# Control Approaches of Permanent Magnet Synchronous Motor Used for Electric Vehicle Power Train

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**ABSTRACT**

An Electric vehicle (EV) is a road vehicle that uses electric propulsion. It has an electric motor consuming a portable and an electrochemical energy source. Some drive circuits of electric vehicles are realized around AC electric motors. Among the AC electric motor types, we can cite the Permanent Magnet Synchronous Motor (PMSM). In this paper, we present and compare a field-oriented control and a direct torque control for an EV power drive train composed of a PMSM. The benefits and the drawbacks of both techniques are explored using various simulation tests.

***Keywords:*** *Field-oriented control, direct torque control, power drive train, Electric vehicle,* permanent magnet synchronous motor.

## 1. INTRODUCTION

An Electric Vehicle (EV) is a vehicle that is partially or fully powered by electric energy. It uses one or several electric motor for propulsion. Among the electrical motors used in EV, we can cite the Permanent Magnet Synchronous Motor (PMSM) [1-2].

The PMSM is a very robust electric actuator characterized by a low inertia, giving this motor a very low time constant and allowing the design of speed, torque or position controls with very interesting precision and dynamic performances. The PMSM is a good propulsion solution because of its several advantages, such as no rotor losses, high overload capacity, stable and constant speed at a given frequency and its high torque mass compared to asynchronous motor and the conventional synchronous motor [3]. PMSM is a multivariable, highly non-linear, and strongly coupled electromechanical system. Moreover, the PMSM parameters are not constant but can fluctuate in a range according to changes in the working environment. In addition, the torque and the speed may oscillate irregularly in certain parameter zones, which is not allowed to ensure stability and safety. The dynamic behaviour of the PMSM as well as the stability condition must therefore be discussed in a general way to provide a theoretical basis for the use of the PMSM.

With permanent magnets, the PMSM can generate torque at zero speed, and it requires a numerically controlled inverter for its operation. PMSMs are typically used for high-performance and high-efficiency motor drives [4].

PMSM design needs a multivariate optimization technique aimed at increasing efficiency and power density, lowering torque ripple and noise, and improving durability. Rigidity and motor cost are two common restrictions.

Surface mounted PMSMs and interior type PMSMs are the two basic forms of PMSMs. Despite the high torque density of the surface mound PMSM, torque ripple is caused by the quasi-rectangular form of the air gap flux, resulting in noise and vibrations. Interior type PMSMs are better suitable for EVs than surface mound

PMSMs because they can give higher dependability and overload capabilities.

This paper is organized as follows. In section 2, we present the studied EV. The electrical mathematical model of the PMSM is given in section 3. In section 4, we present a field-oriented control and a direct torque control designed and applied to the studied EV. Simulation results are given and discussed in section 5.

## 2. STUDIED SYSTEM DESCRIPTION AND MODELLING

As illustrated in Figure 1, the EV is examined in terms of vehicle dynamics, transmission, source voltage, control, and PMSM drive. The vehicle dynamics model takes into account all of the forces acting on the EV, and the behavior can be observed under linear or angular acceleration. This behavior is critical when comparing EV performance to the motor drive's rated attributes. To make the system easier to understand, the transmission is represented by a gain relation. Finally, the inverter and PMSM motor are taken into account while modelling the PMSM motor drive [5-6].

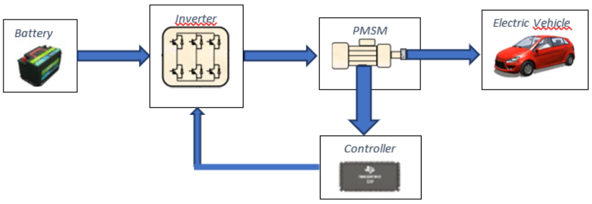


**Figure 1** Powertrain component of the studied EV

The force driving the EV ahead, must overcome the forces listed below:

### 2.1 Tractive Resistance

The vehicle dynamic is the most important aspect of vehicle design and development since it dictates the vehicle's performance. To create the electric powertrain, it is necessary to understand the vehicle's drive requirements and performance standards.

The force required to overcome resistance and propel the vehicle ahead with desired characteristics is computed as tractive force, which is the total of resistant force [7].

$$Ft = Frr + Fg + Fad \quad (1)$$

### 2.2 Rolling Resistance

The force that keeps a wheel from rolling from its idle state (speed = 0 km/h) is known as rolling resistance. Between the wheel frontage and the road surface, Crr is the coefficient of rolling resistance. Crr is 0.03 while automobiles are running on asphalt roads.

$$F_{rolling} = C_{rr}.m.a \quad (2)$$

Crr : coefficient of rolling resistane

m : mass of vehicle in Kg

a : acceleration due to gravity ($m/s^2$)

Power required to overcome this rolling resistance (P) =

$$F_{rolling} * \left(velocity\ of\ vehicle\ in \frac{m}{s}\right) \quad (3)$$

### 2.3 Aerodynamic Resistance

Because of the aerodynamic component, air resistance stops a vehicle from reaching a given speed. V is the vehicle speed in equation (4). The frontal area of a vehicle is the surface area exposed to the wind.

$$F_{Aerodynamic\_Drag} = 0.5\rho.V^2.C_A.A_f \quad (4)$$

Where

$\rho$ :Density of air medium

$\rho = 1.23\ Kg/m^2$ (For air at sea level)

V : the Velocity of vehicle in m/s

$C_A$ : Coefficient of air resistance

$C_A$= 0.82

$A_f$ : Frontal area of vehicle ( in $m^2$)

### 2.4 Gradient resistance

$$F_{gradient} = m.g.\sin\theta \quad (5)$$

where $\theta$ is the angle of an incline for the EV climbing a hill. Consider $\theta = 0°$ when the vhicle travels at flat surface.

## 3. PMSM MATHEMATICAL MODEL

The following equations offer the voltage equations of PMSM in the rotating reference dq-axis using Park transformation.

$$V_d = R_s I_d + L_d \frac{dI_d}{dt} - \omega L_q I_q \quad (6)$$

$$V_q = R_s I_q + L_q \frac{dI_q}{dt} - \omega(L_d I_d + \varphi_f) \quad (7)$$

where

$R_s$, $L_d$ and $L_q$ are phase resistance and direct, quadrature inductance.

$\varphi_f$ presents the flux linkage.

The flux equations are expressed as follows:

$$\varphi_d = L_d I_d + \varphi_f \quad (8)$$

$$\varphi_q = L_q I_q \quad (9)$$

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ \varphi_f \end{bmatrix} + \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ \varphi_f \end{bmatrix} + \omega \begin{bmatrix} 0 & -L_q & 0 \\ L_d & 0 & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ \varphi_f \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} \varphi_d \\ \varphi_q \end{bmatrix} = \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \\ \varphi_f \end{bmatrix} \quad (11)$$

$$[V] = [R][I] + [L]\frac{d}{dt}[I] + \omega[A][I] \quad (12)$$

$$[V] = \begin{bmatrix} V_d \\ V_q \end{bmatrix} ; [R] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \end{bmatrix} ; [I] = \begin{bmatrix} I_d \\ I_q \end{bmatrix} \quad (13)$$

$$T_e = \frac{3}{2} p(\varphi_d I_q - \varphi_q I_d) \quad (14)$$

$$T_e - T_r - f\omega_m = J\frac{d\omega_m}{dt} \quad (15)$$

$$\omega = \omega_m p \quad (16)$$

$\omega_m$ is the mechanical speed of rotor

$T_e, T_r$ are electromagnetic torque and external load torque.

$f, J$ are moment of inertia and friction constant.

p is the pole pair

The simplified model is represented below:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \omega\left( \begin{bmatrix} 0 & L_q \\ L_d & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 \\ \varphi_f \end{bmatrix} \right) \quad (17)$$

$$[V] = [R][I] + [L]\frac{d}{dt}[I] + \omega([A][I] + [\varphi]) \quad (18)$$

$$[V] = \begin{bmatrix} V_d \\ V_q \end{bmatrix} : [R] = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} : [I] = \begin{bmatrix} I_d \\ I_q \end{bmatrix} ; \quad (19)$$

$$[L] = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} ; [A] = \begin{bmatrix} 0 & L_q \\ L_d & 0 \end{bmatrix} : [\varphi] = \begin{bmatrix} 0 \\ \varphi_f \end{bmatrix} \quad (20)$$

## 4. CONTROL OF PMSM

### *4.1. Field Oriented Control (FOC)*

Blaschke proposed the FOC concept in 1970. In the unique dq0 coordinate system, the stator current was separated into the torque component and magnetized under the constant rotor fux, and the control of alternating current (AC) motors can be identical to that of an unexcited DC motor.

FOC has a wide speed range, smooth starting, and minimum torque ripple, making it excellent for machinery with a high dynamic reactivity in challenging working situations. The motor speed-torque-current diagram is used to propose a vector control strategy. The car's range was increased while its power demand and energy consumption were reduced [9]. FOC is a technique for decoupling torque and flux management by translating stator current quantities (phase currents) from a fixed reference frame to torque and flux producing current components in a rotating reference frame [10].

### *4.2. Direct Torque Control (DTC)*

DTC is a control strategy that exploits the possibility of imposing decoupled torque and flux on AC machines supplied by a voltage inverter and do not need current regulation through a feedback loop [11].

Several efforts have been made to minimize the complexity of synchronous machine management, such as flux vector control, which allows magnetic flux and electromagnetic torque to be decoupled. These control techniques are very sensitive to changes in machine characteristics, notably rotor resistance, which is difficult to detect during operation.

The primary operating principle of the DTC is to select a voltage vector based on the discrepancies between necessary and actual torque and stator flux linkage values, as well as a position estimate based on the load angle computed by dividing one electrical revolution into six sectors.

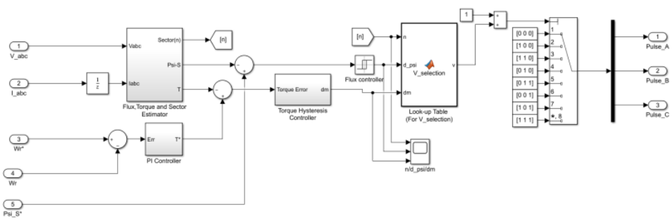

**Figure 2** DTC scheme of PMSM in matlab-simulink.

**TABLE 1**. Sector number θ(N) according to the load angle marge.

| Load angle marge | Sector number | Load angle marge | Sector number |
|---|---|---|---|
| [−π/6,π/6] | 1 | [5π/6,7π/6] | 4 |
| [π/6 , π/2] | 2 | [7π/6, 3π/2] | 5 |
| [π/2 , 5π/6] | 3 | [3π/2, 1π/6] | 6 |

## 5. SIMULATION RESULTS

The simulations are carried out in loaded working conditions for a reference speed set to 3000 rpm. Figures 3 and 4 show the motor speed by application of the FOC and the DTC respectively. Figures 5 and 6 give the torque evolutions respectively. According to the FOC, the DTC has a rapid speed dynamic response, but it has a lot of torque ripple.

The results prove that the DTC system is better if quick dynamic performance is the most important criteria. However, the FOC scheme may be a better choice when good torque quality is required.

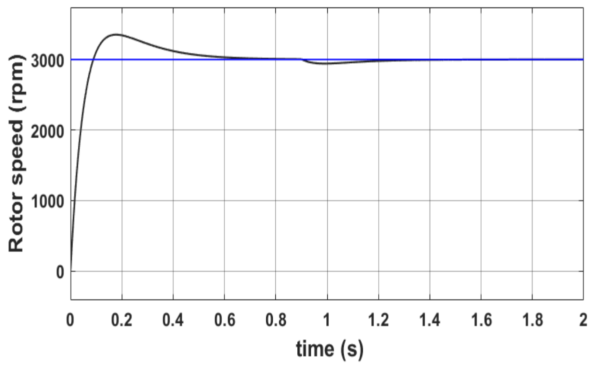


**Figure 3** Speed response using FOC

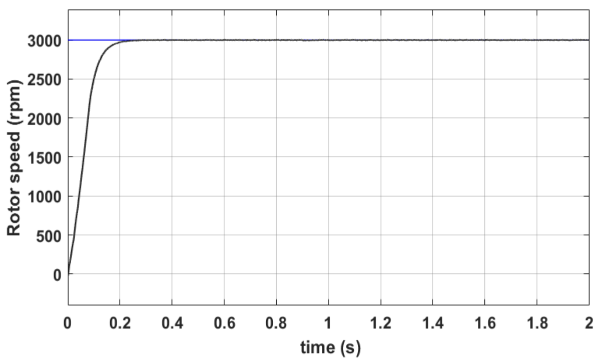


**Figure 4** Speed response using DTC

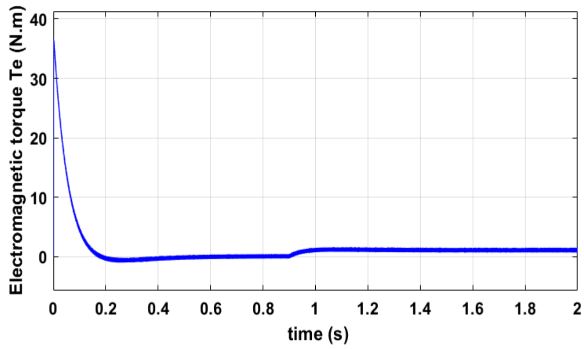


**Figure 5** Torque responses using FOC

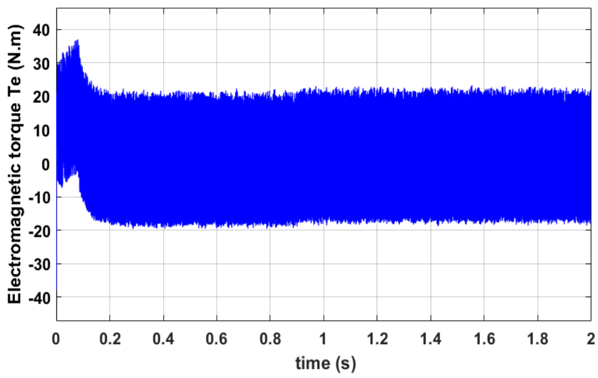


**Figure 6** Torque responses using DTC

## 6. CONCLUSION

Permanent Synchronous motors have high torque-to-current ratios, power-to-weight ratios, efficiency, and reliability. Due to their advantages, PMSMs are commonly employed in current variable speed AC drives, particularly in electric vehicle applications. In high-performance drive systems such as electric cars, PMSMs have surged to the top of the AC motor industry (EVs).

DTC, unlike Field Oriented Control, does not require a rotor position sensor. The starting position, on the other hand, is necessary for the start-up to assure the right rotating direction. In addition, DTC does not require current regulators, transformations to a rotating reference dq frame, or PI regulators.

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