Permanent Magnet Synchronous Motor PMSM Control by Combining Vector and PI Controller

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Abstract: - In this paper, we present the vector control of a permanent magnet synchronous machine (PMSM) by a PI regulator whose tracking performance; speed, stability, and precision are satisfactory. However, we can see the influence of the variation in the resistance and load torque on the behavior of the controlled system. we analyze the simulation results found and then we make an inventory of PI disadvantages. This work is modified with a novelty by introducing a new control law namely sliding mode and backstepping control law. Then we analyze the results found making a comparison to those of the PI regulator.

Key-words: - Permanent magnet synchronous motor (PMSM), PI controller, Vector control.

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1 Introduction

Permanent magnet synchronous motors are widely used in electromechanical actuators. This type of motor is omnipresent in industrial applications, compared to asynchronous and self-commutated reluctant synchronous machines, due to its robustness, high-power density, simplicity of control, and compactness [1].
The constant rise of new needs has significantly extended the fields of application and innovation of variable-speed electric machines [2]. This innovation concerns power electronics devices, electromechanical energy conversion processes, associated control systems, and information processing methods. Recently, research studies have been conducted to reduce the complexities of electronic control and to facilitate the integration of variable speed drive in AC machines. Researchers have developed new semiconductor-based components to ensure a stable and efficient power supply [3].
Because of the flexibility and simplicity of the proportional-integral (PI) controllers [2], they are considered to be the most useful tuning method in the implementation of d-q axis currents and speed control loops [4].
several algorithms have been proposed to optimize the parameters of the PI regulator. Ziegler Nickols proposes an algorithm to determine the parameters of the PID regulator to optimize the performance of this regulator [5]. Another approach proposed is based on a relay feedback test [6]. In [7] Ziegler Nickols's formula for PI autotuning will have to be modified to be completely revised [8]. Due to the parameter's sensitivity which is a major inconvenience for AC machines a fractional-order PI/PID control was introduced to reduce their effect on PMSM control [9].
Because of the no-linear system of PMSM and rapid development in motor control techniques, several non-linear control approaches have emerged such as predictive control, adaptive control, artificial intelligence incorporated control and sliding mode control, and backstepping control [10].

2 Mathematical model of the PMSM

To explain the application of variable speed control, the modeling of the synchronous permanent magnet

machine is based on the established mechanical and electrical parameters, that described electromechanical and electromagnetic phenomena and on the following simplifying assumptions:
-The saturation of the iron in the stator of the motor is ignored
-The effects of the eddy current and hysteresis are ignored
-The three-phase windings of the stator are symmetrical.
The Permanent Magnet Synchronous Motor model can be described in the form of the following nonlinear mathematical equations in the d-q reference frame.

$$\begin{cases} \frac{d_{id}}{dt} = -\frac{R_s}{L_d} i_d + p\frac{L_q}{L_d}\Omega i_q + \frac{v_d}{L_d} \\ \frac{d_{iq}}{dt} = -\frac{R_s}{L_q} i_q - p\frac{L_d}{L_q}\Omega i_d - p\frac{\Omega\varphi_f}{L_q} + \frac{v_q}{L_q} \\ \frac{d\Omega}{dt} = \frac{p}{J}\left(L_d - L_q\right) i_d i_q - \frac{f}{J}\Omega + \frac{P}{J}\varphi_f i_q - \frac{C_r}{J} \end{cases} \quad (1)$$

Where :R_s : Stator resistance (Ω); L_d,L_q: d, q axis self-inductance (H); φ_f : Mutual flux due to permanent magnetic (Wb); i_d,i_q: d, q axis currents (A); Ω : Angle speed (rad/s); θ : Rotor position; J : Moment of inertia (kg.m^2); f : damping constant (N/rad/s); p : Number of pole pairs; C_r: load torque (N.m).

3 Field oriented control of Permanent Magnet Synchronous Motor (PMSM)

Usually, the stator axis component acts as the excitation and adjusts the value of the flux in the machine. The q axis component acts as the armature current and controls the torque. The application of vector control requires the axis of the component I_q to be in quadrature relative to the rotor flux (figure 1)

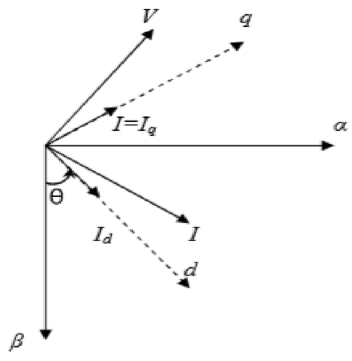

Fig. 1: Phase diagram of the PMSM in the frame of reference linked to the rotating field

For a surface-mounted PMSM, L_d=L_q is fulfilled. When i_d is set to 0 in field-oriented control, also when the system works at optimal linear torque, the direct current must be i_d=0, so:

$$i_d=0 \;\; ; \;\; i_q=i_s \quad (2)$$
$$\varphi_d = \varphi_f \quad (3)$$

The electromagnetic torque formula, since the flux is constant:

$$C_e = \frac{3}{2}\varphi_f i_q = K_f i_q \quad (4)$$

3.1 Field Weakening

In the case of over-speed operation, a defluxing strategy is applied, the current setpoint I_d is no longer equal to zero and the torque is limited to always respect the following relationship:

$$\sqrt{{I_d}^2 + {I_q}^2} \le I_{max} \quad (5)$$

On the first hand, the defluxing block allows optimal use of the machine's magnetic capacities, and also allows constant torque operation if the speed is lower than the rated speed. On the other hand, it is possible to weaken, from this block, the flux inversely proportional to the speed, for the constant power operation when the speed exceeds the rated speed. It is defined by the following nonlinear function:
-under-speed:
$\Phi_r = \Phi_{mom}$ for $|\Omega_r| \le \Omega_{mom}$
-over-speed:
$\Phi_r = \frac{\Omega_{mom}}{|\Omega_r|}.\Phi_{mom}$ for $|\Omega_r| \ge \Omega_{mom}$
And:
Ω_{mom}: Nominal rotational speed.
Φ_{mom}: Nominal rotor flux.

By appealing to equation (1), we have the following equations showing the command variables.

$$\begin{cases} R_s I_d + L_d\frac{di_d}{dt} = V_d - \omega L_q I_q \\ R_s I_q + L_q\frac{di_q}{dt} = V_q + \omega L_d I_d + \omega\varphi_f \end{cases} \quad (6)$$

3.2 Decoupling by Compensation

Definitions of two new control variables V_{sq1} and V_{sq1} such as:

$$V_{sd} = V_{sd1} + e_d \quad (7)$$

And:

$$V_{sq} = V_{sq1} + e_q \quad (8)$$

With:

$$\begin{cases} e_d = -(\omega L_d I_d + \omega \varphi_f) \\ e_q = \omega L_q I_q \\ V_d = V_{d1} + e_q \\ V_q = V_{q1} - e_d \end{cases} \quad (9)$$

4 Application of PI controller

The control law of PI is:

$$u(t) = K_p e(t) + K_i \int e(t) \quad (10)$$

4.1 Flux regulation

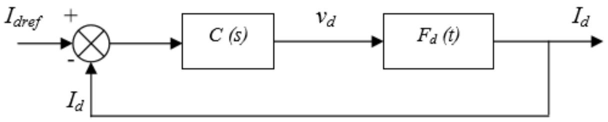

Fig. 2: Flux regulator loop

The open loop transfer function is written:

$$F_d(s) = \frac{i_{sd}}{V_{sd1}} = \frac{\frac{1}{R_s}}{1+T_{ds}.s} \text{ with } T_{ds} = \frac{L_{ds}}{R_s} \quad (11)$$

$$C(s) = \frac{K_{id}}{s}(1 + \frac{K_{pd}}{k_{id}} s) \quad (12)$$

$$OLTF(s) = \frac{K_{id}}{s}(1 + \frac{K_{pd}}{k_{id}} s) \frac{\frac{1}{R_s}}{1+T_{ds}.s} \quad (13)$$

compensate for the pole through $(s + \frac{K_{pd}}{k_{id}})$ which $(1 + T_{ds}.s)$ results in the condition

$$\frac{K_{pd}}{k_{id}} = T_{ds} \quad (14)$$

The closed-loop transfer function is given by:

$$CLTF(s) = \frac{Fi_{sd}}{1+Fi_{sd}} = \frac{1}{1+\tau_d} \quad (15)$$

We obtain a response of the 1st order type of time constant $\tau_\text{d} = \frac{R_s}{K_{id}}$

By choosing $\tau_\text{d} = T_\text{ds}$

Therefore:

$$k_{id} = \frac{{R_s}^2}{L_d}; k_{pd} = k_{id}.T_{ds} \quad (16)$$

4.2 Torque Regulation

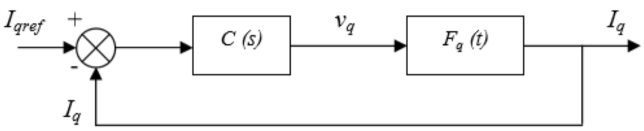

Fig. 3: Torque regulator loop

Knowing that this regulator has the same form as the previous one, we find:

$$k_{iq} = \frac{{R_s}^2}{L_q}; k_{pq} = k_{iq}.T_{qs} \quad (17)$$

4.3 Speed control

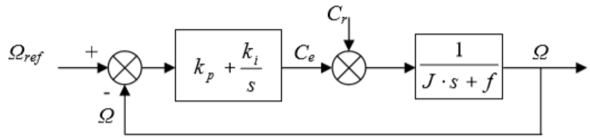

Fig. 4: Speed regulator loop

The open loop transfer function is written as follows:

$$OLTF_\Omega = \frac{K_p}{s}(s + \frac{K_i}{K_p}) \frac{1}{f+Js} \quad (18)$$

The closed loop transfer function is given as:

$$CLTF_\Omega = \frac{K_p(s+\frac{K_i}{K_p})}{Js^2+(K_p+f)s+K_i} = \frac{\Omega(s)}{\Omega_{ref}(s)} \quad (19)$$

The CLTF has a 2nd dynamic order, by identification with the canonical form of the 2nd order. The characteristic equation can be represented by:

$$\frac{1}{\frac{1}{{\omega_0}^2}s^2 + \frac{2\xi}{\omega_0} + 1} \quad (20)$$

so $\frac{\text{J}}{\text{K}_\text{i}} = \frac{1}{{\omega_0}^2}$

$$\frac{2\xi}{\omega_0} = \frac{K_p+f}{K_i} \quad (21)$$

ξ: damping coefficient.

Therefore, we choose the damping coefficient ξ and ω_0 we deduce $K_i$and K_p with:

$$K_i = J{\omega_0}^2; K_p = 2J\omega_0 - f \quad (22)$$

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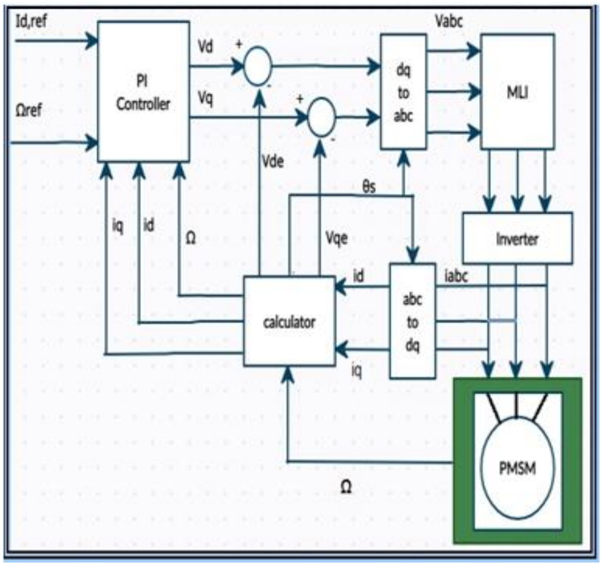
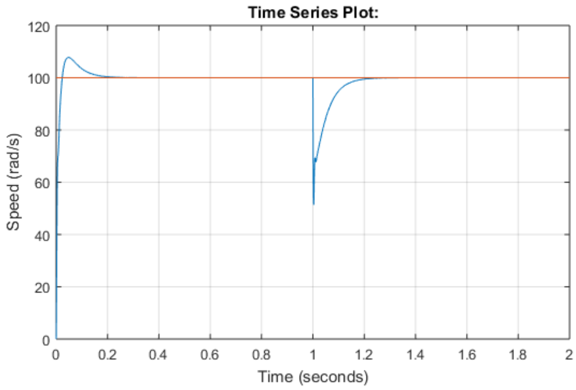


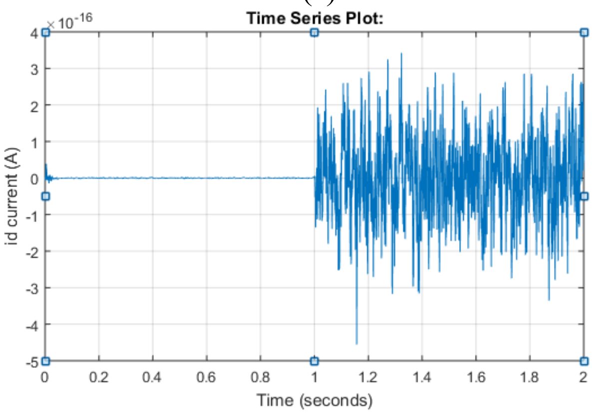
Fig. 5: Vector control scheme

5 Results and Discussion

The simulation results are given in figures 6, 7 and 8.



(a)



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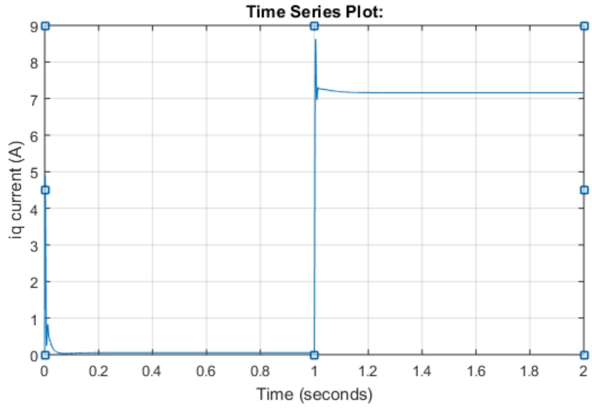

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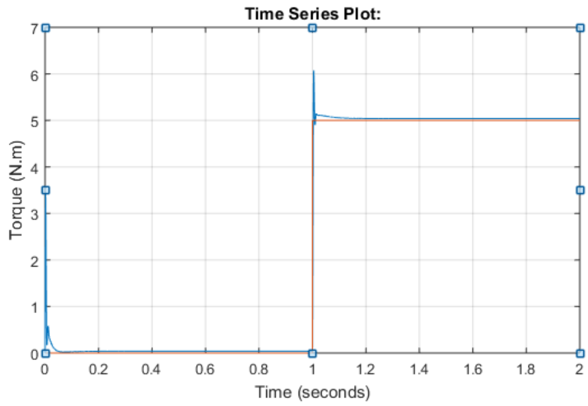
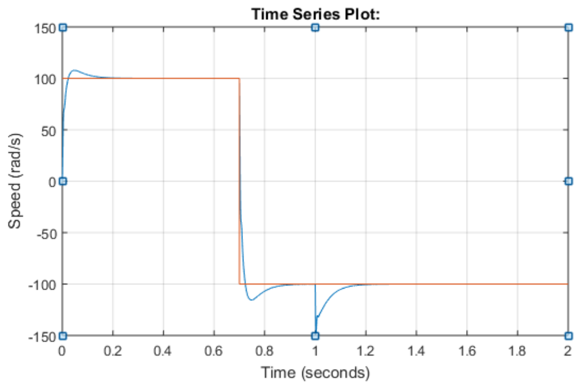


(d)

Fig. 6: Starting with no-load and with load at t=1s



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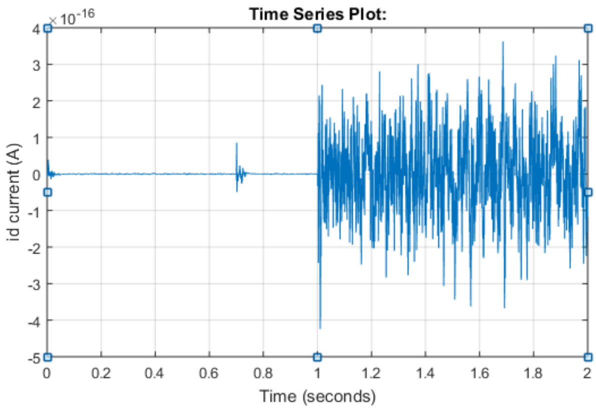

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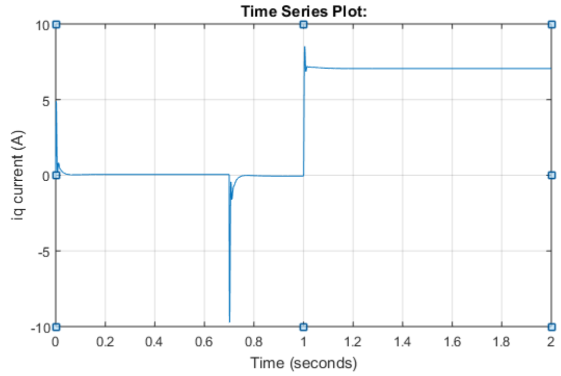

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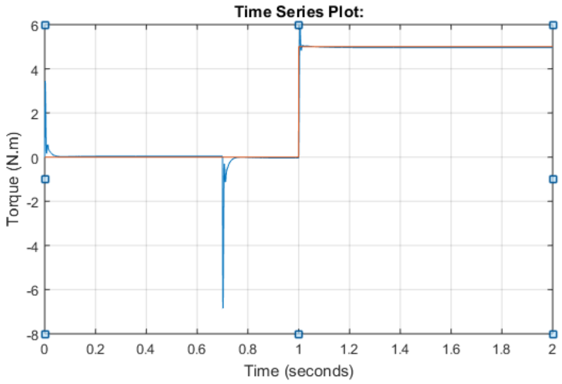
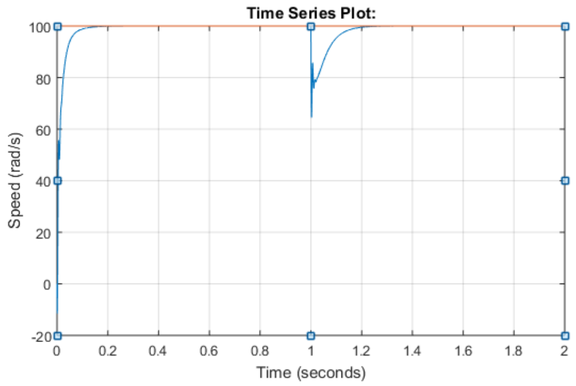


(d)

Fig. 7: inversion of the direction of rotation at 0.7s and with load at 1s



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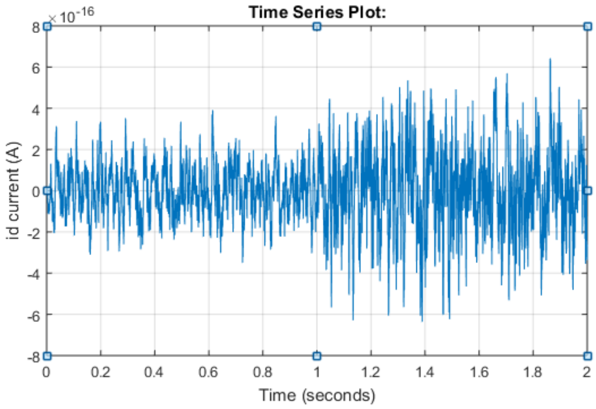

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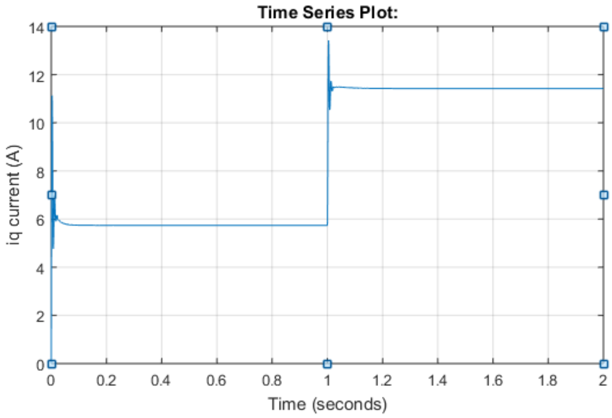

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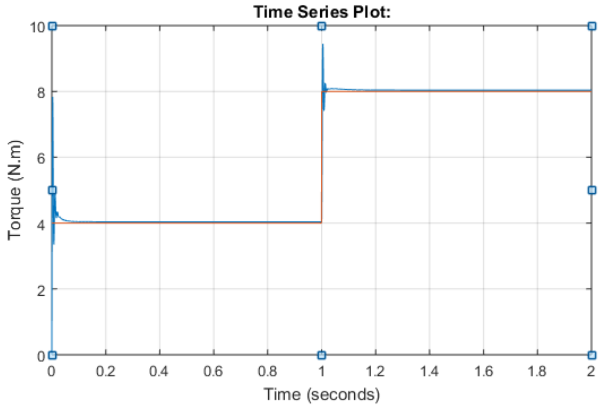

(d)

Fig. 8: variation of the machine setting (at t=1s; $C'_r = C_r$)

Practically, it is necessary to use a sensor of position which complicates the structure of the machine and increases the cost.

The result found in figure 1 (a) shows that the vector control using PI regulator requires a low pass filter in order to get a low over-shoot of speed. As we have already mentioned, the structure gets complicated, and the cost increases.

For the i_q current it takes a very high value when the load is applied (figure 6. b, 7. b), before being stabilized.

After the application of the load, the speed decreases then tracks the desired speed with an important exceeding, and with a response time that might be high as shown in figure 6. a, 7. a

The torque compensates for the load with a high exceeding. During the inversion of speed (figure 7.d), the speed takes the value of the desired speed with a high response time.

The electromechanical torque and i_q current faces a high drop when the speed is inverted as shown in figure 7. b, and takes important time before getting its stabilized value.

According to the figures 8. c and 8.d the variation of the machine setting has a big effect on the i_q and id currents, and also on the torque. Therefore, this technique of control is very sensitive to the variation of the machine settings.
During the inversion of the rotation speed (figure 8. a), the robustness of the PI regulator is not perfect.

6 Conclusions

The permanent magnet synchronous motor PMSM is an electric actuator of great industrial interest, due to its compactness, low inertia, efficiency, robustness, and high-power density, but its non-linear structure makes its control more complex, which led us to use the non-linear control model that can provide good performance. The application of the PI regulator of PMSM is widely used in the industry because of its simplicity. However, this type of regulator has several disadvantages which push researchers to develop new non-linear control laws.

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