Hybrid Excitation Synchronous Motor Control with a new Flux Weakening Strategy

Laid KEFSI*, Youssef TOUZANI*, Mohamed GABSI**
*IFP, Rueil Malmaison, France, e-mail: laid.kefsi@ifp.fr , youssef.touzani@ifp.fr
**SATIE, ENS Cachan, France, e-mail: gabsi@satie.ens-cachan.fr

Abstract — **Permanent magnet synchronous motors (PMSM) have been developed for numerous applications due to their attractive features especially after the development of rare earth permanent magnet materials as NdFeB or SmCo. However, the magnets on the rotor accentuate the thermal constraints and limit the high speed operation. To eliminate these drawbacks, a new Switching Flux Synchronous Motor with Hybrid Excitation (SFSMHE) is developed. With the hybrid excitation (coil and magnet), we have an extra degree of flexibility and hence an improved torque-speed characteristics to meet HEV operating constraints. This paper deals with a new method of a torque control and flux weakening of SFSMHE, for electric/hybrid vehicles traction drive conditions. The principles, control structures, simulation and experimental results are given.**

Keywords — **Hybrid excitation, PMSM, Hybrid Vehicles HEV, Field Oriented Control, flux wreaking.**

I. Introduction

The development of hybrid electric vehicles (HEV) is proceeding rapidly. High starting torque and a wide constant power speed area characterize the electric drive of an HEV. Widely used electrical machine for this purpose is the Permanent Magnet Synchronous Motor (PMSM). The PMSM offers high power factor, efficiency and high torque density, but has high cost [1], difficult to cool the magnets, and the flux weakening is limited by the constant flux of the magnets.

The aim of flux weakening is the optimal setting of the direct current to reach the highest power and efficiency of a PMSM drive during flux weakening operation. There are many ways of implemeting flux weakening. Some interesting solutions are given in papers [1][5].

In this objective, and for operating with a maximum torque to current ratio, the reluctance torque cannot be neglected, therefore the d-axis current will not be equal to zero even in the constant torque area. The reluctance torque is proportional to the product of the direct and quadrature axis currents. Therefore, given a d-axis current unequal to zero, the system to be controlled is nonlinear and the strict separation between flux generating and torque generating currents is not possible.

The problem is to determine the minimal-loss d and q axis current reference values for a given rotor speed, DC bus voltage and torque reference. Because of the required constant power range, current and voltage limits have to be taken into consideration. With this method, we risk to demagnetize the magnets due to the passage of the armature reaction flux through the magnets [3]. Such solutions have been based on a new structure called "hybrid excitation motors" [4][5]. The hybrid excitation refers to the fact that in the excitation circuit of an electrical motor there are permanent magnets as the main component of the flux source and, additionally, an auxiliary excitation winding. The excitation winding is used to control the air gap field which improves flux weakening capability, and consequently the speed of the electrical drive.

In this paper we are presenting a new method of flux weakening. The aim of this method is to use the benefit of the double excitation to improve the characteristics torque-speed during flux weakening, and also reducing the disadvantages of the classical method on the motor's torque, and try to maintain the highest possible value until high speed (infinite theoretically).

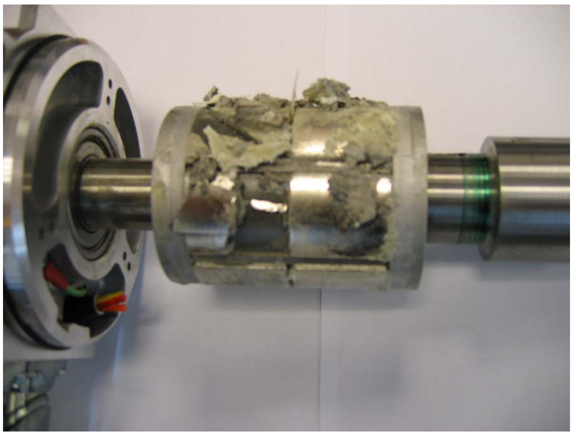

Fig 1 – Mounted PMS damage in over-speed

II. Hybrid Excited Synchronous Motor

Hybrid excitation allows, by controlling excitation flux, the design of machines with a relatively low armature magnetic reaction and, at the same time, the extension of the speed limit. Furthermore, it improves efficiency in the most frequently used operating areas of the traction motor [6]. In the SFSMHE under study, as it is shown in Fig.2, the permanent magnet and the excitation winding are placed on the stator armature, so the flux density can be controlled locally at the air gap level and the sliding contact is removed. The main disadvantage is an additional voltage source (bi-directional DC-DC converter) for the field excitation.

978-1-4244-8218-4/10/$26.00 ©2010 IEEE

In the rotor-fixed *d/q* reference frame, the voltage equations of the SFSMHE are given by :

$$v_d = R \cdot i_d + \frac{d\Phi_d}{dt} - p \cdot \Omega \cdot \Phi_q$$
$$v_q = R \cdot i_q + \frac{d\Phi_q}{dt} + p \cdot \Omega \cdot \Phi_d \qquad (1)$$

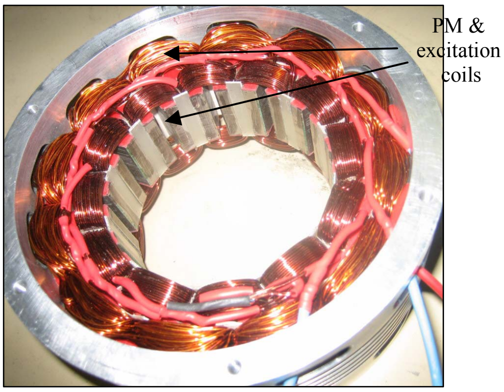

Fig 2. Stator iron core and hybrid excitation

$$V_{exc} = R_{exc} . i_{exc} + L_{exc} \cdot \frac{di_{exc}}{dt} + \frac{d\Phi_{PM}}{dt} \qquad (2)$$

For hybrid excitation, Φ_{exc} is variable and a function of the excitation current.

$$\Phi_{exc} = \Phi_{PM} + L_{exc} \cdot I_{exc} \qquad (3)$$

The motor torque is described by:

$$T = \frac{3 \cdot p}{2}(L_d - L_q) \cdot i_d \cdot i_q + \frac{3 \cdot p}{2} \cdot \Phi_{exc} \cdot i_q \qquad (4)$$

Where

u_d, u_q	*d*- and *q*-axis voltage components
i_d, i_q	*d*- and *q*-axis current components
L_d, L_q	*d*- and *q*-axis self inductances
V_d, V_q	*d*- and *q*-axis voltage components
R	Stator resistance
p	Number of pole pairs
Ω	Electrical angular velocity
$\Phi_{exc} = \Phi_f$	Excitation flux

The voltage and current limits of a SFSMHE are restricted by the following equations:

$$I^2 = i_d^{\ 2} + i_q^{\ 2} \le I_{\max}^{\ \ 2} \qquad (5)$$

$$V^2 = V_d^{\ 2} + V_q^{\ 2} \le V_{\max}^{\ \ 2} = (\frac{V_{DC}}{\sqrt{3}}) \qquad (6)$$

At the steady state and by neglecting the stator armature phases resistances, we can write equation (6) as:

$$\sqrt{(L_q \cdot i_q)^2 + (\Phi_{exc} + L_d \cdot i_d)^2} = \frac{V_{\max}}{\omega} \qquad (7)$$

Equation (7) is an ellipse with center $(-\frac{\Phi_{exc}}{L_d}, 0)$

As presented in the introduction, the Loss-minimal control of the SFSMHE is based on the utilization of the reluctance torque, it means guarantee the maximum torque to current ratio.

III. Flux Weakening Strategy

Here we are presenting a comparison between a classical flux weakening control and our new strategy using the excitation coils.

A. control strategy without excitation coils

For this first control strategy, and for getting the maximum torque at the motor starting, we take the maximum excitation flux. After measurement on the SFSMHE machine, we found that there was no significant difference between the direct and quadrature inductances. Thus, we suppose that the considering torque depend on the two parameters i_q and Φ_{exc}, see eq (4).

In Fig. 3 two constant-current circles and three constant flux circles ($L_d \approx L_q$) which correspond to the maximum allowable flux at the rotor speeds ω_1, ω_2, and ω_3, are depicted. The dashed lines are lines of constant torques.

Obviously C_1 is the maximum torque. We may have the magnitude of current I_1, but it is true up to the speed ω_2. Before this speed, we can apply all torques below C_1, and in this case, we do not need to inject the direct current i_d. Beyond ω_2, it is necessary to reduce i_q (hence torque) to provide maximum torque at each speed between ω_2 and ω_3 (we remains on the current circle between points A and E).

Finally, if we have a torque C_3 and we want greatest torques at the same speed ω_3, in this case, we will increase the current I_2 and stay on the circle ω_3 from point C to the maximum torque C_2 at point E.

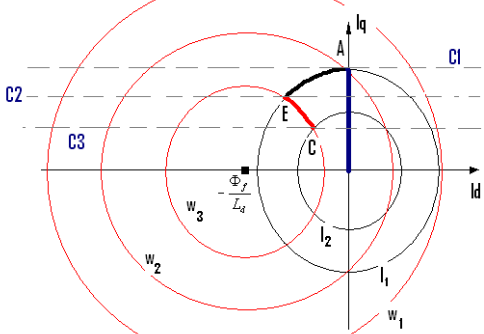

Fig 3. Torque, flux and currents in the i_d, i_q plane

We can conclude that in order to apply the previous flux weakening method for a given torque reference, we begin first by applying the current on the *q* axis, then we choose the operating point (intersection between constant current and constant flux circles) to find a suitable value of the direct current i_d by solving equation (7).

There are two major drawbacks of with this method :

- the first is rapid drop of i_q and consequently the torque for a small increase of i_d and hence speed ω_1 is close to $\omega_{\lim}$, Fig.4.
- The second problem is that we can not reach speeds above ω_{Limit}, if one wants to maintain a maximum flux (i.e the centre of the ellipse is outside the circle of maximum current, I_{Max}). In against, if we decrease the flux will not be able to achieve high torque at low speeds, Fig.4.

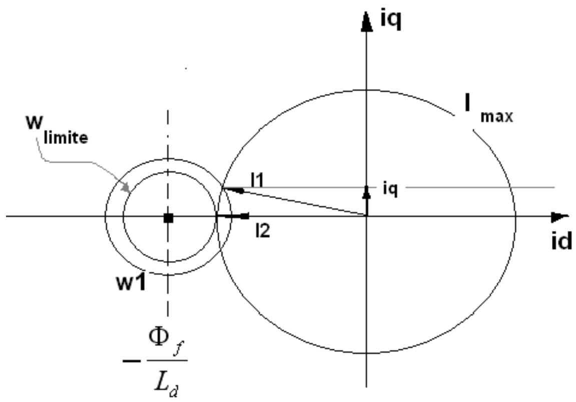

Fig. 4. Torque, flux and currents in the i_d, i_q plane

B. control strategy with the excitation coils

In this paragraph, we present a novel technique which use the benefit of the double excitation to reduce the negative impact of the previous algorithm on the machine torque and trying to maintain it the highest possible (up to infinite speeds theoretically).

As depicted on Fig.5, and for maximum torques, here the flux weakening process can be decomposed into three essential steps :

a. For speeds below rated speed, the flux weakening can be assured by using the classical method, presented above, till the optimal point "PO". Beyond this point, the use of the double excitation for weakening the flux is more effective than injecting negative i_d current. In other words, the flux weakening by using the double excitation will reduce the torque less than the classical method for the same increase in speed, for example during HEV acceleration, Fig.5.a.

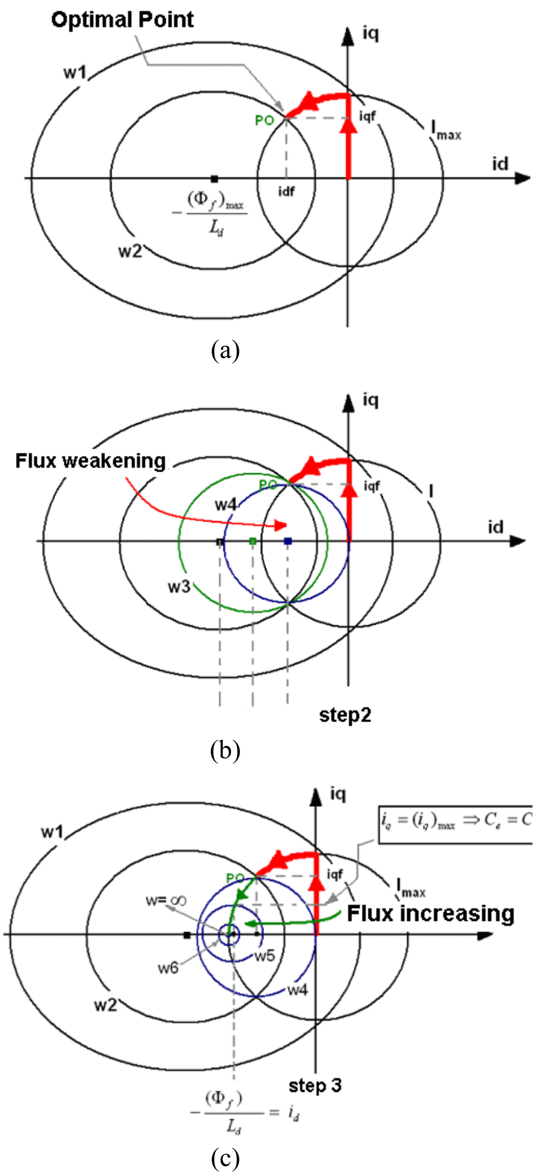

Fig. 5. Novel strategy of flux weakening

b. In the second step, and beyond the optimal point "PO", we begin by decreasing the flux Φ_{exc} while trying to maintain the value of the quadrature current i_q constant and equal to i_{q_PO} at the optimal point. That means, in this point we estimate the specific flux Φ_{exc} for all the speeds between ω_2 and ω_4, Fig5.b.

c. Beyond the speed ω_4, we can not keep the quadrature current constant ($i_q \neq cst$), and here begins the third step, were we use the both methods together. The change in the excitation flux, will keep the ellipse's centre equal to the direct current ($-\frac{\Phi_{exc}}{L_d}=i_d$). This will allow the classical algorithm to weaken the flux always with $i_q = i_{q\_Max}$ for all speeds above ω_4, because the intersection point is at the top of the ellipse. Through this step the speed go to infinite value if and only if $-\frac{\Phi_{exc}}{L_d} = I_{Max}$, Fig.5.c.

IV. Simulation and Experimental Results

We analyzed the two flux weakening control algorithms by Matlab Simulink tools. The first of them uses the classical method. The second one used the double excitation coils. Fig.6 shows the structure of the controller based Field Oriented Control "FOC". The simulations and the experimental setup have been carried out using a *1,76kW* SFSMHE motor prototype with the following parameters: nominal torque *2.8Nm*, nominal speed *6000tr/min*, nominal phase current I_{max} *=15A*, nominal excitation current *15A* and number of poles *p=10*. The model parameters are:

$R = 0.60\Omega$, $L_d = 3.73mH$, $L_q = 3.37mH$

$\Phi_{exc\max} = 0.1045Wb$, $R_{exc} = 0.77\Omega$, $\Phi_{PM} = 0.028Wb$, $L_{exc} = 5.1mH$.

For applying the classical algorithm, and for a given maximum torque ($I_{exc} = 15A$), we have calculated first the value of the current $i_q = \frac{C_e}{3/2 \times \Phi_{exc} \times p}$, and we solved the equation (8) to determine the i_d current.

$$i_d^2((p\Omega.L_d)^2 + R_s^2) + i_d(2(p\Omega)^2\Phi_{exc}.L_d + 2R_s.i_q.p\Omega.(L_d - L_q)) + 2p\Omega\Phi_{exc}.R_s.i_q + (R_s.i_q)^2 + (p\Omega)^2.(\Phi_{exc}^2 + (L_q.i_q)^2) - V_{max}^2 = 0 \quad (8)$$

The torque producing current component i_q, where its maximum value is limited to:

$$i_q = \sqrt{I_{\max}^2 - i_d^2} \quad (9)$$

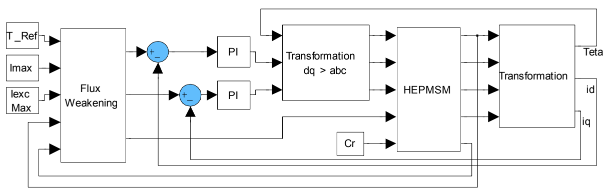

Fig. 6 FOC control with flux weakening strategy

A. Simulation results

Fig.7 presents the simulation results for a maximum torque demand under the above conditions. We can note the positive effect of this algorithm to slow the fall of the torque. But the drawbacks of the algorithm are clear beyond the rated speed, where the power drops rapidly and the final speed limited to *24,2 Hz*.

Obviously we got the required torque at low speeds. But because of the distance between the voltage ellipse (centre $-\frac{\Phi_{exc}}{L_d} \succ I_{\max}$) and the maximum current circle, the algorithm has failed to keep this torque in high speeds.

Figures 8 and 9 shows the simulation results for the optimal flux algorithm, were the excitation current was chosen to bring the voltage ellipse centre to the maximum current $(-\frac{\Phi_{exc}}{L_d} = I_{\max})$, as explained in the III-*B* paragraph, thus the machine can reach infinite speed. so we found:

$\Phi_{exc} = I_{\max}.L_d = 0.055Wb$

$I_{exc} = \frac{\Phi_{exc} - \Phi_{PM}}{L_{exc}} = 5.39\ A$

$C_{\max} = 12.3\,Nm$

The algorithm maintains constant power beyond the rated speed, which allows the machine to accelerate at high speeds, the speed reaches *4239trs/min* (*70,65Hz*) in 6 seconds.

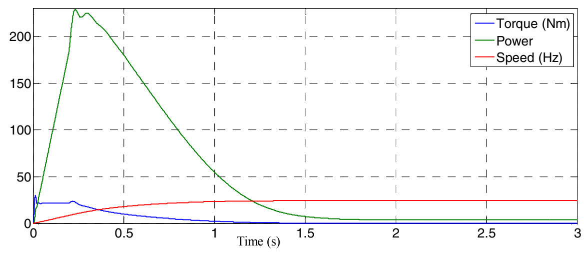

Fig. 7. Maximum torque and speed using the classical algorithm

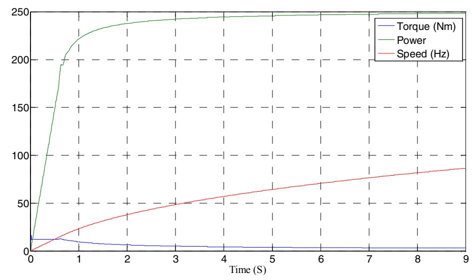

Fig. 8. Maximum torque and speed using optimum flux

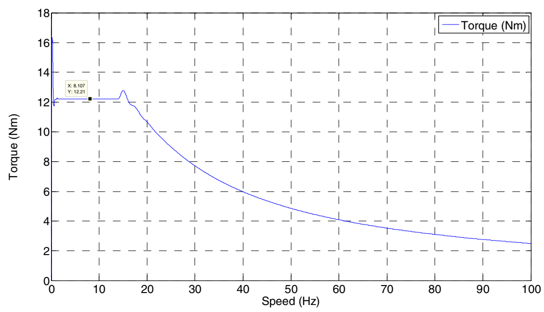

Fig. 9. Torque / Speed characteristics

For realizing our new flux weakening strategy in simulation, we used the state machine. As explained before, for the first step we use the classical method, then the double excitation, and finally both the algorithms are used. The following equation gives the condition for passing from step 1 to step 2, which described the optimal point:

$$i_q^{\ 2} L_d + \Phi_f . i_d \le 0 \qquad (9)$$

Figure 10 and 11 gives the simulation results of the new algorithm. We can notice that, the power rises much more quickly to its maximum value. Thanks to maximum torque applied at the beginning, around 22 Nm.

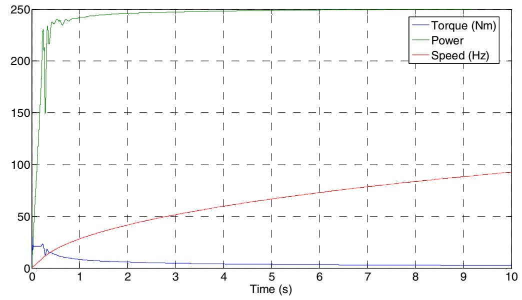

Fig. 10. Torque / Speed characteristics in the second method

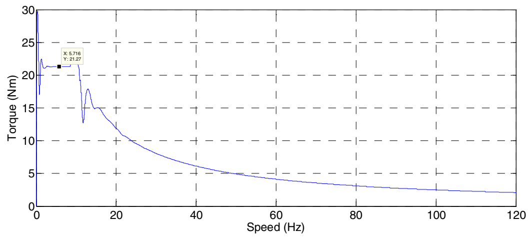

Fig. 11. Torque / Speed characteristics in the second method

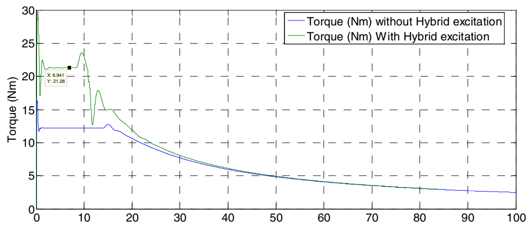

Fig. 12. Torque / Speed characteristics in the second method

Fig.12 depicts a comparison between the two flux weakening methods. The torque is much in our new method, for speeds below rated speed.

B. *Experimetal Results*

The experimental setup is a Hybrid Excitation Synchronous Motor in the Loop Fig 13, consists of two electrical machines, mechanically coupled. One is the SFSMHE under observation with an incremental encoder 4096 points, and the other acts as a load to simulate an electrical or hybrid vehicle, a three-phase 2-level IGBT inverter (400VDC) with current and voltage sensors, a high speed acquisition system, a buffer card for gate signal conditioning with incorporated dead time, a DC-DC converter (500W) for the double excitation, and a battery simulator. All the experimental results will be included in the final presentation.

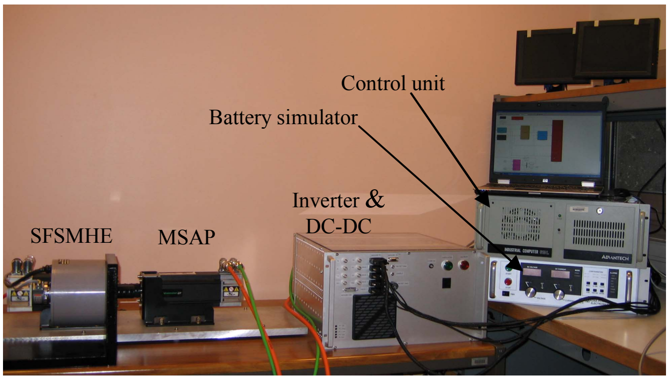

Fig. 13. Experimental setup

V. Conclusions

The study presented in this paper has shown the benefit of hybrid excitation synchronous machines for hybrid and electric traction systems. Advantages and drawbacks of different flux weakening strategies have been also discussed. Simulation confirmed the advantages of an additional degree of freedom offered by hybrid excitation and by the new flux weakening strategy . To complete this study and draw final conclusions concerning advantages of hybrid excitation and our new flux weakening strategy for hybrid and electric traction applications (improve efficiency in regions where electric drives are operating most of the time, which enhance autonomy for electric vehicles and reduce fuel consumption for hybrid vehicles), no load and on-load tests on torque/speed characteristics will be carried out and will be presented in the final presentation.

References

[1] Michael Meyer, Joachim Böcker, "Optimum Control for Interior Permanent Magnet Synchronous Motors (IPMSM) in Constant Torque and Flux Weakening Range" EPE-PEMC 2006, Slovenia, pp 282-286.

[2] Radovan D, Jaroslav N and Ondrej C, "Traction Permanent Magnet Synchronous Motor Torque control with Flux weakening" Radioengineering, VOL 18, NO.4 Dec 2009.

[3] Y. Amara, K Oujehani, E. Hoang, M. Gabsi, " Flux Weakening of Hybrid Synchronous Machines" Proc. IEEE IEMDC'2001, Cambridge, Massachusetts, USA (2001), pp. 367-373.

[4] L. Vido, Y. Amara, M. GABSI, , M. Lécrivain, F chabot "Compared performances of Homopolar and bipolar Hybrid excitation synchronous machines" ICEM, Cracow, Poland, September, 2004

[5] X.P Liu, H.Y Lin, Z. Q. Zhu, C. F. Yang, S. H Fang, and J Guo " A Novel Dual-Stator Hybrid Excited Synchronous Wind Generator" IEEE TRANS ON Industry Applications, VOL. 45, pp 947-953, NO. 3, May-June 2009.

[6] Y. Amara, L. Vido, M. Gabsi, E. Hoang, A. H Ben Ahmed, and M. Lécrivain, "Hybrid Excitation Synchronous Machines: Energy-Efficient Solution for Vehicles Propulsion", IEEE Trans on Vehicular Technology, Vol. 58, N0.5, pp 2137-2149, June 2009.

[7] L. Vido, Y. Amara, E. HOANG, M GABSI, F chabot, M. Lécrivain, "Comparison and Design of interior permanent magnet synchronous machines for a hybrid vehicle application: International Conference on Electrical Machines ICEM, Cracow, Poland, September, 2004.

[8] Z. Q. Zhu, Y. S. Chen, and David Howe, "Online Optimal Flux-Weakening Control of Permanent-Magnet Brushless AC Drives, IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. 36, NO.6, pp 1661-1668, Nov 2000.