Abstract — In the last decade, new applications in the area of electric vehicles and automation have been developed, due to the technology development in power and control electronics [1]. In order to match the rising of those applications areas, more effective, flexible and efficient new generation of electric drive control systems as well as electric motors were conceived.

The purpose of this work is to study a system constituted by a vector control electric variable speed drive controlling a double stator permanent magnet synchronous motor, for electric vehicle applications. Throughout this paper the new concept of the double stator will be studied, combined with the electronic control unit. This approach includes the discussion about topologies, characteristics and advantages, comparison between old and conventional control systems having as reference conventional DC (Direct Current) machines and AC (Alternating Current) induction machines. A model of the speed drive with the RFOC (Rotor Field Oriented Control) algorithm and the motor will be introduced. To study and understand the system’s functionality and dynamics with a set of load and test conditions, the MATLAB®/Simulink simulation environment is used.

The double stator configuration is technically approved and validated not only with constant and dynamic torque and speed responses to mechanical loads, but also the possibility to test the outer stator and inner stator separately with external perturbations, in order to get test conditions similar to real situations. Since this solution would be seen a conjunction between high efficiency and torque density, the double stator permanent magnet synchronous motor will be a viable and adequate solution for the electric mobility.

Index Terms — Electric Vehicle, Double Stator Permanent Magnet Synchronous Motor, RFOC (Rotor Field Oriented Control), Variable Speed Drive, Vector Control

I. INTRODUCTION

This work present a control system for electric vehicles, combining a commercial electronic speed drive for special applications with a double stator permanent magnet synchronous motor, granting high precision control and high torque density and simultaneously with lesser weight, dimensions and maintenance requirements, in comparison with conventional and old fashion electric motor systems. The electronic speed drive chosen to this work is as important as the motor component itself, capable of reacting quickly and stable enough to the user commands (car driver), and also, dynamic and resilient to whatever the load and other external conditions [2].

II. ELECTRIC SYSTEM

In this section the double stator permanent magnet synchronous motor concept will be introduced and also the reasons of choice for the electric control system that drives it.

A. Double Stator Permanent Magnet Synchronous Motor

The new double stator permanent magnet synchronous motor concept is proposed for integration in an electric vehicle [3], in order to increase the viability, flexibility and high level of precision and system control due to higher electromagnetic useful torque, comparing to a standard permanent magnet synchronous motor. As any electric machine, a double stator permanent magnet synchronous motor is mainly composed by two principal components, the fixed and the non-fixed, respectively designated the stator and the rotor. The source of the electromagnetic flux is a set of high performance permanent magnets that are installed on the rotor surface, or inside it. For this study it will be assumed the configuration with surface mounted permanent magnets. The magnetic interaction between the stator ad the rotor field will result in the electromagnetic useful torque. This torque will be responsible to drive all the mechanical component composed by the rotor, the transmission axle, the wheels and the external load [4].

In terms of construction, there are two air gaps instead of one as the conventional motor, because the rotor is positioned between the outer and inner stator, giving it a cup physical form, as illustrated in the figure 1 and in figure 2.

Given the fact there is additional space to equip an inner stator with a three phase wiring system, it is possible to increase the global cable section and extension, for a better cooling performance by superior heat dissipation. So for a given nominal parameter, such as nominal power and useful torque, the principal consequence of the electric motor’s optimization is to decrease the electric resistance and therefore a lesser current level for the same electromagnetic torque.
Apart the construction superiority and optimization, other factor that influence the higher performance of this motor philosophy is the outer and inner stator turns per phase ratio [3], which dictates directly the values of both outer and inner stator inductances.

For modelling the double stator permanent magnet synchronous motor, firstly it is assumed in this section that the three phase wiring system of the outer stator is electrically connected in series with the inner stator’s wiring system. Second, it is also assumed that both wiring systems are uniform distributed and angled apart by 120 °, both air gaps are uniform, the magnetic circuit is linear and only fundamental components of the electric voltages and currents are assumed; on the other hand it is neglected the magnetic saturation, iron losses and also the mechanical friction. In figure 3 it can be seen a representative electric diagram of the proposed motor.

![Fig. 1. Transversal cut view of a Double Stator Permanent Magnet Synchronous Motor [5].](image1)

![Fig. 2. Radial cut view of a Double Stator Permanent Magnet Synchronous Motor [5].](image2)

![Fig. 3. Diagram representing outer and inner stator voltages and phase currents.](image3)

The equations that describes the electric motor are the following:

1) **Stator Voltages**

\[
\begin{align*}
U_a &= (R_{in} + R_{out})i_a + \frac{\delta \psi_{a, in}}{\delta t} + \frac{\delta \psi_{a, out}}{\delta t} \\
U_b &= (R_{in} + R_{out})i_b + \frac{\delta \psi_{b, in}}{\delta t} + \frac{\delta \psi_{b, out}}{\delta t} \\
U_c &= (R_{in} + R_{out})i_c + \frac{\delta \psi_{c, in}}{\delta t} + \frac{\delta \psi_{c, out}}{\delta t}
\end{align*}
\]  

(1)

2) **Link Magnetic Flux in Matrix Form**

\[
\begin{bmatrix}
\psi_{a, in} \\
\psi_{a, out} \\
\psi_{b, in} \\
\psi_{b, out} \\
\psi_{c, in} \\
\psi_{c, out}
\end{bmatrix} =
\begin{bmatrix}
(t_{in_{ab}} + M_{out-in}) & (t_{out_{ab}} + M_{in-out}) & (t_{out_{ac}} + M_{in-out}) \\
(t_{out_{ab}} + M_{out-in}) & (M_{out-in} + M_{out-out}) & (M_{in-in} + M_{in-out}) \\
(M_{in-in} + M_{in-out}) & (M_{out-in} + M_{out-out}) & (M_{in-in} + M_{in-out}) \\
(M_{in-in} + M_{in-out}) & (M_{out-in} + M_{out-out}) & (M_{in-in} + M_{in-out}) \\
(M_{out-in} + M_{out-out}) & (M_{out-out} + M_{out-out}) & (M_{out-out} + M_{out-out}) \\
(M_{out-out} + M_{out-out}) & (M_{out-out} + M_{out-out}) & (M_{out-out} + M_{out-out})
\end{bmatrix}
\times
\begin{bmatrix}
\psi_{mag \cos \theta} \\
\psi_{mag \cos \theta} \\
\psi_{mag \cos (\theta - 120^\circ)} \\
\psi_{mag \cos (\theta - 120^\circ)} \\
\psi_{mag \cos (\theta - 240^\circ)} \\
\psi_{mag \cos (\theta - 240^\circ)}
\end{bmatrix}
\]  

(2)
3) Electromagnetic Torque

\[ T_{em} = p [I_d \quad I_b \quad I_q] \frac{d}{dt} \begin{bmatrix} \psi_{mag} \cos \theta \\ \psi_{mag} \cos(\theta - 120^\circ) \\ \psi_{mag} \cos(\theta - 240^\circ) \end{bmatrix} \]  

(3)

4) Motor Mechanical Equation

\[ \frac{d}{dt} \omega_m = T_{em} - T_{load} \]  

(4)

For further simplifications in order to create a dq model of the proposed double stator permanent magnet synchronous motor, it is considered the following assumptions: the high performance permanent magnets are externally installed on the outer perimeter of the rotor, being the inductances \( L_q \) and \( L_d \) approximately equal and having low values; for the maximum relationship between the current and the electromagnetic torque it is assumed \( i_0 = 0 \) in the algorithm; the control method implemented is based in the Vector Control principle, also known as RFOC (Rotor Field Oriented Control) [7].

Therefore we have the following general equations in dq components:

5) Stator Voltages

\[ \begin{cases} v_d = -w_m \psi_q \\ v_q = (R_{a, in} + R_{a, out})i_q + \frac{\delta \psi_q}{\delta t} + w_m \psi_{mag} \end{cases} \]  

(5)

6) Link Magnetic Flux

\[ \begin{cases} \psi_d = \psi_{mag} \\ \psi_q = L_q i_q \end{cases} \]  

(6)

7) Electromagnetic Torque

\[ T_{em} = 3/2(p)(\psi_d i_q) \]  

(7)

8) Motor Mechanical Equation

\[ \frac{d}{dt} \omega_m = T_{em} - T_{load} \]  

(8)

B. Commercial Variable Speed Drive

The electronic speed drive unit chosen to supply and control the proposed electric motor is from the Schneider Electric Altivar 71 series, which are created and conceived to special and complex applications like the electric vehicles, due to its high flexibility and performance. In terms of technical specifications this solution has permanent magnet synchronous motor compatibility, high dynamic response, a vector control algorithm with constant torque control, among other advantages. In figure 3 it is shown a picture of one of such devices.

![Fig. 3 Schneider Electric Altivar 71](image)

1) Altivar 71 Technical Characteristics

Within the wide range of products of the Altivar 71, the variant designated ATV71HD45N4 with a nominal power 45 kW or 60 hp is selected, because it is in accordance with the typical power of a wide range of electric vehicles. Table I presents the nominal parameters of the proposed Altivar unit.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Designation</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>Three Phase Voltage</td>
<td>380 V (-15%) to 480 V (+10%)</td>
</tr>
<tr>
<td>S</td>
<td>Apparent Power</td>
<td>68.50 kVA</td>
</tr>
<tr>
<td>P</td>
<td>Active Power</td>
<td>45 kW (60 hp)</td>
</tr>
<tr>
<td>I_{min}</td>
<td>Maximum Continuous Current</td>
<td>94 A</td>
</tr>
<tr>
<td>I_{max, 2sec}</td>
<td>Maximum Current for two seconds</td>
<td>155 A</td>
</tr>
<tr>
<td>T_{max, 2sec}</td>
<td>Overload Torque for two seconds</td>
<td>220 % of Nominal Torque</td>
</tr>
<tr>
<td>f_{IGBT}</td>
<td>IGBT adjustable switching frequency</td>
<td>1 to 16 kHz</td>
</tr>
</tbody>
</table>

2) Vector Control or Rotor Field Oriented Control

The proposed control method is the Direct Rotor Field Oriented Control, in which the torque control is performed through the speed control for any external load conditions. In figure 4 it is illustrated the field oriented control diagram adjusted to the present work, where it can be seen the two closed control loops. The inner one is for torque control, which is subordinated to the outer closed speed control loop that is directly commanded by the user by setting the machine speed. The Direct Control variant within the RFOC is used in this work, because electric vehicles usually operate within high and medium speed ratings. One advantage of this control...
variant is that the machine parameters are kept constant during motor working conditions.

As it is shown in the figure 4, the electric motor is controlled directly by a closed loop torque having current regulation, commanded by the speed controller outer closed loop. In this way, the ATV 71 will control the electric motor with a set of command stator voltages in order to impose the adequate running conditions to the motor obtaining high dynamics performances according to the load demands.

Mechanical speaking, the system behavior follows the block diagram illustrated in figure 5.

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**A. Electric Speed Drive**

The electric speed drive model was created to behave like its real counterpart system, the ATV71HD45N4, designed and created to work in most case scenarios, both in constant and dynamic regimen, with fast and smooth responses to different loads and unexpected external perturbations. Combined with the PI speed controller and the PWM inverter, the vector controller is the main component of the control algorithm, which block diagram is represented in figure 7.

![Fig. 4 Direct Rotor Field Oriented Control diagram](image)

**B. Double Stator Permanent Magnet Synchronous Motor**

In a similar way to that of the control drive unit, a model of the double stator permanent magnet synchronous motor was created which is shown in figure 8. Comparing with the first approach in the previous section, the Simulink model proposed is more complex because the outer and inner stators are not connected in series, but on the other hand, they have independent supply circuits. In this way it resembles as real as possible a real double stator electric motor in order to simulate...
its full potential.

![Diagram of Double Stator Permanent Magnet Synchronous Motor model.](image)

Fig. 8 Double Stator Permanent Magnet Synchronous Motor model.

In figure 8 to simulate the electric equations there are two blocks designated by “Outer Stator q axis Block” and “Inner Stator q axis Block”, where the q axis current component is calculated for each stator. The block that describes the mechanical component will determine the variables needed for the speed and torque control.

C. Simulation Results

For system performance and behavior analysis, several simulations were done in order to simulate real test conditions, with step and slope type speed commands with various load torque demands. Also the system response to unexpected disturbances were studied, particularly electromagnetic torque anomalies inside the vector controller due to external or/and internal perturbations and short circuit tests to both stators separately. From many tests done to the system, the following two were chosen for this work: a starting and speed slope command and an inner stator short circuit, both with nominal load torque conditions. For each simulation test, it is shown the motor speed, both electromagnetic torque and its reference calculated by the vector controller, outer and inner stator currents responses, respectively.

1) Starting and Slope Speed Command

This simulation consists in a slope speed command type, with three steps. The first one is a starting procedure up to 100 rpm from 100 to 1000 ms, followed by a speed increase to 500 rpm from 2 to 2.5 s, and finally the last speed increase to 1000 rpm from 3.5 to 4 s, always with a nominal load torque demand.

In figure 9 it is shown the motor speed response to the above commands. Figure 10 shows both the electromagnetic torque develop by the motor (green curve) and the reference torque calculated by the speed controller (blue curve) to be the input of the vector controller. In figure 11 and 12 it is shown the outer and inner stator currents behavior respectively.

The system’s mechanical component reacts very quickly and also smoothly to the various speed commands with a nominal torque, without speed static error. The electromagnetic torque (green curve) follows the electromagnetic reference (blue curve) with accuracy and without saturating itself. The same non saturating behavior can be observed for both stator currents.
2) Inner Stator Short Circuit System Response

With this simulation it is observed the system behavior to a short circuit in the inner stator wirings and consists in a slope speed command type, with two steps. The first one is a starting up to 60 rpm from 100 to 500 ms, followed by a speed increase to 120 rpm from 1.5 to 2 s, always with a nominal load torque demand. The short circuit is forced in the inner stator wiring system at 1s.

In figure 13 it is shown the motor speed response to the above commands, while figure 14 shows both the electromagnetic torque develop by the motor (green curve) and the reference torque calculated by the speed controller (blue curve). In figure 15 and 16 it is shown the outer and inner stator currents behavior, respectively.

As it was expected, after the short circuit instant the speed motor drops very quickly and the inner stator currents as well as the electromagnetic torque developed by the motor increase instantly to a high peak saturated value. In opposition, the outer stator currents in order to balance the system instability that follows the short circuit, present a high value commanded by the vector controller. After the perturbation, only the outer stator contributes to the electromagnetic torque that drives the motor.

IV. Conclusion

In this work a detailed model of the electric system constituted by a commercial variable speed drive and double stator permanent magnet synchronous motor was developed and studied by several real condition type tests in Matlab®/Simulink simulation environment. Throughout the simulations done with step and slope speed commands, from starting to high speed operating conditions and nominal load torque levels, the system responds very quickly and smoothly with low oscillations and without static errors involved, which are important requirements for electric vehicles. Electromagnetic and electric perturbations were also tested separately in each stator, in order to simulate possible real mechanic and/or electric malfunctions that might damage the electric drive system.

For nominal load torque when starting and low speed ratings, which are very common in real operation of an electric vehicle, the electromagnetic torque and electric currents do not reach the saturation values. This system also behaves saving energy stored (battery bank) on board of the electric vehicle and avoiding high level starting current levels that happen very often in conventional drive systems.

A particularity of the studied motor combined with the RFOC speed drive unit is when it suffers an external or internal perturbation to the system and in order to minimize the negative consequences to the system’s mechanical variables, such as the motor speed and the electromagnetic torque, each stator component will separately contribute to it by changing its own electric current amplitude and frequency. On the other hand, if a single stator permanent magnet synchronous motor had been subjected to a perturbation of the same nature, that for some reason might disable the electric stator terminals, the consequences might be certainly negative and unexpected to both the system and user safety.

The system advantages and characteristics studied in this work will certainly be useful and important to any real electric vehicle, enhance the global energy efficiency, resilience to
electric and/or mechanical perturbations and also to increase the useful vehicle autonomy.

REFERENCES


