

Robust speed control of five-phase permanent magnet synchronous motor using super-twisting sliding mode control

Fayçal Mehedi ^{1*}, Lazhari Nezli ¹, Mohamed Oul Hadj Mahmoudi ¹ and Rachid Taleb ²

¹ Process Control Laboratory, PCL
Ecole Nationale Polytechnique, ENP
10 Avenue Hassen Badi, B.P. 182, El Harrach, 16200, Algiers, Algeria

² Department of Electrical Engineering,
Hassiba Benbouali University of Chlef,
Hay Salem, National Roads N°19, Chlef, 02000, Algeria

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Abstract - This paper is devoted to the study of the performances of a robust speed nonlinear control of five-phase permanent magnet synchronous motor (PMSM). The dynamic response speed and overshoot is contradictory and the system is weak in terms of anti-interference in classical PI speed regulator. In this work, the controllers are designed using two methods: the first one using a nonlinear control based on sliding mode control (SMC). In the second, the super twisting algorithm sliding mode speed control (STSMC) is used to overcome the occurring chattering phenomena. This second solution shows good robustness with respect to parameter variations, measurement errors and noises. Finally, simulation results are given to demonstrate the effectiveness and the good performance of the proposed control methods.

Résumé - Cet article est consacré à l'étude des performances d'un contrôle non linéaire robuste de la machine synchrone à aimants permanents (PMSM) à cinq phases. La vitesse de réponse dynamique et le dépassement sont contradictoires et le système est faible en termes d'anti-interférences dans le régulateur de vitesse PI classique. Dans ce travail, les contrôleurs sont conçus en utilisant deux méthodes: la première utilisant un contrôle non linéaire basé sur le contrôle de mode coulissant (SMC). Dans la seconde, l'algorithme de super-twisting de contrôle de vitesse de mode coulissant (STSMC) est utilisé pour surmonter les phénomènes de chattering qui se produisent. Cette deuxième solution présente une bonne robustesse vis-à-vis des variations de paramètres, des erreurs de mesure et des bruits. Enfin, des résultats de simulation sont donnés pour démontrer l'efficacité et la bonne performance des méthodes de contrôle proposées.

Keywords: Five-phase PMSM - Sliding mode control (SMC) - Chattering phenomena - Super-twisting sliding mode control (STSMC) - Robust nonlinear control.

1. INTRODUCTION

Ever-increasing demands on advanced manufacturing applications, such as gantry robots [1], wafer scanners [2], have continued to motivate and stimulate the development of the high-speed and high precision repetitive motion control system [3]. PMSM have gained an increasing attention due to the development of permanent magnet material [4]. Their main features are: low inertia and high torque [5].

However, once the applications require very high power, problems appear as well on the inverter as on the machine. The multiphase machines offered numerous advantages. Indeed, multiphase motors reduce the current per phase without increasing the stator voltage then the semiconductor current rating can be reduced [6].

Multiphase machines have gained attention in numerous fields of applications such as Aircraft, ship propulsion, petrochemical and automobiles, where high reliability is required [7-9]. The additional number of phases guarantees that the system continues to

* faycalmehedi@yahoo.fr

operate in faulty conditions compared to the traditional three-phase machine due to the high degree of freedom [10].

Many different multiphase machine control schemes such as multiphase direct torque control (DTC) and field orientation control (FOC) have been introduced [11, 12]. Control system design is a multi-stage process including more than designing the controller itself. Before a controller is designed, a control engineer must have sufficient knowledge of the system to be controlled.

Traditional vector control structures which include proportional-integral (PI) regulator for application to an multiphase machine driven have some disadvantages such as parameter tuning complications, mediocre dynamic performances and reduced robustness. To overcome the poor robustness and static and dynamic performances of PI speed controller, the SMC approach suitable for five-phase PMSM has been presented.

The SMC theory was proposed by Utkin, 1977 [13]. Thereafter, the theoretical works and its applications of the sliding mode controller were developed. Since the robustness is the best advantage of a SMC, it has been widely employed to control the nonlinear systems that have model uncertainty and external disturbance [14]. Nevertheless, this type of control has an essential disadvantage, which is the chattering phenomenon caused by the discontinuous control action [15, 16].

In this paper, STSMC for robust speed control of five-phase PMSM is proposed. In order to enhance the system's performance; the performance of the controller is compared with PI controller and the classical SMC.

The paper is structured as follows: Modeling and the vector control strategy of the five-phase PMSM using PI controller are respectively discussed in sections 2 and 3. In section 4. Super-twisting sliding mode speed control of the five-phase PMSM is presented.

Session 5 shows the simulation results of the speed control of five-phase PMSM using PI and two different nonlinear controllers; sliding mode, super twisting sliding mode. Finally, in section 6 the main conclusions of the work are drawn.

2. MODELING FIVE-PHASE PMSM

The electric equation of a five-phase PM synchronous machine in the natural base is given by the following expression for each phase (here the k_{th} phase) [17].

$$v_s = R_s \cdot i_k + \frac{d\phi_{sk}}{dt} + e_k \quad (1)$$

The model of the five-phase PMSM is presented in a rotating $d-q$, frame as:

$$\begin{aligned} v_{ds} &= R_s \cdot i_{ds} + L_d \frac{d}{dt} i_{ds} - \omega_r \cdot L_q \cdot i_{qs} \\ v_{qs} &= R_s \cdot i_{qs} + L_q \frac{d}{dt} i_{qs} + \omega_r \cdot L_d \cdot i_{ds} + \sqrt{5/2} \omega_r \cdot \phi_f \end{aligned} \quad (2)$$

The electromagnetic torque developed by the machine is equal to:

$$T_e = p \left((L_d - L_q) i_{ds} \cdot i_{sq} + \sqrt{5/2} \phi_f i_{qs} \right) \quad (3)$$

On the other hand, the mechanical equation of the machine is:

(4)

This set of equations allows characterizing the electromechanical behaviour of a five-phase PMSM machine.

3. VECTOR CONTROL OF FIVE-PHASE PMSM MOTOR DRIVE

Vector control technique aims to make equivalence between the five-phase PMSM and DC motor. This objective can be achieved by controlling the d-axis current component to zero, so the torque depends only on the amplitude of q-axis current [12]. Therefore, the reference currents can be calculated using the following equation:

(5)

In figure 1, the speed controller output T_e^* determines the reference quadrature current i_q^* of the machine. In order to keep the current control performance, a decoupling control is needed. Indeed, d-q components of the reference voltage vectors are calculated by:

(6)

Where v'_{ds} and v'_{qs} are the d-q current controllers outputs.

A system illustration of the vector control of five-phase motor is given in figure 1.

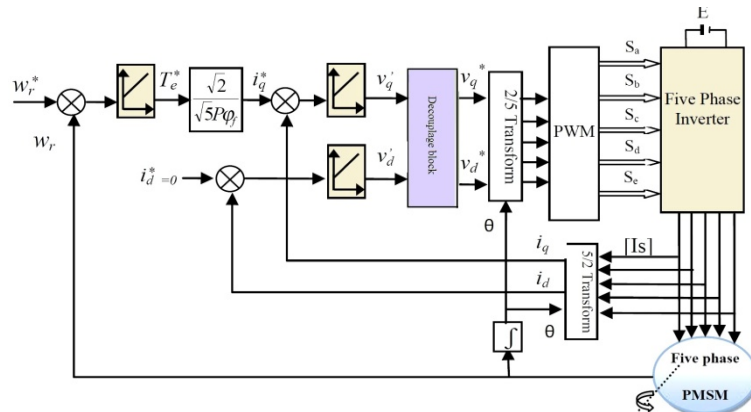


Fig. 1: Vector control for a five-phase PMSM

4. SUPER TWISTING SLIDING MODE SPEED CONTROL OF THE FIVE-PHASE PMSM

The first order SMC is an effective nonlinear robust control. However, a few problems arise in some practical applications, such as chattering effect and undesirable mechanical stresses.

The second order sliding mode algorithm synthesizes a discontinuous control which makes the surface and its derivative null with continuous control, therefore reducing chattering and avoiding strong mechanical efforts while preserving SMC advantages [18]. The block diagram of the super twisting sliding mode speed control applied to the Five-Phase PMSM is illustrated in figure 2. Let us consider the following surfaces:

$$S(\omega_r) = \omega_r^* - \omega_r \quad (7)$$

Based on the proposed switching surface, the current and speed control laws are:

$$i_q^* = \frac{J_m \cdot \dot{\omega}_r^* + p T_r + f_m \cdot \omega_r}{p \cdot ((L_d - L_q) i_{ds} + \sqrt{5/2} \phi_f)} + K_1 \cdot \text{sign}(S(\omega_r)) \quad (8)$$

Where K_1 is positive constant.

The second-order sliding mode control proposed based on the super twisting algorithm known which is introduced by Levant [19].

In order to reduce the chattering, a STSMC for five-phase PMSM is used. Considering the sliding mode surface given by (7), the following expression can be written:

$$\begin{cases} \dot{S}(\omega_r) = \dot{\omega}_r^* - \frac{p}{J_m} \cdot ((L_d - L_q) i_{ds} + \sqrt{5/2} \phi_f) i_{qs} + \frac{p}{J_m} T_r + \frac{f_m}{J_m} \omega_r \\ \ddot{S}(\omega_r) = Y(t, x) + \Lambda(t, x) \cdot i_{qs} \end{cases} \quad (9)$$

Where $Y(t, x)$ and $\Lambda(t, x)$ are uncertain functions which satisfy:

$$Y > 0, |Y| > \lambda, 0 < K_m < \Lambda < K_M \quad (10)$$

Basing on the super twisting algorithm introduced by Levant in [19], the proposed high order sliding mode controller contains two parts [20]:

$$i_{qs} = z_1 + z_2 \quad (11)$$

avec

$$\begin{cases} \dot{z}_1 = -K \cdot \text{sign}(S(\omega_r)) \\ \dot{z}_2 = -l |S(\omega_r)|^\gamma \cdot \text{sign}(S(\omega_r)) \end{cases} \quad (12)$$

In order to ensure the convergence of the sliding manifolds to zero in finite time, the gains can be chosen as follows [20].

$$\begin{cases} k > \lambda / k_m \\ l^2 \geq \frac{4\lambda}{k_m^2} \frac{k_M (k + \lambda)}{k_m (k - \lambda)} \\ 0 < \gamma \leq 0.5 \end{cases} \quad (13)$$

The bloc diagram of the super-twisting sliding mode speed control of the five-phase PMSM is given by fig. 2.

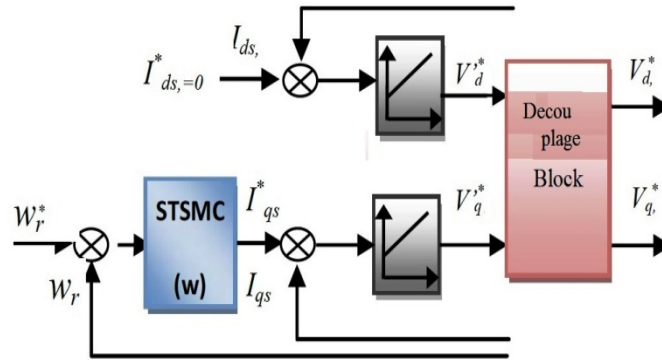


Fig. 2: Block diagram of the super-twisting sliding mode speed control

5. SIMULATION RESULTS AND DISCUSSIONS

In this section, simulations are realized with a five-phase PMSM. Parameters of the machine are given next in appendix. In the aim to evaluate the performances of the three controllers PI, SMC and STSMC, three categories of tests have been realized: pursuit test, sensitivity to the speed variation and robustness against machine parameter variations.

5.1 Pursuit test

The objective of this test is the study of the three controllers' behavior in reference tracking, while the load torque is considered equal to zero and a step change of the reference speed from 200 rad/s to -200 rad/s at $t = 0.9$ s .

The simulation results are shown in figure 3. As it's shown by this figure, for the three controllers, the mechanical speed tracks almost perfectly their reference but with an important response time for the PI controller compared to the other controllers. Therefore it can be considered that the two types of sliding mode controllers have a very good performance for this test.

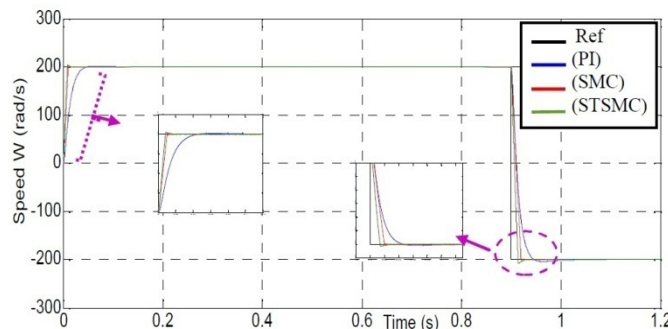


Fig. 3: Comparison of speed responses of PI, SMC and STSMC for five-phase PMSM (tracking test)

5.2 Sensitivity to the load torque variation

The goal of this test is to analyze the influence of the load torque variation on five-phase PMSM for the three controllers. For this objective and in the time

$t = [0.3 \text{ s} - 0.6 \text{ s}]$, the load torque is kept equal to its value $T_r = 0.5 \text{ N.m}$. The simulation results are presented in figure 4.

This figure express that the effect produced by the load torque variation is very clear on the speed curve of the system with PI controller, while the effects are almost negligible for the system with the two other controllers. It can be noticed that these last have a nearly perfect speed disturbance rejection (less than 1%).

The electromagnetic torque, it's clear that the STSMC reduces the existing fuzziness in the case of SMC (attenuation of the chattering phenomenon). The current I_q is the image of the torque. The response of the component current I_d shows decoupling introduced by vector control of the five-phase motor.

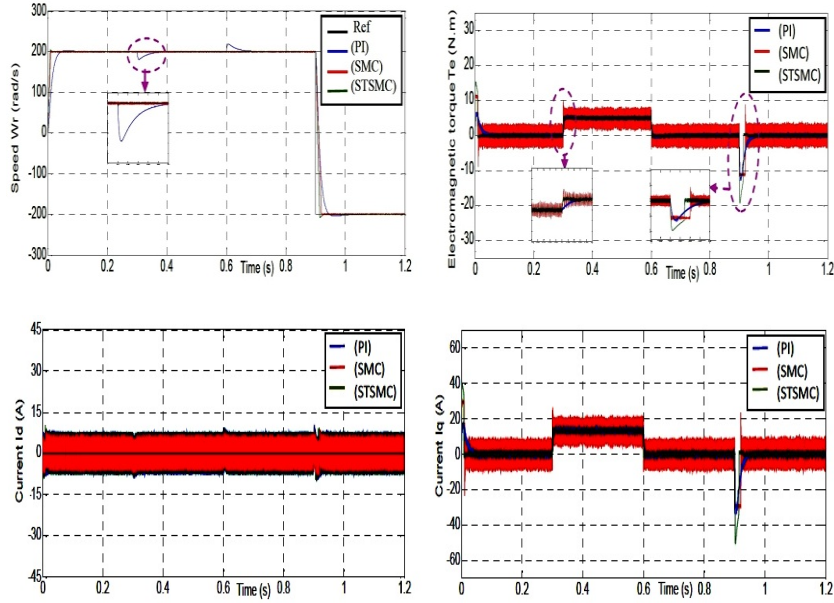


Fig. 4: Sensitivity to the load torque variation for five-phase PMSM

5.3 Test of the robustness

The aim of these tests is to analyze the influence of the five-phase PMSM parameters variation on the controllers' performance. The machine is running at its nominal speed. To test the robustness of the controllers used, parameters of the machine has been modified: the values of the stator resistance R_s and the inertia variation J_m are doubled and the values of the inductances L_d and L_q are reduced by 20 % of the nominal value.

The gotten results are represented in figure 5. These results show that the parameter variations of the five-phase PMSM presents a clear effect on the speed curves (especially in their errors curves) and that the effect proves more significant for PI controller than that with the SMC and STSMC. This result enables us to conclude that these last controllers are more robust.

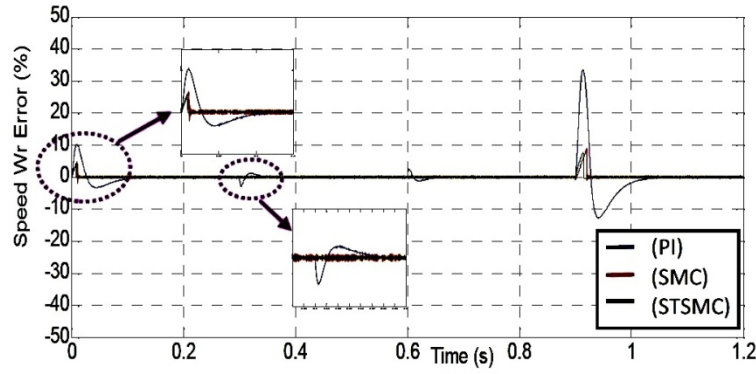


Fig. 5: Sensitivity to the machine parameter variations on the five-phase PMSM

6. CONCLUSION

In this paper, a nonlinear control based on super-twisting sliding mode control was applied for robust speed control of five-phase PMSM. The vector control strategy of the five-phase PMSM and the theoretical study of this nonlinear control SMC have been discussed and control stability verified via Lyapunov stability analysis.

A super-twisting sliding mode control was used for two main reasons: in order to reduce the chattering effect and assure the robustness of the system so that it gives a better response and good result in all conditions. The obtained results by Matlab/Simulink show that the STSMC are very interesting compared to the conventional PI controllers and the classical SMC especially in eliminating of the chattering phenomenon.

APPENDIX A

A.1 List of symbols

Table 1: List of symbole

Symbole	Significance
$v_{ds}, v_{qs}, i_{ds}, i_{ds}$	d and q axis stator voltages and currents
R_s	Stator resistances
L_d	d axis stator induction
L_q	q axis stators inductance
ϕ_f	Main magnetic flux of the permanent magnet
p	Number of pole pairs
J_m	Inertia moment
f_m	Viscous damping
ω_r	Rotational speed (rd/s)
T_r	Load torque
T_e	Electromagnetic torque

A.2 Machine parameters

Table 2: Parameters of five-phase PMSM

Parameters	Rated value
Stator resistance R_s	3.6 Ω
Stator inductance L_d	0.0021 H
Stator inductance L_q	0.0021 H
Stator frequency f	50 Hz
Number of pairs poles p	02
Inertia moment J_m	0.0011 kg/m ²
Viscous damping f_m	0
Magnetic flux ϕ_f	0.12 Web

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