SEBHA UNIVERSITY CONFERENCE PROCEEDINGS, VOL.04 NO. 1 2025
DOI: 10.51984/SUCP.V4I1.3913

المؤتمر العلمي الأول للتطبيقات الهندسية (ICEA'2024)
The First Scientific Conference on Engineering Applications (ICEA'2024)
Conference homepage: www.icea.ly

Nonlinear Control of Permanent Magnet Synchronous Generators (PMSG) Using Feedback Linearization and Sliding Mode Control

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Keywords:
Field Oriented Control
Hurwitz polynomials
Input-Output Feedback Linearization
Lyapunov Stability
Sliding Mode Control
Permanent Magnet Synchronous Machine

ABSTRACT

Controlling permanent magnet synchronous machines (PMSM) is particularly challenging due to their nonlinear dynamics. Traditional linear controllers, such as PI and PID, perform adequately in systems with constant parameters, but they often fall short when applied to nonlinear systems with variable parameters, lacking the necessary robustness. To address these limitations and achieve decoupled control of the machine, several methods have been proposed, with robust nonlinear control techniques gaining significant attention in power electronics and drive systems. Notable among these are sliding mode control (SMC) and nonlinear input output feedback linearization (IOFL). SMC is well-regarded for its exceptional dynamic performance in PMSM drives, offering high robustness and straight forward implementation in both software and hardware. However, its main limitation lies in the chattering phenomenon. In contrast, input-output linearization control demonstrates excellent behavior in both steady-state and dynamic regimes, while also providing effective decoupling of system variables. This article synthesizes two control approaches—sliding mode control and feedback linearization control based on input-output linearization—to regulate the speed of a PMSM. A comparative analysis conducted in Matlab/Simulink highlights the superior performance of the feedback linearization controller over SMC.

التحكم غير الخطي في المولدات المتزامنة ذات المغناطيس الدائم (PMSG) باستخدام خطية التغذية الراجعة والتحكم في وضع الانزلاق

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الكلمات المفتاحية:
التحكم الموجه نحو المجال
متعددات حدود هورويتز
خطية التغذية الراجعة للإدخال والإخراج
استقرار ليابونوف
التحكم في وضع الانزلاق
آلة التزامن ذات المغناطيس الدائم

الملخص

إن التحكم في الآلات المتزامنة ذات المغناطيس الدائم (PMSM) يشكل تحديًا خاصًا نظرًا لديناميكياتها غير الخطية. تعمل وحدات التحكم الخطية التقليدية، مثل PI وPID، بشكل كافٍ في الأنظمة ذات المعلمات الثابتة، ولكنها غالبًا ما تفشل عند تطبيقها على الأنظمة غير الخطية ذات المعلمات المتغيرة، وتفتقر إلى المتانة اللازمة. لمعالجة هذه القيود وتحقيق التحكم المنفصل في الآلة، تم اقتراح العديد من الطرق، حيث اكتسبت تقنيات التحكم غير الخطية القوية اهتمامًا كبيرًا في إلكترونيات الطاقة وأنظمة القيادة. ومن بين هذه الطرق التحكم في وضع الانزلاق (SMC) وخطية التغذية الراجعة غير الخطية للإدخال والإخراج (IOFL). تتمتع SMC بتقدير كبير لأدائها الديناميكي الاستثنائي في محركات PMSM، حيث توفر متانة عالية وتنفيذًا مباشرًا في كل من البرامج والأجهزة. ومع ذلك، فإن قيدها الرئيسي يكمن في ظاهرة الثرثرة. على النقيض من ذلك، يُظهر التحكم في خطية الإدخال والإخراج سلوكًا ممتازًا في كل من الأنظمة الثابتة والديناميكية، مع توفير فصل فعال لمتغيرات النظام. تلخص هذه المقالة طريقتين للتحكم - التحكم في وضع الانزلاق والتحكم في خطية التغذية الراجعة استنادًا إلى خطية الإدخال والإخراج - لتنظيم سرعة PMSM. يسلط التحليل المقارن الذي تم إجراؤه في ماتلاب / سيميماينك الضوء على الأداء المتفوق لوحدة التحكم في خطية التغذية الراجعة على SMC.

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Article History : Received 15 March 2024 - Received in revised form 25 September 2024 - Accepted 15 October 2024

1. Introduction

Permanent magnet synchronous machines have known remarkable development in recent years. The PMSM is an alternating current machine in which the rotor's rotational speed equals the speed of the rotating magnetic field created by the stator. This machine is used across a wide range of power levels, from watts to megawatts, in various applications such as positioning, synchronization, constant-speed drives, traction etc. It is replace DC motors and asynchronous motors because they offer higher efficiency, power factor, and torque density. Moreover, PMSM do not have an excitation circuit in the rotor, which leads to reduced maintenance demands. The challenge in controlling the PMSM lies in the complex coupling between the input variables, output variables, and the machine's internal variables, such as current, torque, speed, and position [1]. The vector control, also known as flow orientation control (FOC), allows for dynamics similar to those of a DC machine, meaning asymptotically linear and decoupled dynamics. However, this control structure requires that the machine parameters be constant. Furthermore, it demands accurate parameter identification. Consequently, the use of robust control regulators is necessary to maintain an acceptable level of decoupling and performance [2]. Traditional control algorithms, such as PI or PID, become insufficient when stringent performance requirements are imposed [3]. To address the aforementioned challenges and achieve decoupled machine control, various methods have been proposed in this context. Intelligent techniques, such as fuzzy logic and artificial neural networks, have been extensively studied in numerous research efforts. However, they are often highly complex and demand substantial computational power [4]. Robust nonlinear control techniques have been extensively investigated in the field of power electronics and drives. Among of them, we mention backstepping, sliding mode control and input-output feedback linearization. (SMC) Sliding mode control can provide high robustness and fast response control. However, the chattering phenomenon is the major drawback of this method [5, 15]. Moreover, to solve this phenomenon, in this work we proposed a non-linear control method based on input/output linearization which can provide good behavior in static and dynamic regimes. In addition, it also provides good decoupling between system variables [06]. The principle of this technique is to transform the nonlinear multi-input-output system into a chain of linear and decoupled systems, using a linearizing state feedback with input-output decoupling. From there, we can apply the theory of systems linear [07], [08], which can be summed up in a pole placement to ensure an asymptotic follow-up of the reference trajectories and a study of the dynamics of the zeros. In this paper, we present the principle of the linearization technique in the input-output sense. We will design a non-linear controller based on this technique to regulate the speed of a permanent magnet synchronous motor and compare its performance to that of a sliding mode controller.

2. Modeling Of Permanent Magnet Synchronous Motor PMSM

- **Stator voltages [09]**

$$\begin{cases} v_d = R_s.i_d + \dfrac{d\phi_d}{dt} - w_r.\phi_q \\ v_q = R_s.i_q + \dfrac{d\phi_q}{dt} + w_r.\phi_d \end{cases}$$

(01)

- **Stator flux:**

$$\begin{cases} \phi_d = L_d.i_d + \varphi_f \\ \phi_q = L_q.I_q \end{cases}$$

(2)

Based on equations “(1)” and “(2)”, the stator voltages can be expressed as:

$$\begin{cases} v_d = R_s.i_d + L_d \dfrac{di_d}{dt} - w_r.L_q.i_q \\ v_q = R_s.i_q + L_q \dfrac{di_q}{dt} + w_r.(L_d.i_d + \varphi_f) \end{cases}$$

(3)

The electromagnetic torque of the PMSM can be represented as:

$$C_{em} = P.[(L_d - L_q).i_d.i_q + \varphi_f.i_q] \quad (4)$$

The mechanical equation:

$$\dot{\Omega} = \frac{1}{J} C_{em} - \frac{f}{J}\Omega - \frac{C_r}{J} \quad (5)$$

The active and reactive stator power of PMSM in the Park reference frame are expressed as follows:

$$\begin{cases} P = v_d.i_d + v_q.i_q \\ Q = v_q.i_d - v_d.i_q \end{cases}$$

(6)

i_d, i_q : Components of stator current in the dq-axes

v_d, v_q : Components of stator voltage in the dq-axes,

R_s : Stator resistance,

L_d, L_q : d-axis and q-axis inductances,

ψ_f : Permanent magnetic flux and

w_e : Electrical rotor speed of the generator which is related to the mechanical rotor speed by $w_e = P.\Omega$, where P is the generator number of pole pairs.

The PMSM model demonstrates significant nonlinearity due to the interaction between the electric currents, flux, and the torque. To mitigate this coupling, Field-Oriented Control (FOC) is applied. The most commonly adopted control strategy involves maintaining the "id" current at zero. When id = 0, and since the flux of the PMSM φf is constant, the electromagnetic torque becomes directly proportional to the current iq. FOC or VC is composed of two primary loops: an outer loop for speed control and an inner loop for current regulation, as well as the direct and inverse Park transformation.

3. Speed and Current Regulation of PMSM Using Sliding Mode Control

Sliding mode control is a variable structure control that can change structure and switch between two values according to a very specific switching logic. The principle of SMC is to drive the system to attain a specific surface, named the sliding surface, and stay there until it reaches the stability.

The SMC controller has two parts. The first one is continuous representing the dynamics of the system during the sliding mode and another discontinuous representing the dynamics of the system during the convergence mode. The second term of SMC is important as nonlinear control, because its role is to eliminate the effects of model imprecision and disruptions.

The structure of a first-order sliding mode controller is comprised of two distinct components: [11, 12, 14]:

$$U = U_{eq} + U_N$$

(6)

- **Speed adjustment**

The speed controller generates the reference current i_{q-ref} . The relative degree of variable to adjust the law command is equal to one. In this case, the adjustment error is chosen as the surface:

$$S(w_r) = w_{ref} - w_r$$

(7)

The derivative of the surface is:

$$\begin{cases} \dot{S}(w_r) = \dot{w}_{rref} - \dfrac{p(L_d - L_q)i_d i_q + p\varphi_f i_q}{J} - \dfrac{1}{J}C_r + \dfrac{f}{J}w_r \\ i_q = i_{qeq} + i_{qN} \end{cases} \quad (08)$$

During the sliding mode and the steady state, we have: $S(w_r) = 0 \Rightarrow \dot{S}(w_r) = 0$. So, we deduce the equivalent command from equation (08):

$$i_{qeq} = \frac{\dot{w}_{rref} + \dfrac{f}{J}w_r + \dfrac{1}{J}C_r}{\dfrac{p(L_d - L_q)}{J}i_d + \dfrac{\varphi_f\, p}{J}} \quad (09)$$

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

$$\dot{V}(w_r) = S(w_r).\dot{S}(w_r) \prec 0 \quad (10)$$

By replacing equation (09) in (08), we obtain:

$$\dot{S}(w_r) = -\left[\frac{p(L_d - L_q)}{J}i_d + p\varphi_f\right]i_{qN}$$

(11)

Thus:

$$i_{qN} = k_{\Omega}.sign(S(w_r)),$$

k_{Ω} : Positive gain.

- **Current setting iq**

The sliding surface is chosen as:

$$S(i_q) = i_{qref} - i_q \quad (12)$$

In this case, the V_{qeq} and V_{qN} commands are expressed by:

$$\begin{cases} V_{qeq} = \left(\dot{i}_{qref} + \dfrac{R_s}{L_q}i_q + p\dfrac{L_d}{L_q}w_r i_d + \dfrac{p w_r \varphi_f}{L_q}\right)L_q \\ V_{qN} = k_q.sign(S(i_q)) \end{cases} \quad (13)$$

k_q : Positive gain.

- **Current setting id**

The sliding surface is chosen as:

$$S(i_d) = i_{dref} - i_d \quad (14)$$

In this case, the V_{deq} and V_{dN} commands are expressed by:

$$\begin{cases} V_{deq} = \left(\dot{i}_{dref} + \dfrac{R_s}{L_d}i_d + p\dfrac{L_q}{L_d}w_r i_q\right)L_d \\ V_{dN} = k_d.sign(S(i_d)) \end{cases}$$

(15)

k_d : Positive gain.

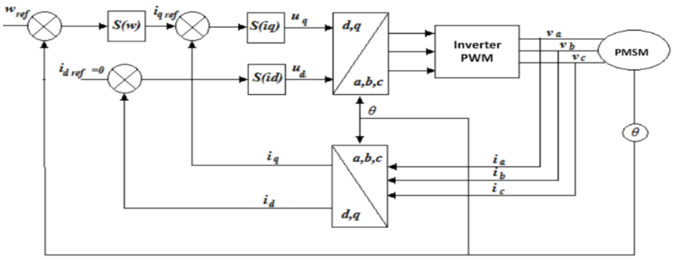


Fig. 1: Diagram of global FOC strategy with Sliding Mode Controller.

4. Feedback Linearization Controller Based On Input-output Feedback Linearization Of PMSM :

The goal of this technique is to find a linear relationship between the inputs and outputs of a multivariable, nonlinear and coupled system using the linearization by input-output looping technique. First, the relative degree of each output to be controlled is calculated in order to establish the decoupling matrix D(x), then a linearizing control law is constructed, and finally, a control for the decoupled system and linearized for a reference trajectory tracking problem is developed [10,16].

4.1 Non-linear model of PMSM

The MSAP equations are rewritten in the following form for lineari zation application in the input-output sense [07]:

$$\dot{x} = f(x) + g_1(x).V_d + g_2(x).V_q$$

(16)

Where the vectors of states X and commands U are given by:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \\ \Omega \end{bmatrix} u = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} V_d \\ V_q \end{bmatrix}$$

(17)

With:

$f(x)$: Field of vectors of order (n = 3) and g(x) is a matrix [3*2].

f , h and g are nonlinear functions [2,3].

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ x_3(x) \end{bmatrix} = \begin{bmatrix} -\dfrac{R_s}{L_d}.i_d + \dfrac{L_d}{L_q}p\Omega i_q + \dfrac{1}{L_q}.v_d \\ -\dfrac{R_s}{L_d}.i_q - \dfrac{L_d}{L_q}p\Omega i_d - \dfrac{\varphi_f}{L_q}p\Omega \\ \dfrac{p}{J}[(L_d - L_q).i_d.i_q + \varphi_f.i_q] - \dfrac{f}{J}\Omega - \dfrac{1}{J}C_r \end{bmatrix} \quad (18)$$

$$g_1(x) = \begin{bmatrix} \dfrac{1}{L_d} \\ 0 \\ 0 \end{bmatrix}; g_2(x) = \begin{bmatrix} \dfrac{1}{L_d} \\ \dfrac{1}{L_q} \\ 0 \end{bmatrix} \quad (19)$$

The controlled variables are the mechanical speed Ω and the current I_d , which are expressed as:

$$y_1 = I_d \qquad y_2 = \Omega \quad (20)$$

$$y(x) = \begin{pmatrix} y_1(x) \\ y_2(x) \end{pmatrix} = \begin{pmatrix} h_1(x) \\ h_2(x) \end{pmatrix} = \begin{pmatrix} x_1 \\ x_3 \end{pmatrix} = \begin{pmatrix} i_d \\ \Omega \end{pmatrix}$$

(21)

The linearization condition used to determine whether a nonlinear system allows for input-output linearization is the system's relative degree order [13].

4.2 Relative Degree

The relative degree of an output is the number of times that it is necessary to derive the output to reveal the input U.

a) **Relative degree of the id current:**

$$\dot{y}_1 = \dot{h}_1(x) = L_f h_1(x) + L_{g_1} h_1(x)V_d + L_{g_2} h_1(x)V_q \quad (22)$$

Where:

$$\begin{cases} L_f h_1(x) = f_1(x) \\ L_{g_1} h_1(x) = \dfrac{1}{L_d} \\ L_{g_2} h_1(x) = 0 \end{cases} \quad (23)$$

Thus:

$$\dot{y}_1 = -\frac{R_s}{L_d}I_d + \frac{L_q}{L_d}p\Omega I_q + \frac{1}{L_d}V_d$$

(24)

We note that, the input Vd appears in the equation (24), we stop here and we take the relative degree of this output $r_1 = 1$.

b) **Relative Degree of the mechanical speed Ω**

$$\begin{cases} y_2 = \Omega = h_2(x) \\ \dot{y}_2 = L_f h_2(x) + L_{g1}h_2(x)V_d + L_{g2}h_2(x)V_q = f_3(x) \end{cases} \quad (25)$$

Note that no entry appears in (25), so we are forced to derive another time:

$$\ddot{y}_2 = L_f^2 h_2(x) + L_{g1}(L_f h_2(x))V_d + L_{g2}(L_f h_2(x))V_q =$$
$$\frac{p}{J}[(L_d - L_q)i_q f_1(x)$$
$$+\frac{p}{J}(\varphi_f + (L_d - L_q).i_d).f_2(x) - \quad (26)$$
$$\frac{f}{J} f_3(x) + \frac{p}{JL_d}(L_d - L_q)I_q V_d +$$
$$\frac{p}{JL_q}((L_d - L_q)I_d + \varphi_f)V_q$$

The relative degree of equation (21) is $r_2 = 1$

c) Relative Degree of the Whole System

We can see that the degree of the system is equal to its order n (r = r1 + r2 = N = 3), indicating that the system is exactly linearizable.

4.3 Decoupling matrix D(x)

The matrix that defines the relationship between the physical input U and the output derivative Y(x) is provided by expression (27).

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = \xi(x) + D(x).u$$

(27)

Where:

$$\xi(x) = \begin{bmatrix} L_f h_1(x) \\ L_f^2 h_2(x) \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d}.i_d + \frac{L_q}{L_d} p\Omega i_q \\ \frac{p}{J}[(L_d - L_q)i_q f_1(x) + \\ \frac{p}{J}(\varphi_f + (L_d - L_q).i_d).f_2(x) - \frac{f}{J} f_3(x) \end{bmatrix} \quad (28)$$

And

$$D(x) = \begin{bmatrix} \frac{1}{L_d} & 0 \\ \frac{p}{JL_d}(L_d - L_q)i_q & \frac{p}{JL_q}((L_d - L_q)i_d + \varphi_f) \end{bmatrix} \quad (29)$$

4.4 Laws Linearizing Control of PMSM

To linearize the input-output behavior of the machine in a closed loop, we use the nonlinear state feedback described by equation (30).

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = D^{-1}(x)\left(\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} - \zeta(x)\right) \quad (30)$$

By substituting the linearizing control law (30) in the expression (27) we get:

$$\begin{bmatrix} \dot{y}_1 \\ \ddot{y}_2 \end{bmatrix} = \begin{pmatrix} \frac{d}{dt} i_d \\ \frac{d^2}{dt^2}\Omega \end{pmatrix} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

(31)

The application of the linearizing law leads to two mono-variable, linear, and decoupled subsystems:

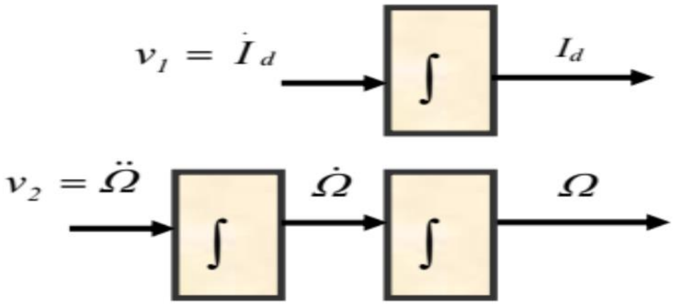


Fig. 2: linear and decoupled subsystems.

4.5 Current and Speed Control

a) Internal control profiles

To ensure perfect control of the current and speed into their references ***idref*** and ***wref***, the internal inputs ***v1*** and ***v2*** are calculated as follows

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} k_d(i_{dref} - i_d) + \dot{I}_{dref} \\ \ddot{w}_{ref} + k_{w1}(\dot{w}_{ref} - \dot{w}) + k_{w2}(w_{ref} - w) \end{bmatrix}$$

(32)

However, if the imposed trajectory is a step, the expression (32) becomes:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} k_d(i_{dref} - i_d) \\ -k_{\Omega1}\dot{\Omega} + k_{\Omega2}(\Omega_{ref} - \Omega) \end{bmatrix}$$

(33)

This leads to the dynamic:

$$\begin{cases} \frac{d}{dt}e_1 + k_d e_1 = 0 \\ \frac{d^2}{dt^2}e_2 + k_{\Omega1}\frac{d}{dt}e_2 + k_{\Omega2}e_2 = 0 \end{cases}$$

(34)

Where tracking errors e_1 and e_2 are defined by:

$$\begin{cases} e_1 = id_{ref} - id \\ e_2 = w_{ref} - w \end{cases} \quad (35)$$

The coefficients k_d , $k_{\Omega1}$ and $k_{\Omega2}$ are chosen such that $k_d + s$ and $S^2 + k_{\Omega1}S + k_{\Omega2}$ are Hurwitz polynomials (roots of the polynomial with negative real parts). These coefficients are calculated by placing poles.

b) Physical control laws

This non-linear control law involves the vector voltage U=(Vd, Vq) as follows:

$$\begin{cases} V_d = R_s.i_d - p\Omega L_q i_q + L_d k_d(I_{dref} - I_d) \\ V_q = R_s.i_q + \\ p\Omega.(L_d.i_d + \varphi_f)\frac{(L_d - L_q)L_q i_q}{(L_d - L_q)i_d + \varphi_f} k_d(I_{dref} - I_d) \\ + \frac{JL_q}{p(L_d - L_q)i_d + \varphi_f}\left[k_{\Omega2}(\Omega_{ref} - \Omega) + \dot{\Omega}(\frac{f}{J} - k_{\Omega1})\right] \end{cases} \quad (36)$$

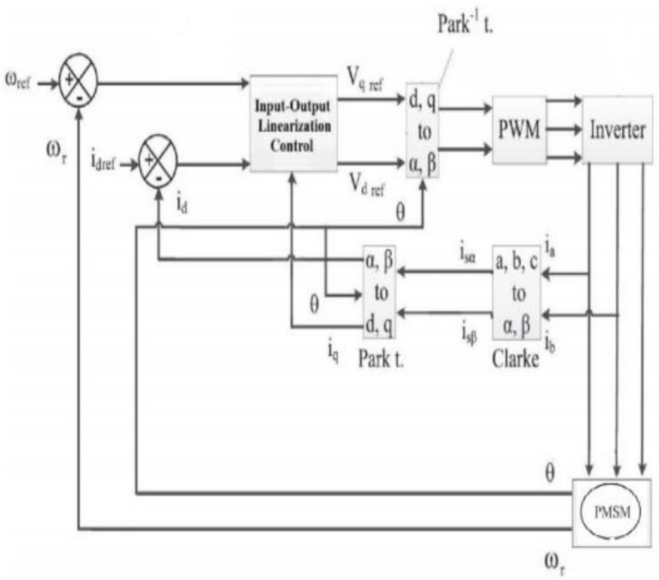
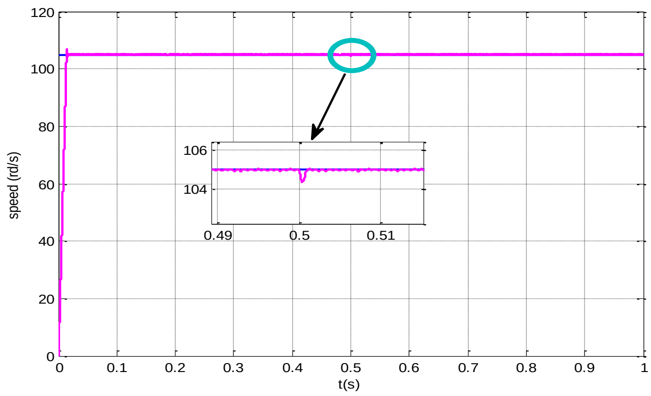


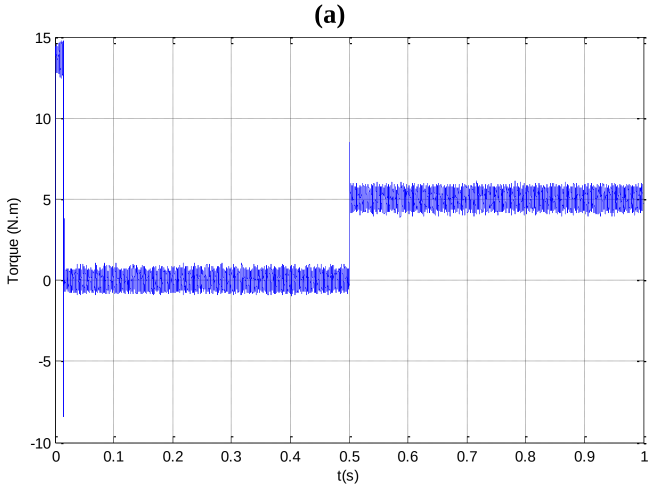
Fig. 3: PMSG feedback linearization control model.

5. Simulation Results and Discussion

In this section, we present some simulation results to show the feasibility of the nonlinear controls of the PMSM in Matlab / Simulink environment. The parameters adopted in this simulator are: P=3,f=0.0003881, φ_f =0.1564 Wb, R=1.4 Ω; Ld=6,6mH, Lq=5,8mH, J=0.00176.



(a)



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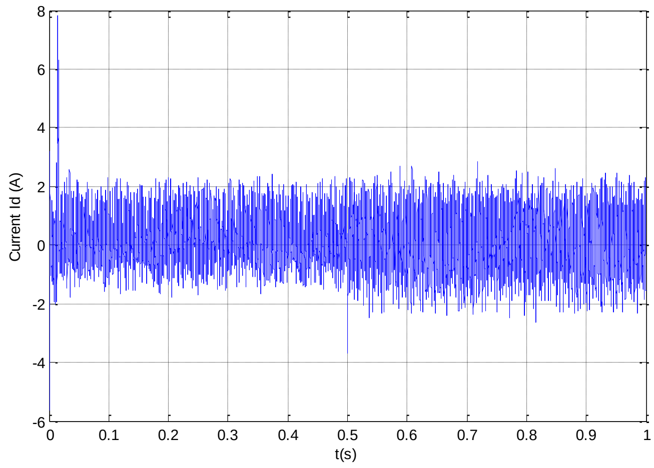

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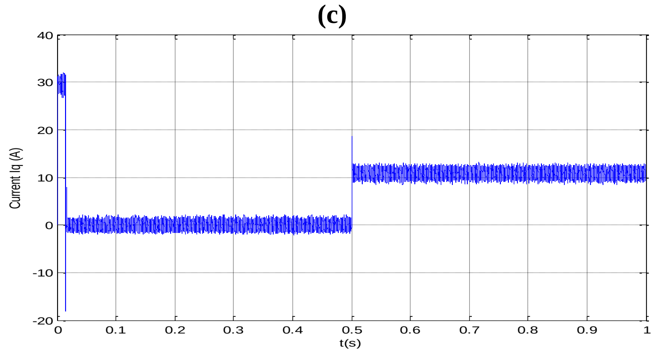
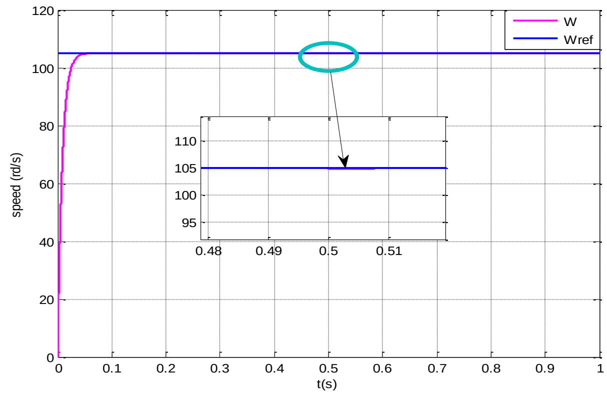
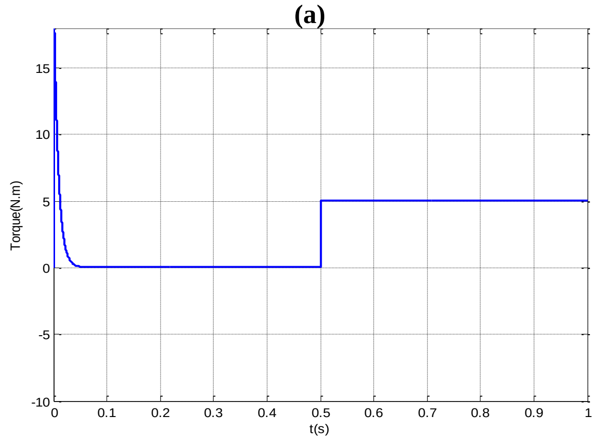


Fig.4. Simulation results with sliding mode control for PMSM during a no-load start followed by a load torque of 5 N.m at t = 0.5 s.



(a)



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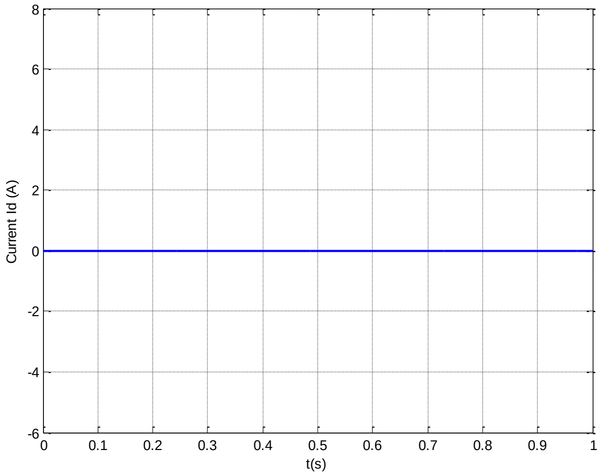

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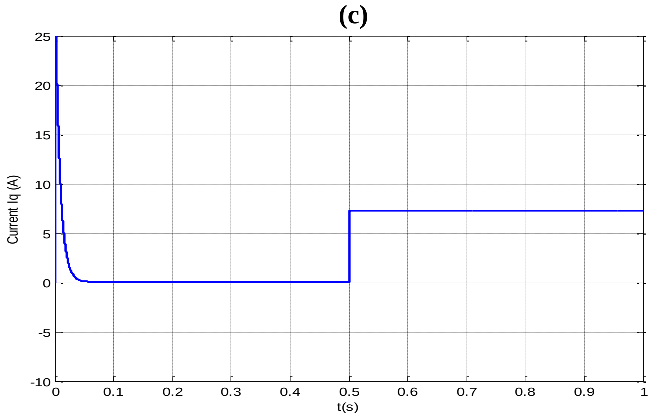

Fig .5. Simulation results with Input-Output Feedback Linearization technique for PMSM during a no-load start followed by a load torque of 5 N.m at t = 0.5 s.

The various simulations carried out allow us to observe that:

– A very low response time for both controls;
– Practically zero static error;
– A successful decoupling by maintaining $i_d = 0$;
- The speed curve has an almost linear characteristic and reaches the reference speed in a very short response time.
- The responses of the electromagnetic torque and the shape of the speed in the two control cases are compared. It is clear that the input-output linearization control reduces chattering compared to the sliding mode control.

It can be concluded that the nonlinear control based on the input-output linearization control provides a significant improvement in system performance.

6. Conclusion

The major challenge of our research work is to design a control law for the permanent magnet synchronous machine to control the speed and current of the PMSM that is more efficient in terms of trajectory tracking, disturbance rejection, stability, robustness against parametric uncertainties, all while preserving the nonlinear aspect. In this context, two types of nonlinear control have emerged as ideal solutions. A feedback linearization controller based on input-output feedback linearization and slid mode controller. The sliding mode control exhibits limited robustness due to the apparition of the chattering phenomenon. To address these limitations and achieve high-performance robust control, the input-output feedback linearization approach was applied. Simulation results are presented under identical operating conditions within the Matlab/Simulink framework. A comparative study was conducted to evaluate the performance of the two control laws in terms of trajectory tracking and disturbance rejection. We noticed that the tracking and disturbance rejection are satisfactory and a suitable selection of the input output linearization controller coefficients ensures excellent performance than the sliding mode control. The realization of these simulations with other methods will be experimentally validated using a test bench based on the dSPACE 1104 system.

7. Acknowledgement

Appear after the appendix, you MUST define in full name all your abbreviations at the first

8. References

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