$ H
viscous damping	$f_m = 0.00038$ Nms/rad
moment of inertia	$J_m = 0.0016$ kgm^2
rotor flux	$\Phi_f = 0.1546$ Wb
rated torque	$T_n = 10$ Nm



(a)



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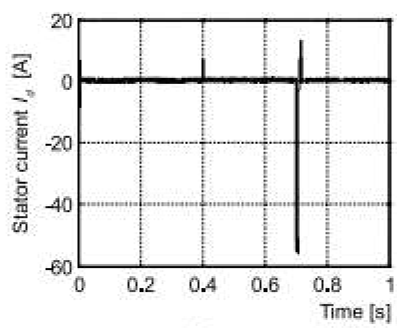

(c)

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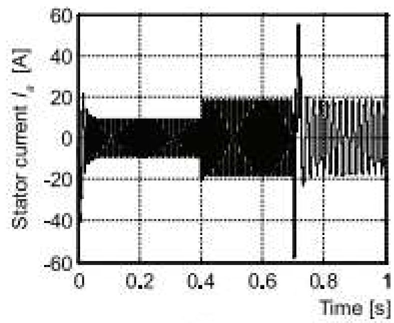
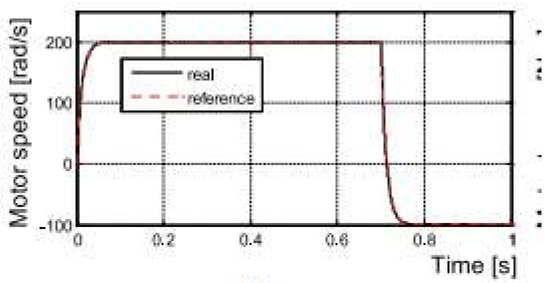
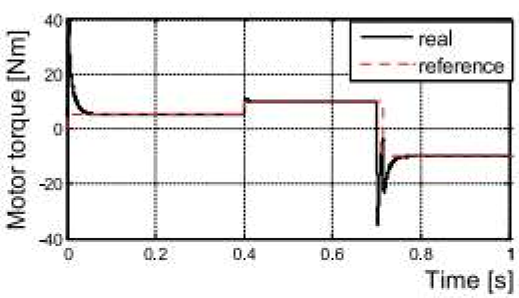


(d)

Fig. 3 – Simulation results of feedback linearization control (IOC) : (a) motor speed; (b) motor torque; (c) stator current Id; (d) stator current Ia [A].



(a)



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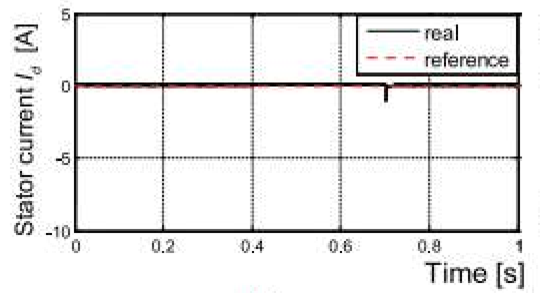

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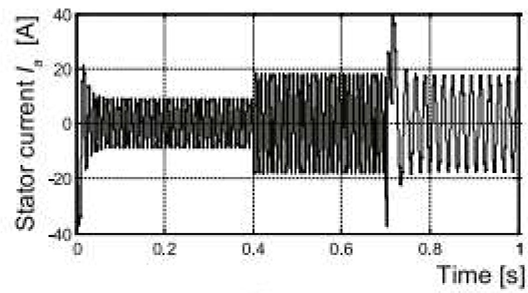

(d)

Fig. 4 – Simulation results of nonlinear control based on Lyapunov theory (NLC): (a) motor speed; (b) motor torque; (c) stator current Id; (d) stator current Ia [A].

In the first part of this section, two schemes have been simulated: input output feedback linearization (IOC) and the proposed nonlinear control based on Lyapunov theory scheme (NLC), to analyze and compare the performance of the PMSM in terms of accuracy, dynamic performance and load disturbance rejection. Figs. 3 and 4 show the PMSM response to square-wave speed reference 200 rad/s, using the IOC and NLC. The NLC PMSM drive speed trajectory is characterized by zero steady-state error and very fast dynamic response. To test the robustness of the two controls with respect to motor parameters variations, the following profile of speed reference is applied: The PMSM

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started with a constant acceleration after 0.1 s, the speed was maintained to10 rad/s, while the motor is loaded with a constant torque of 5 Nm at starting. Then the motor is loaded with a constant torque of 10 Nm at t = 0.4 s At t = 0.7 s, the speed change form 10 rad/s to 0 rad/s with same constant load torque. Maintaining a reference current Id to zero. Two sets of simulation tests are carried out. The first set is carried out with stator resistance having a mismatch of 100% at t = 0.5 s using the control law, the results of this test set are shown in Fig. 5 (IOC). It is clear that when considering stator resistance uncertainty, a very large steady state error occurred in motor speed. Finally the motor having a fi (NLFF) mismatch of 300% at t = 0.5 s and in the presence of noise is simulated using the proposed control. The results are shown in Fig. 5 (NLC). The control shows better speed response in the presence of parameter uncertainty and measurement noises.

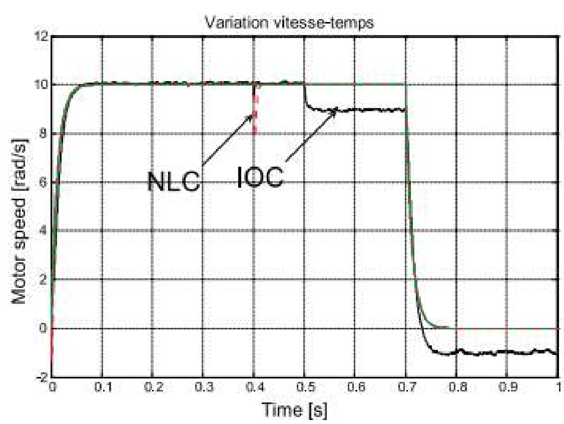


Fig. 5 – Comparison between IOC and NLC speed transient evolutions with parameter uncertainty and measurement noises

In the second part of this section, we illustrate the performance of the proposed Sensorless Control. The typical step references of the speed and load torque are given in Fig. 6a and Fig. 6b, respectively.

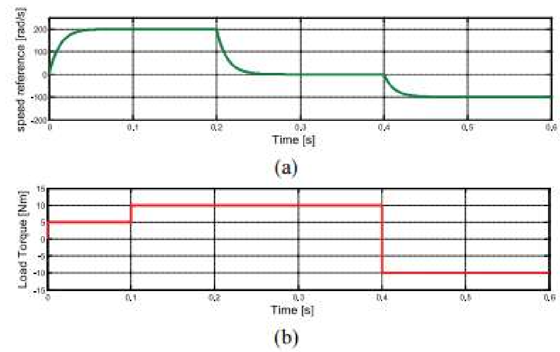
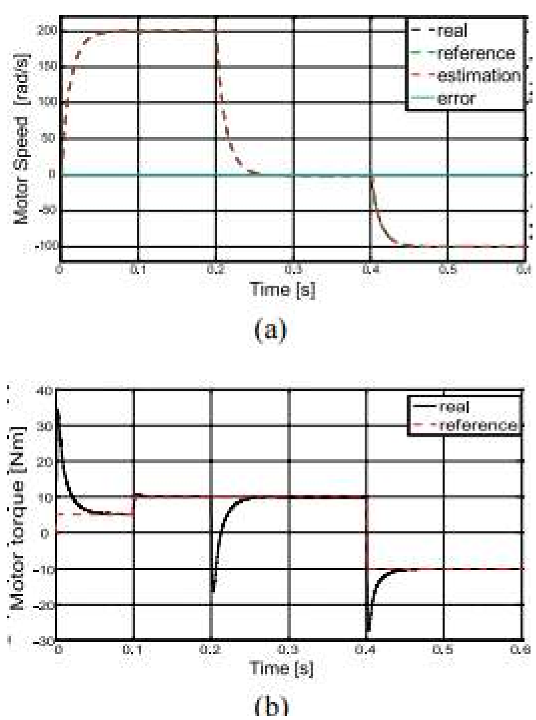


Fig. 6 – *The typical step references.*



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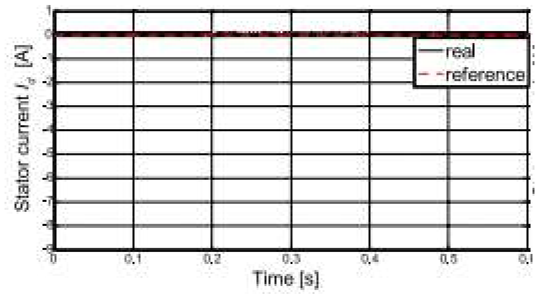

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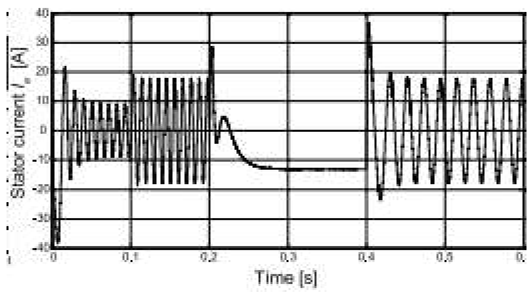
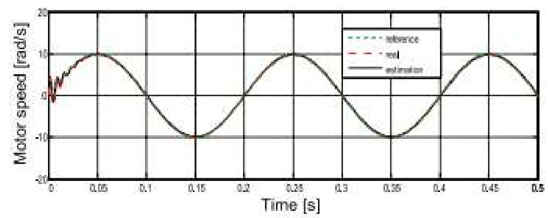


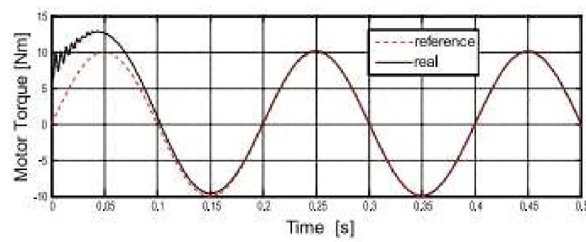
(d)

Fig. 7 – Simulation results of NLC_super twisting observer: (a) motor reference, actual and estimated speed; (b) motor torque; (c) stator current Id; (d) stator current Ia [A].

Fig. 7 shows the simulation result. The actual speed is compared with the estimated one. It can be seen that very good performances are obtained (Fig. 8). Another test with 5 Hz sinusoidal reference speed of 10 rad/s peak value is realized confirm the above results. The comparison between the actual speed and the estimated one shown by Fig. 8a demonstrate the effectiveness of the method. To track a reference torque, a 5 Hz sinusoidal torque reference with magnitude 10 Nm is applied to the machine where the speed is maintained at 200 rad/s. Good performances are obtained Fig. 8b.



(a)



(b)

Fig. 8 – Behavior at low motor speed: (a) sinusoidal reference, actual and estimated speed; (b) torque-tracking response reference and actual.

7 Conclusion

In this paper, a nonlinear control in light of Lyapunov hypothesis conspire joined with sliding mode spectator was connected for vigorous speed sensorless control of PMSM. The hypothetical investigation of this nonlinear control (NLC) has been examined and control strength checked by means of Lyapunov steadiness investigation. A moment arrange sliding mode onlooker in view of a correct differentiator (super-Twisting calculation) was utilized for two fundamental reasons: the limited time joining and the capacity to consider the variable idea of the framework structure.

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The recreation comes about show the adequacy and the great execution of the proposed control strategies.

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