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Modeling and Control of Permanent Magnet Synchronous Motor Used in Electric Vehicle

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***Abstract* — This paper deals with the modeling and control of a permanent magnet synchronous motor driving an hybrid electric vehicle. The recurred energy for this motor is provided by two energy sources, which are fuel cell and a super capacitor. The implementing concept of the Rotor-Oriented speed controller and the PWM inverter control are illustrated. The proposed strategy of the control is digitally simulated using the MATLAB/ Simulink/Sim Power Systems software. The dynamic performances of the electric vehicle drives are for the standardized European speed cycle type.**

***Keywords*— Electric vehicle; fuel cell; super capacitor; permanent magnet synchronous motor (PMSM); field oriented vector control.**

I. INTRODUCTION

Today, the major vehicle is equipped with an internal combustion engine that runs on gasoline or diesel. Carbon dioxide and several other emissions are produced. Exhaust emissions and the dependency on imported foreign crude oil have motivated interest in, and also technology advancement of electrical vehicle [6]. Selection of traction motors for hybrid propulsion systems is a very important step that requires special attention. The different types of electric motors used in the field of electric vehicles are asynchronous machines, synchronous machines with variable reluctance, machines DC and permanent magnet synchronous machines. In general, DC motors are downgraded for application in hybrid or electric vehicle [6]. Indeed, they are bulky, inefficient and require periodic maintenance because of the presence brushes manifold system. The variable reluctance motors have the following drawbacks: high noise level, current ripple levels and considerable torque [6]. The synchronous permanent magnet motor including its electrical power may exceed the Mega Watt, seems the most favorable solution for electric traction [2]. Its choice in the field of hybrid and electric vehicles becomes very attractive and very competitor other engines thanks to the evolution of the permanent magnets constituent materials [8]. The technical performances of the engines of this type are: yield, good performance dynamic (low stator inductances, silent, strong magnetic field the air gap and no excitation voltage) [4]. In addition, in our application, the weight criterion is important, so we have to choose a high power density engine to retrieve one hand the maximum space for the cabin space without increasing the outer volume of the vehicle and secondly to minimize the mass of the vehicle (minimizing power consumption) [11].

In recent years several techniques have been developed so that the synchronous speed controllers with permanent magnets reach high performances. However, the vector control, which allows a decoupling between variables control, remains more used with regard to the high dynamic performances which offers a wide range of applications[4] [9].

We present in this work a Modeling and control a magnet synchronous motor used in electric vehicle. In the first section, the energy chain is presented; the mechanical model of the vehicle and the electrical model of the synchronous motor are developed. In the second section, the vector control of PMSM is presented. The Simulation results are presented and discussed in the last section.

II. MODELING AND DESIGN OF ELECTRIC VEHICLE ENERGY CONVERSION SYSTEM

The considered electrical vehicle uses a fuel cell as the principal energy source its role is to ensure the average power required by the vehicle. It is connected to the DC bus via a unidirectional converter DC/DC. Packs of the super capacitor in addition to the fuel cell are necessary to ensure obtaining the maximum power on the one hand, (at the time of accelerations) and on the other hand recovering the kinetic energy during the braking operation. This aims is to minimizing hydrogen quantity consumed by the fuel cell. To adjust the voltage level of the super capacitor to that of DC bus, a bidirectional converter DC/DC is used between the pack of the super capacitor and the DC bus. The traction system of electrical vehicle is achieved through the permanent magnet synchronous motor associated with a three-phases inverter its voltage supply is ensured by the DC bus [1] [7].

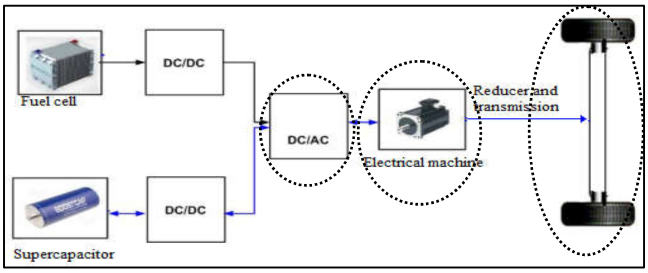

Fig. 1. Energy Conversion System.

A. Dynamic Model of the Electrical Vehicle

The various forces and the moving vehicle are presented on the following Fig.2.

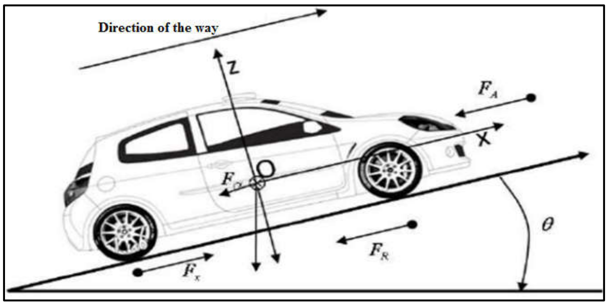

Fig.2. Forces operating a vehicle

Three main resistance forces $\overrightarrow{F_A}$, $\overrightarrow{F_R}$ and $\overrightarrow{F_G}$ called respectively aerodynamic force, rolling resistance force and gravity force. The tensile force $\overrightarrow{F_x}$ propels the vehicle forward. The propulsion system (the permanent magnet synchronous machine) must provide the necessary force to the vehicle traction at the wheels. This force must firstly provide the necessary effort to speed and partly overcome the resistant force to the coil, the aerodynamic force and road inclination [1] [10] [11].

- Rolling resistance force

  The rolling resistance force acts on the level of tires and is opposed to the free movement of the vehicle. It is caused by the deformation of the tires on the road way which generates a rolling friction. It depends on the vehicle mass M (kg), the acceleration of gravity g ($m.s^{-2}$) and the rolling resistance coefficient C_R.

  $$F_R = MgC_R \tag{1}$$

- Gravity force:

  The gravity force affects immediately the vehicle on the slope. It retains it in rise and pushes it in descent. It depends on the inclination of the slope θ and the vehicle mass M.

  $$F_G = Mg\sin(\theta) \tag{2}$$

- Aerodynamic Force:

  This is the air resistance force. It varies depending on the vehicle speed and depends on non-linear phenomena within the fluid mechanics. It is proportional to the voluminal density of the air ρ (Kgm^{-2}), to the front section S_f (m^2) of the vehicle, the drag coefficient C_x of the air and vehicle speed V(ms^{-1}) .

  $$F_A = \frac{\rho C_x S_f V^2}{2} \tag{3}$$

- Traction force:

  The tensile force indicates the force which is exerted on the periphery of the driving wheels in contact with the ground to create or maintain the movement of vehicle. The intensity of this force depends on the engine torque, gear transmission and the ray of the driving wheels.

  $$F_x(t) = M\frac{dV(t)}{dt} + Mg\sin(\theta) + \frac{\rho C_x S_f V(t)^2}{2} + MgC_R \tag{4}$$

The energy required to move the vehicle at a distance d which is expressed by the following equation (5)

$$W(t) = F_x(t)\,d = \int F_x(t)V(t)\,dt \tag{5}$$

The mechanical power provided to the wheels is :

$$\begin{aligned} P_m(t) &= \frac{dW(t)}{dt} = F_x V(t) \\ P_m(t) &= V(t)M\frac{dV(t)}{dt} + Mg\sin(\theta) + \frac{\rho C_x S_f V(t)^2}{2} + MgC_R \end{aligned} \tag{6}$$

B. Model of the PMSM

The permanent magnet synchronous motor model is approximated with a second order state representation by using the Park transformation. This representation is necessary because the inputs and the outputs of the model of the synchronous machine are expressed in the reference a,b,c.

The Park transformation is used to convert voltage and current in the reference a, b, c into two components in the d,q reference frame [2] [5] (Fig.3).

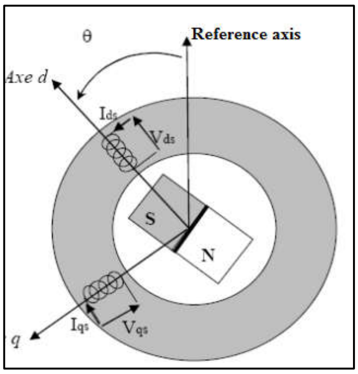

Fig.3. Equivalent Diagram of a PMSM in the Park reference frame

The electrical and mechanical equations of the synchronous machine are expressed as follows:

$$\begin{aligned} \dot{I}_{sd} &= \frac{1}{L_{sd}}\left(V_{sd} - R_s I_{sd} + \omega L_{sd} I_{sd}\right) \\ \dot{I}_{sq} &= \frac{1}{L_{sq}}\left(V_{sq} - R_s I_{sq} - \omega L_{sq} I_{sq} + \omega\varphi_f\right) \\ Ce &= \frac{3}{2}p\left[\left(L_{sd} - L_{sq}\right)I_{sd}I_{sq} + \varphi_f I_{sq}\right] \\ J\frac{d\Omega}{dt} &= Ce - Cr - f\Omega \end{aligned} \tag{7}$$

In these equations:

R_s: Stator phase resistance

L_{sd}: d-axis inductance ,
L_{sq}: q-axis inductance ,
Φ_f: Rotor Flux,
Ce: Electromagnetic torque provided by the motor,
Cr: Load torque,
J: Motor Inertia,
Ω: Angular speed of the motor,
P: number of pole pairs.

III. VECTOR CONTROL OF THE PERMANENT MAGNET SYNCHRONOUS MACHINE

In the field oriented control of the PMSM the direct current component (id) is null and electromagnetic torque is controlled by the quadrature component of the stator current (iq) [5] [9] [12]. The quadrature current component i_{qref} is therefore proportional to the required torque. The vector control amounts imposing the two reference voltage standards Vds ref and Vqs ref to order the inverter by controlling the two components of currents ids and iqs [5] [6] (Fig.4).

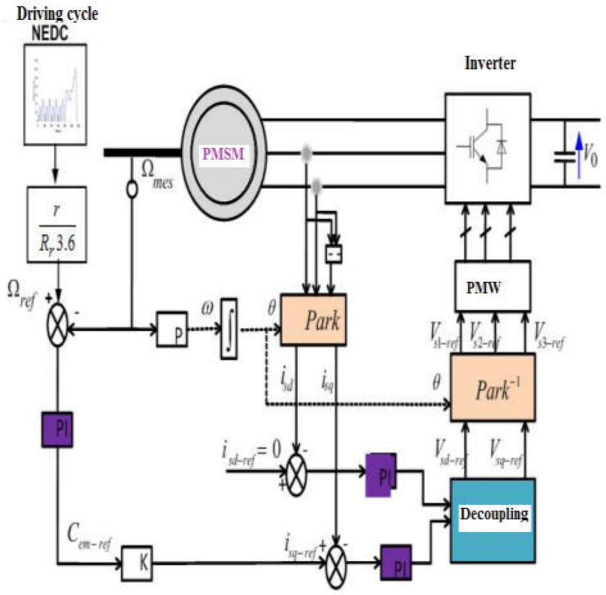

Fig.4. Structure of the vector control of PMSM

A. *Decoupling by compensation*

The voltage supply is obtained by imposing the reference voltage standards input to the control of the inverter. These voltages allow determining the cyclic ratios on the arms of the inverter, so that the voltage delivered by this inverter at the boundaries of the stator of the machine is closest to possible reference voltage standards. But, we must define the terms of compensation, because in the stator equations, there are terms of coupling between the axes d and q (Fig.5).

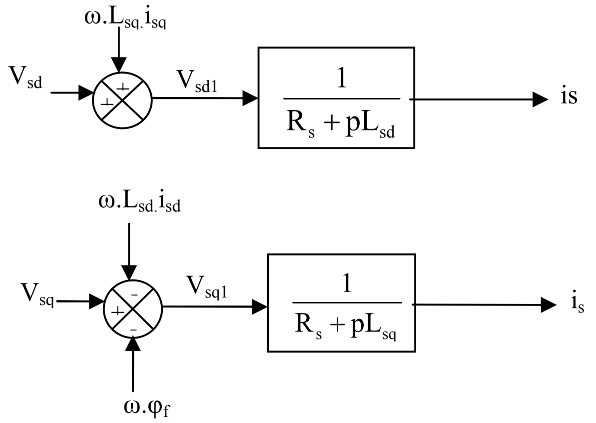

Fig.5. Coupling of the two stator tensions

The voltages V_{sd} and V_{sq} depend at the same time on both currents on the axes 'd' and 'q', thus lead to establish a decoupling. This decoupling is based on the introduction of compensatory terms e_{sd} and e_{sq}.

With:
$$\begin{aligned} e_{sd} &= \omega L_{sq} I_{sq} \\ e_{sq} &= \omega\left(L_{sd} I_{sd} + \varphi_{sf}\right) \end{aligned} \quad (8)$$

From the previous equations we have:

$$\begin{aligned} V_{sd} &= V_{sd1} + e_{sd} \\ V_{sq} &= V_{sq1} + e_{sq} \end{aligned} \quad (9)$$

With:
$$\begin{aligned} V_{sd1} &= \left(R_s + pL_{sd}\right) I_{sd} \\ V_{sq1} &= \left(R_s + pL_{sq}\right) I_{sq} \end{aligned} \quad (10)$$

B. *Regulators design*

The regulation is performed by using the PI or PID controllers (proportional, integral, derivative). The algorithms, even the most powerful, are always a combination of these actions. We adopted a proportional integral regulator (PI). The integral coefficient Ki is used to reduce the difference between the instruction and the controlled size thus reducing the overflow. As the term proportional Kp allows the adjustment of the speed of the system and thus the response time [6].

- Currents Regulators :

Quadrature current regulator iq :

The transfer function test of the used PI regulator is expressed as follows:

$$R_{iq}(p) = K_{pq} + \frac{K_{iq}}{p} = \frac{K_{pq}\left(1 + \tau_{iq} p\right)}{\tau_{iq} p} \quad (11)$$

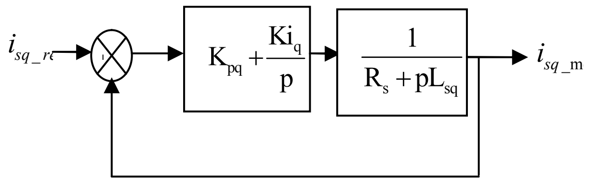

Fig.6. Loop of current regulation i_q

The transfer function $H_{BO}(p)$ in open loop is expressed by the following equation.

$$H_{Bo}(p) = \frac{K_{pq}\left(1+\tau_{iq}\right)}{\tau_{iq}p}\,\frac{1/R_s}{1+\tau_{eq}p} \qquad (12)$$

With $\tau_{eq} = \dfrac{L_q}{R_s}$: Electrical constant time of the axis q.

By using the pole compensation method, we have: $\tau_{iq} = \tau_{eq}$.

The transfer function $H_{Bf}(p)$ in closed loop is expressed by the following expression.

$$H_{Bf}(p) = \frac{1}{1+\tau_q p} \qquad (13)$$

By identification, we have:

$$\tau_q = R_s \tau_{iq} / K_{pq} \qquad (14)$$

The response time is equal to:

$$T_{rep} = 3\tau_q \qquad (15)$$

Finally we obtain;

$$K_{iq} = \frac{1}{\tau_q} = \frac{3R_s}{T_{rep}} \;;\; K_{pq} = \frac{3L_q}{T_{rep}} \qquad (16)$$

Current Regulator of i_d :

Figure (7) represents the loop of current regulation i_d:

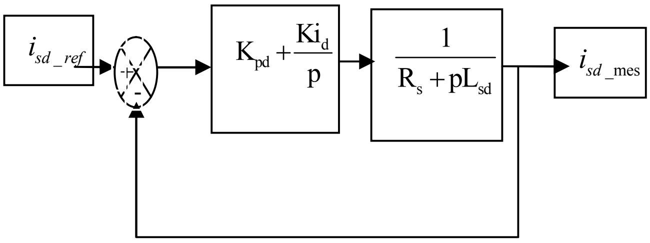

Fig.7. Loop of current regulation i_d

The PI regulator type has a transfer function of the following form:

$$C_{id}(p) = K_{pd} + \frac{K_{id}}{p} = \frac{K_{pd}\left(1+\tau_{id}p\right)}{\tau_{id}p} \qquad (17)$$

The transfer function $H_{Bo}(p)$ in open loop is expressed by the next equation.

$$H_{Bo}(p) = \frac{K_{pd}\left(1+\tau_{id}\right)}{\tau_{id}p}\,\frac{1/R_s}{1+\tau_{ed}p} \qquad (18)$$

With $\tau_{ed} = \dfrac{L_d}{R_s}$: Electrical constant time of the axis d.

By using the pole compensation method, we have: $\tau_{id} = \tau_{ed}$.

The transfer function $H_{Bf}(p)$ in closed loop is expressed by:

$$H_{Bf}(p) = \frac{1}{1+\tau_d p} \qquad (19)$$

By identification, we have:

$$\tau_d = R_s \tau_{id} / K_{pd} \qquad (20)$$

The response time equal to:

$$T_{rep} = 3\tau_d \qquad (21)$$

Finally we obtain;

$$K_{id} = \frac{1}{\tau_d} = \frac{3R_s}{T_{rep}} \;;\; K_{pd} = \frac{3L_d}{T_{rep}} \qquad (22)$$

- Speed Regulator:

The speed regulation is made by using a regulator; its transfer function is expressed by the next equation.

$$R_{\Omega}(p) = K_{p\Omega} + \frac{K_{i\Omega}}{p} \qquad (23)$$

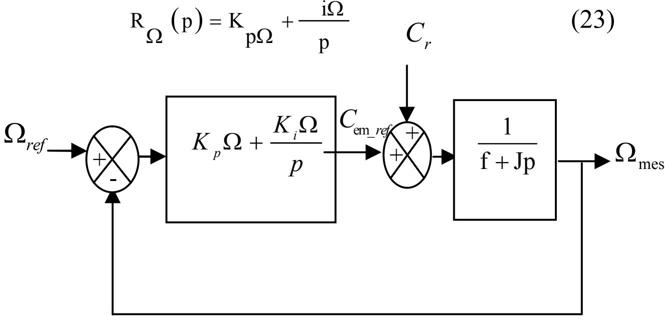

Fig.8. Speed control loop

The transfer function in closed loop is :

$$H_{Bf}(p) = \frac{\Omega_{mes}}{\Omega_{ref}} = \frac{1+\tau_{\Omega}.p}{\left(\tau_{\Omega}.J/K_{p\Omega}\right)p^2 + \tau_{\Omega}\left(1+f/K_{p\Omega}\right)p+1} \qquad (24)$$

With $\tau_{\Omega} = \dfrac{K_{p\Omega}}{K_{i\Omega}}$ (25)

By identification with the canonical form of a second order system, we have:

$$\omega_{0\Omega} = \frac{K_{p\Omega}}{J.\tau_{\Omega}} \;;\; m = \frac{\tau_{\Omega}\left(1+f/K_{p\Omega}\right)}{2\omega_{0\Omega}} \qquad (26)$$

IV. SIMULATION RESULTS

The simulation results is formed on a magnet synchronous machine in which these characteristics were given in table I and supplied with a controlled inverter according to the principle of space vector PWM. For purposes of the simulation and for reproducing a road section with different driving conditions are used in the standardized European speed cycle (NEDC), [3] given in Fig.9.

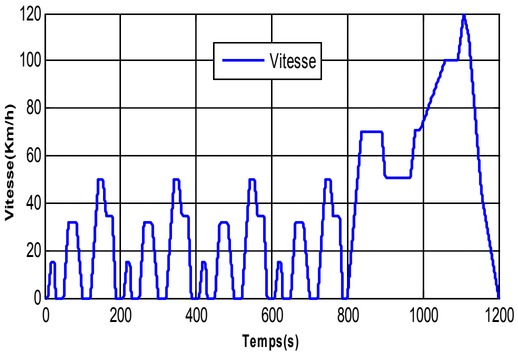

Fig. 9. Normalized European Cycle speed (NEDC).

TABLE I. PARAMETRES OF THE MOTOR

Parameters	Values
Stator resistor R_s	4 Ω
Stator inductance L_s	0.0025 H
Poles pairs P	4
Flux of permanent magnet φ_f	0.053Wb
Rotational inertia J	9e-7 Nm/A
Rated speed Ω	Tr/min
DC voltage U_{DC}	540 V
friction coefficient f	0 Nm/rad/s

TABLE II. PARAMETRES OF THE VEHICLE

Parameters	Values
Vehicle mass M	300 kg
Rolling resistance coefficient C_R	0.001
Vehicle front section S_f	1 m^2
Gravitational field g	9.81 ms^{-2}
slope $\tan(\Theta_{max})$	10 %
Radius of the wheels R_r	0.14 m
Volume density of air ρ	1.2 $Kg.m^{-3}$
Coefficient of air penetration C_x	0.25
Acceleration γ	0.78 $m.s^{-2}$

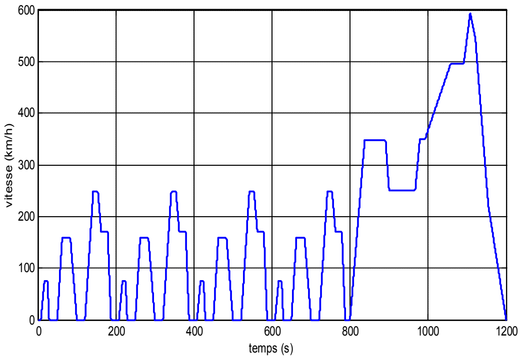

Fig. 10. Vehicle speed.

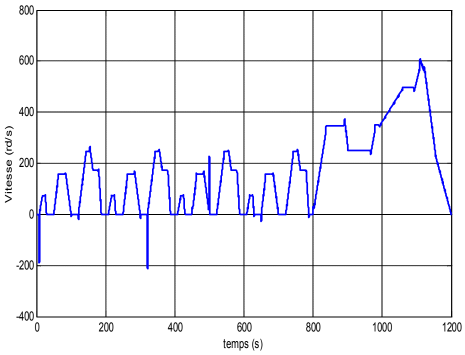

Fig. 11. Motor speed.

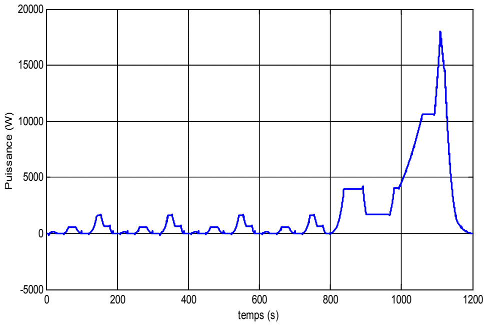

Fig. 12. Motor power

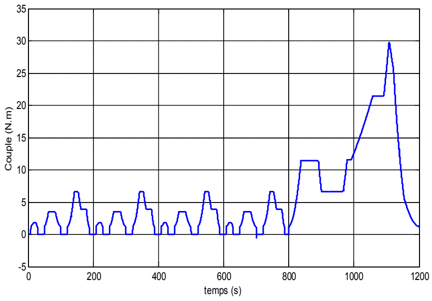

Fig. 13. Electromagnetic torque.

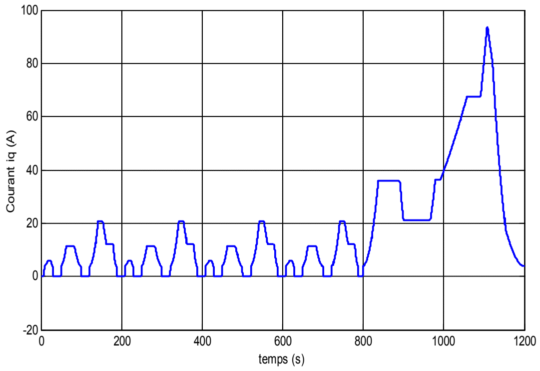

Fig. 14. Component in squaring iq.

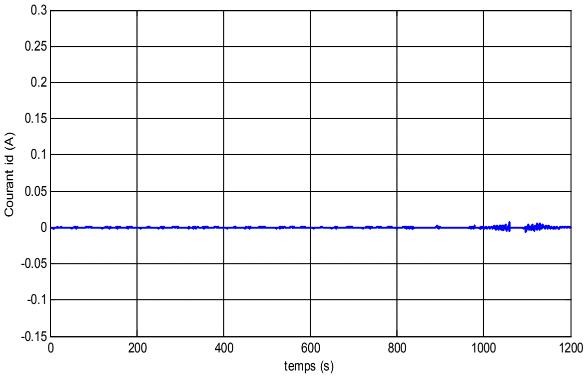

Fig15. direct component id.

Figures 10 and 11 shows the evolution of the speed of that vehicle motion and angular speed of the permanent magnet synchronous motor. It is observed that in Fig. 11 shows oscillations. Fig.12 presents the evolution of the electric power provided by the permanent magnet synchronous motor. The results got in digital simulation highlight the performances of the control system. The torque Cem (Fig.13) and the Iq current (Fig.14) have the same shape. The Id current (Fig. 15) follows its references.

IV. CONCLUSION

This paper presents a validation study of field oriented control strategies for PMSM driven Electric Vehicles. We made the modeling and control vector of this machine to ensure better vehicle performance. Then, a PI regulator and an integrator are used to calculate the speed and d-q axis voltages references. Starting from the PM motors drives, the FOC strategies have been divided in to three groups: the current and speed control loops a device of nonlinear decoupling and schemes operating with PWM inverter. The simulations results under Simulink/Matlab show that the torque and the q-axis stator current have the same pace and the forward current Id follows the reference. The proposed control scheme provides acceptable dynamic and robust responses. In the future work, we intend to implement the standardized European speed cycle in order to improve the robustness of the Field Rotor Oriented speed control of PMSM drives system using dSpace DS1104 control.

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