Speed and Current Control for the PMSM Using a Luenberger Observer

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Abstract—In this article, we present the mathematical model of the permanent magnet synchronous motor (PMSM) permitting the simulation of its dynamic behavior under the MATLAB/SIMULINK environment. This model is based on the Park transformation. This paper proposes a realization of robust speed and current control for the PMSM using a PI-Regulator with and without a Luenberger observer. The simulation results show the very good decoupling between the torque and the stator currents. Thus the presence of the observer improves dramatically the performance of the PMSM in particular the response time and overshoot of the torque.

Keywords: *Permanent Magnet Synchronous Motor (PMSM), Proportional Integral Control (PI-C), Variable Structure System (VSS), Luenberger Observer.*

I. INTRODUCTION

The Permanent Magnet Synchronous Motor (PMSM) have attracted increasing interest in recent years for industrial drive application. The high efficiency, high steady state torque density and simple controller of the PM motor drives compared with the induction motor drives make them a good alternative in certain applications[1][10][11].

The Technique of the vectorial control allows comparing the PMSM to the DC machine with separate excitation from the point of the view torque. The flux vector must be concentrated on the d axis with the i_{sd} current null [5]. However the exact knowledge of the rotor flux position gives up a precision problem. Thus, it is possible to control independently the speed and the forward current i_{sd}. The traditional algorithm of control (PI or PID) proves to be insufficient where the requirements in performances are very severe. Various nonlinear analysis tools have been used by many authors to investigate the speed control of PMSM such as sliding-mode control technique [5][9][13], adaptive backstepping method [11][7], Input-Output linearization Control by Poles placement[10].

In the objective to improve the dynamic performances of the speed-regulation for the PMSM, we considered interesting to appeal to an observer of state to reconstruct the states variables and to estimate the disturbance load from the variables of command i_{sq} and the variable to be controlled Ω .The observer used to estimate the load torque and rotor speed is an observer of lunbuerger.

II. MODELING OF THE MSAP

The electrical and mechanical equations of the MSAP in the plane d-q can be written as follows [1]:

$$\begin{aligned} u_{sd} &= R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega\varphi_{sq} \\ u_{sq} &= R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega\varphi_{sd} \end{aligned} \tag{1}$$

With the field's equations as:

$$\begin{aligned} \varphi_{sd} &= L_d i_{sd} + \varphi_f \\ \varphi_{sq} &= L_q i_{sq} \end{aligned} \tag{2}$$

We replace equation (2) into (1), the latter becomes:

$$\begin{aligned} u_{sd} &= R_s i_{sd} + L_d \frac{di_{sd}}{dt} - \omega L_q i_{sq} \\ u_{sq} &= R_s i_{sq} + L_q \frac{di_{sq}}{dt} + \omega L_d i_{sd} + \omega\varphi_f \end{aligned} \tag{3}$$

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The electromagnetic Torque it is given by:

$$C_e = \frac{3}{2} p.\left[(L_d - L_q).i_{sd} i_{sq} + \varphi_f i_{sq} \right] \qquad (4)$$

And the Mechanical Equation:

$$J\frac{d\Omega}{dt} + f.\Omega = C_e - C_r \qquad (5)$$

Where:

R_s : Stator resistance

L_d, L_q : Stator d and q axis inductance

f : Viscous friction coefficient

J : Rotor moment of inertia

p : Number of pairs pole

ϕ_f : Permanent magnet flux

Ω : Motor speed

$\omega = p.\Omega$: Inverter frequency

i_{sd}, i_{sq} : d-q axis currents

u_{sd}, u_{sq} : d-q axis voltages

C_e : Electromagnetic Torque

C_r : Load Torque

III. FLUX ORIIENTED CONTROL OF PMSM

Analyze the system in equation (3) governing the PMSM, we can observe that the model is nonlinear and coupled. So, the electromagnetic torque (4) depends on the direct current i_{sd} and the quadratic current i_{sq}.

if we compensate the coupling terms between the axes d and q, the voltage u_{sd} can control the current i_{sd} and voltage u_{sq} can control the current i_{sq} and thus torque. This strategy amounts to keep the stator current in quadrate with the rotor flux which reduces the stator current to the single component i_{sq}. To get it requires the variable θ to have a value such that i_{sd} will always be zero. this choice yields an expression of the electromagnetic torque depending only of the current i_{sq} also note that the cancellation of the current i_{sd} causes a reduction of the stator current which allows the machine to operate in the non-saturation

A. *Decoupling and compensation*

To uncouple perfectly the axes d and q, we add on the output of the controllers the e.m.f $(E_d - E_q)$ of compensation. If the compensation is exact, the compensations of the stator current depend only on their reference.

$$\begin{aligned} u^*_{sd} &= u_{sd} + E_d \\ u^*_{sq} &= u_{sq} + E_q \end{aligned} \qquad (6)$$

With:

$$\begin{aligned} u_{sd} &= R_s i_{sd} - L_d \frac{di_{sd}}{dt} \\ u_{sq} &= R_s i_{sq} - L_q \frac{di_{sq}}{dt} \\ E_d &= -p\Omega L_q .i_{sq} \\ E_q &= p\Omega L_d i_{sd} + p\Omega \phi_f \end{aligned} \qquad (7)$$

B. *Functional diagram:*

For an ideal VSI, $u^*_{sd} = u_{sd}$. In the ideal tuned case, i.e., the estmated parameters are equal to the PMSM paraeters, a decoupling between d,q axis is obtained from (3) and (6). The current transfer functions are equivalent to tho first-order lag elements (7) with time constants $\tau_d (= \frac{L_d}{R})$ and $\tau_q (= \frac{L_q}{R})$ respectely. In the case $i_{sd} = 0$, the equation (4) becomes:

$$C_e = \frac{3p}{2} \phi_f .i_{sq} \qquad (8)$$

It's the desired torque control.

Three PI loops are used to control three interactive variables independently. The rotor speed, direct current and quadrate current are each controlled by a separate PI module.

The PI regulator choice contributes to find the decoupling quality between the two axes d and q. The quadrate current reference i^*_{sq} is provided by a speed PI regulator; the reference limitation prevents the torque to exceed the fixed maximal value. At closed loop the system characteristics equation is identified to desire one and it results the differences regulators with their specific transfer function $k_x (1 + \frac{1}{\tau_{ix} s})$ (9)

($x = d, q \quad or \quad \Omega$) as shown in figure 1, 2 and 3:

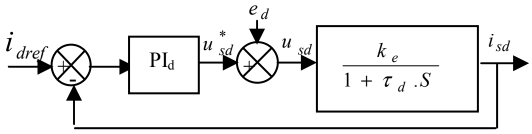

Figure 1. isd current loop using a PI controller

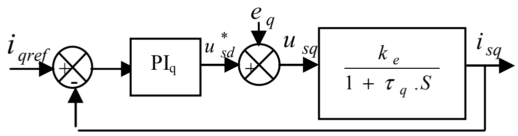

Figure 2. isq current loop using a PI controller

NB: in steady state, it's assumed that the i_{sq} current loop is fast enough compared to the speed loop to be considered equivalent to a gain A (A≈1) .

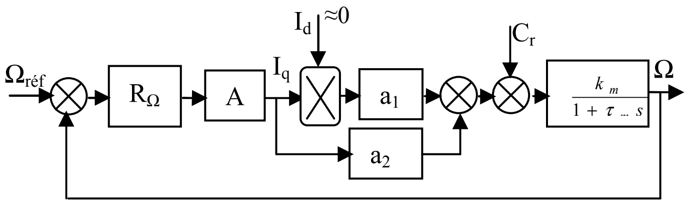

Fig ure 3. The cascade control relating to q axis

With $a_1 = \frac{3p}{2}(L_d - L_q)$, $a_2 = \frac{3p}{2}.\phi_f$

R$_\Omega$ is a PI regulator with anti-windup.

1) Current control

Determining the parameters of the current correction is done by offsetting the poles of the system. Or $\tau_{id} = \tau_d$, $\tau_{iq} = \tau_q$, $k_d = \frac{\gamma_d}{k_e}$ and $k_q = \frac{\gamma_q}{k_e}$ where γ_d and γ_q characterize the acceleration of current loops (respectively d and q axis) and correspond to the ratio between the actual dynamics and the dynamics desired.

2) Speed control

The speed is controlled using a PI controller with anti-windup. The technique of imposing closed loop poles has been used here to determine the parameters of this controller.
If the condition $i_{sd} = 0$ is satisfied and if we impose $C_r = 0$, the transfer function of open loop system without correction of figure 3 can be written as follows:

$$H(s) = \frac{3p\phi_f / 2}{f_c(1+\tau_m s)} = \frac{k_m}{1+\tau_m.s} \tag{10}$$

Or the closed loop transfer function with correction can be written as follows:

$$T(s) = \frac{1+\tau_{i\Omega}s}{1+\tau_{i\Omega}\frac{1+k_\Omega k_m}{k_\Omega k_m}s + \frac{\tau_{i\Omega}\tau_m}{k_\Omega k_m}s^2} \tag{11}$$

Equation (10) is the characteristic equation of a second order system whose standard form is:

$$1+\frac{2\xi}{\omega_n}s+\frac{1}{\omega_n^2}s^2 \tag{12}$$

Where ξ is damping coefficient and ω_n is cut-off pulse to have a good dynamic with an acceptable overshoot and a fast response time we have imposed two conjugate poles:

$$p_1 = \omega_n(-\xi + j\sqrt{1-\xi^2}) \text{ , } p_2 = \omega_n(-\xi - j\sqrt{1-\xi^2}) \tag{13}$$

The overall scheme of simulation is shown in figure below:

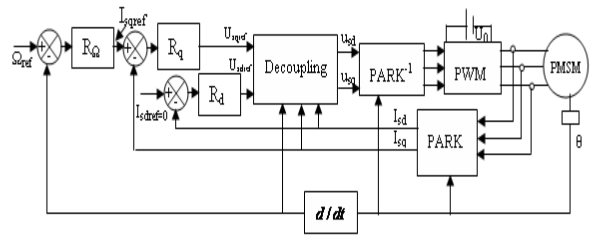

Fig ure 4. Classical control of the PMSM without observer

IV. Luenberger Observer

A. Principle

Using the mathematical model of the motor given in equations (1), the control law of PMSM has been achieved using the system model and a Luenberger observer. In this work, a separation of time scales is used to give a linear model of the PMSM. With this approach, the fast electrical dynamics are represented by:

$$\begin{aligned} \dot{x} &= A.x + B.u \\ y &= C.x \end{aligned} \tag{14}$$

Where the state, input and output vectors are given by:

$$\begin{aligned} x &= [\theta \quad \omega \quad C_r]^T \\ u &= i_{sq} \\ y &= \theta \end{aligned} \tag{15}$$

The state space matrices are given by:

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & \frac{-f}{J} & \frac{-1}{J} \\ 0 & 0 & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} 0 & \frac{3p}{2J}\Phi_f & 0 \end{bmatrix}^T,$$

$$C = [1 \quad 0 \quad 0]$$

The basic structure of such an observer can be written as follows (Figure 5):

It is based on a system model called estimator operating in open-loop. The complete structure of the observer includes a Feed-Back loop to correct the error between the actual output (θ) of the system and that ($\hat{\theta}$) estimated by the observer.

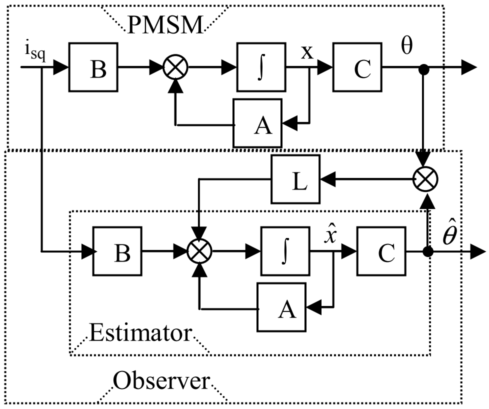

Figure 5. basic structure of the Luenberger observer

The equations of state of the observer can be written:

$$\dot{\hat{x}} = A.\hat{x} + B.u + L(x - \hat{x})$$
$$\hat{y} = C.\hat{x} \qquad (16)$$

From equations (14) and (16) we have:

$(14) - (16) \leftrightarrow \quad \dot{e} = (A - L)e$

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

The observer gains L are chosen to make the continuous-time error dynamics converge to zero asymptotically (i.e., when A − LC is a Hurwitz matrix) i.e the eigenvalues are negative real parts in the continuous case or have a modulus less than 1 in the discrete case..

C. *Scheme of simulation*

To ensure the validity of the decoupled model and get the desired dynamic performance with a simple structure we used the following simulation scheme:

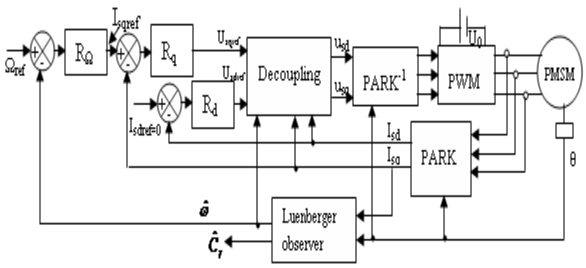

Figure 6. Simulation Scheme with a luenberger observer

V. Simulation Results

A. *PMSM parameter's*

TABLE I PARAMETERS OF PMSM

parameter	**value**
Maximal voltage of food	300 v
Maximal speed	3000 tr/s to 150 Hz
Nominal Torque : C_{enom}	14.2 N.m
Stator resistance: R_s	0.4578 Ω
Number of pair poles : p	4
Stator inductance in d-axis : L_d	3.34 mH
Stator inductance in q-axis : L_q	3.58 mH
The moment of inertia: J	0.001469 kg.m^{2}s
Coefficient of friction viscous f	0.0003035 Nm/Rad/s
Flux of linquage: Φ_f	0.171 wb

B. *Results*

The following figures (7 to 10) illustrate the dynamic behaviour of the PMSM using a classical PI'controllers.

These results show the effectiveness of the PI controllers because the reference current i_{qref} is delivered by the correction speed.

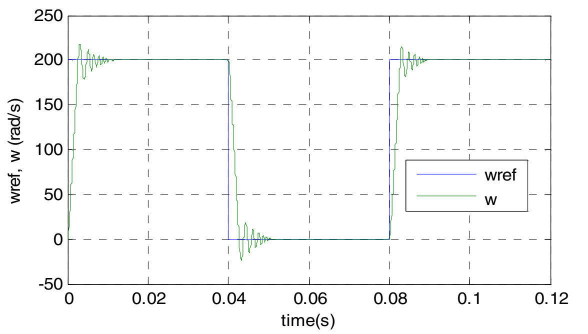

Figure 7. Evolution of speed for reference speed (wref=200 rad/s at t=0s, wref=100 rad/s at t=0.04s, wref=200 rad/s at t=0.08s)

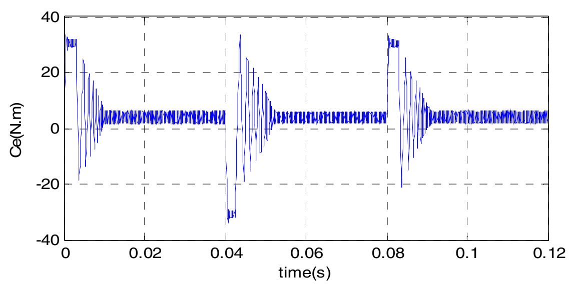

Figure 8. Evolution of Electromagnetic Torque

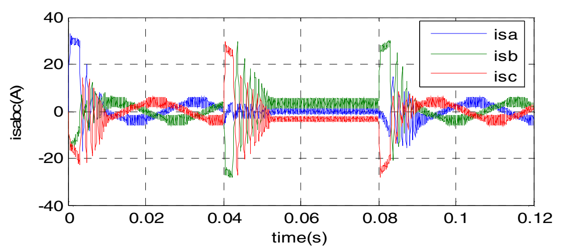

Figure 9. Evolution of phase currents

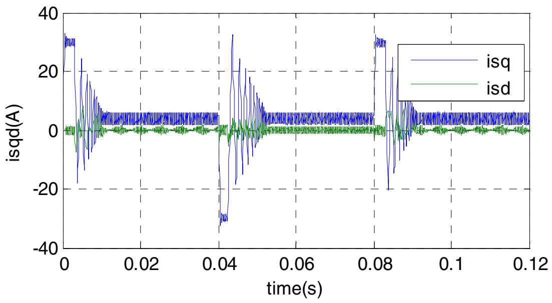

Figure 10. Evolution of the d-q axis currents

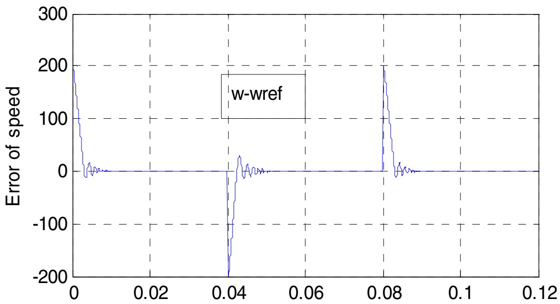

Figure 11. Speed Error

The following figures, (12) to (16), illustrate the dynamic behavior of PMSM in combination with the Luenberger observer. In this control we have replaced the measured speed (Ω_{mes}) by the estimated speed (Ω_{est}). These results are obtained under the same conditions as those obtained without an observer (figures, 7 to 11).

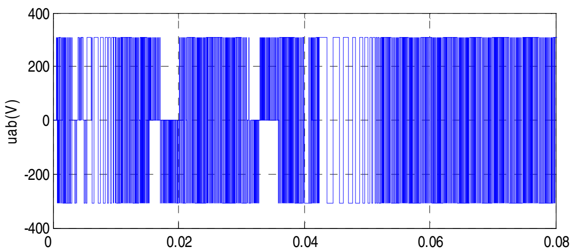

Figure 12 : Phase voltage Uab

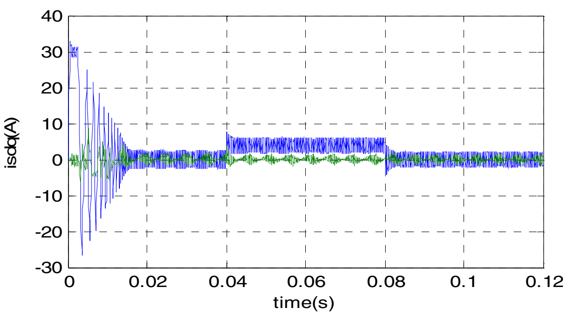

Figure 13.Evolution of the d-q axis currents in the presence of external disturbance (C_r=0Nm at t=0s, C_r=4Nm at t=0.04s, C_r=0 at t=0.08s)

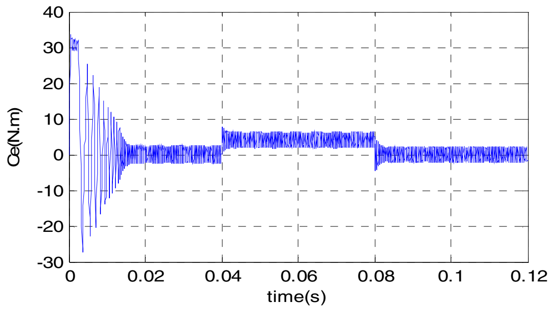

Figure 14. Electromagnetic torque in the presence of external disturbance (C_r=0Nm at t=0s, C_r=4Nm at t=0.04s, C_r=0 at t=0.08s)

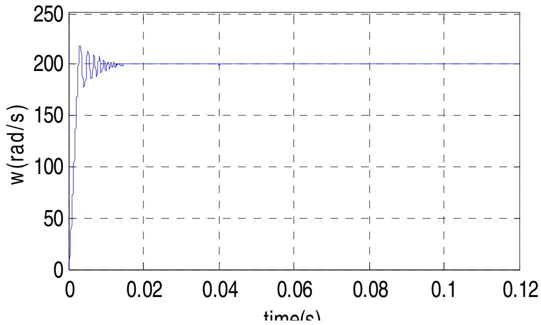

Figure 15. Tracking performance in the presence of external disturbance (Cr=0Nm at t=0s, Cr=4Nm at t=0.04s, Cr=0Nm at t=0.08s) - (wref=200 rad/s)

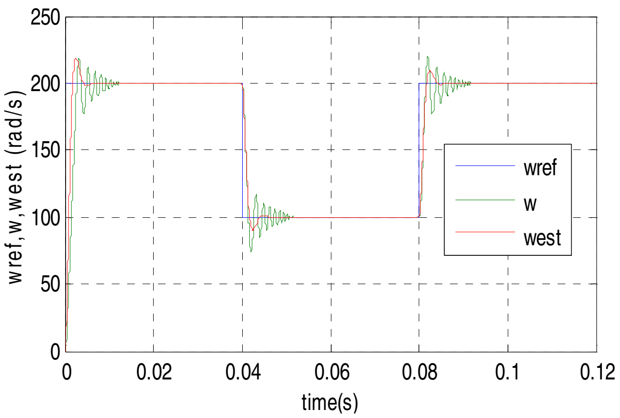

Figure 16. Evolution of the mesured speed and the estimated speed for speed reference (wref=200 rad/s at t=0s, wref=100 rad/s at t=0.04s, wref=200 rad/s at t=0.08s)

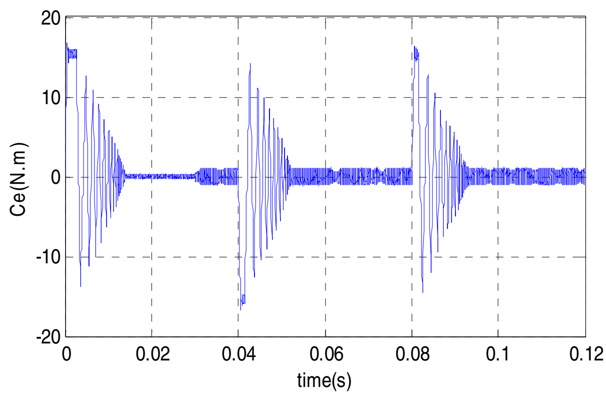

Figure 17. Evolution of Electromagnetic Torque

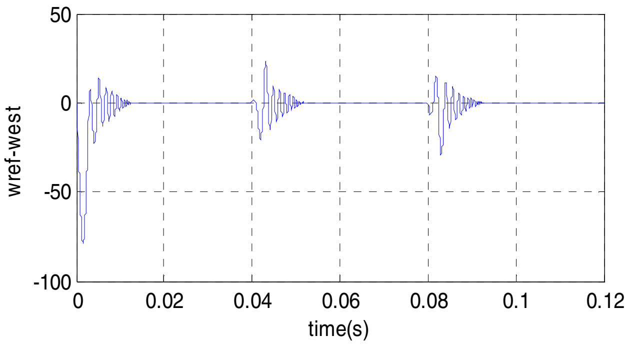

Figure 18. Error between the estimated speed and reference speed

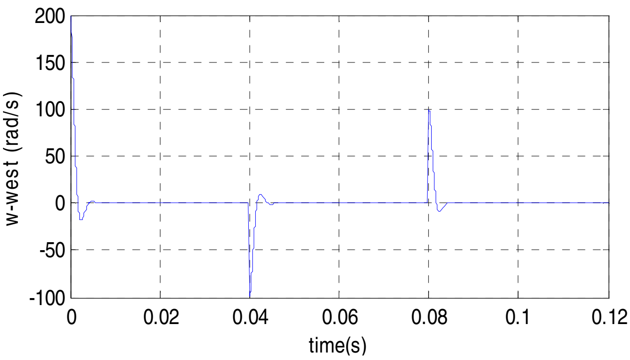

Figure 19. Error between the estimated speed and actual speed of the PMSM

VI. CONCLUSION

In this article we have modelled and simulated a simplified and robust control structure for pectoral control of the PMSM.

At first we used a simple structure using a PI controller to control separately the two currents i_{sd} / i_{sq} and speed of the machine.

Then, faced with the insufficiency of dynamic performance of these controllers especially for adjusting the motor speed, we use a state observer called "Luenberger observer" to reconstruct the state variables such as rotor position, rotor speed and load torque.

The simulation results show that using the estimated speed instead of speed measured or calculated from the position generated by the encoder further improves the dynamics of speed and reduces the excess torque .

We can confirm that the use of a PI-regulator and a Luenberger observer, yields satisfactory results.

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