HYBRID SYNCHRONOUS MOTOR WITH FLUX WEAKENING WINDING

Abdellatif MIRAOUI
L^{2E}S, Parc Technologique, 2
Avenue Jean Moulin, 90000
Belfort, France,
abdellatif.miraoui@utbm.fr

Ioan Adrian VIOREL
Technical University of Cluj
Depart. of Electrical Machines
3400 Cluj, Daicoviciu 15, Romania
ioan.adrian.viorel@mae.utcluj.ro

Daniel FODOREAN
Technical University of Cluj
Depart. of Electrical Machines
3400 Cluj, Daicoviciu 15, Romania
daniel.fodorean@mae.utcluj.ro

ABSTRACT

This paper deals with the design of the synchronous motor with permanent magnet and flux weakening excitation winding. Two-dimensional finit element model of the machine has been developed to evaluate the double excited motor's performances.

1. INTRODUCTION

The possibility of not taking into account the mechanical parts used for transmission, reduction, made from the direct drive system the last simplification in energy conversion. The increasing demand for solution of the environmental problems due to pollution leads to new drives vehicles. Only electrical vehicles fulfill zero emission requirements. The development of electrical propulsion vehicles is very heavily linked to optimising the performance, autonomy, and cost. Both, permanent magnet synchronous motor drives as well as induction motor drives are suitable for propulsion of electrical car. But only the synchronous machine with permanent magnets provides the advantages of high torque/mass ratio, simplicity in building the rotor (no windings, no sliding contact), and therefore, an enhanced level of reliability. The difficulty with respect to the permanent magnet machines lies in controlling the magnetic flux, in particular for high-speed operations or in discharge alternators on the diode rectifier. For the motor driven operating mode, flux weakening is accomplished by applying a large demagnetizing current on the d-axis of the permanent magnets.

An adequate field weakening can be achieved also with PMSM with small number of poles producing extra stator negatives currents into the direct axis of the machine. With a high number of poles the volume of the machine can be drastically reduced. That imposes a high frequency supply converter (for example with IGBT's by 10-20 kHz) but the direct reactance (x_{d0}) is too small and a large flux weakening range is not possible. For this reason an auxiliary excitation winding is needed in the rotor (or stator) armature to reduce directly the flux in the machine and reach the high speed.

This paper is concerned with the design (including FEM analysis) and initially results of a permanent magnet synchronous motor with auxiliary winding. The term of double-excitation (hybrid) indicates that these machines make use of two inductor circuits: one with permanent magnets and the other with excitation windings. In what follows, the principle behind such machines will be laid out.

2. PROPOSED DOUBLE EXCITED SYNCHRONOUS MOTOR

Generally, the choice for an electrical machine used in a direct drive system or the choice of an excitation circuit (series or parallel) in a situation with double excitation, is made by taking into account the application and the particular needs, like increasing the speed domain. In this case, for an in-wheel motor with an outer rotor, the series excitation circuit is, for a first view, a good choice. In what will follow it will be presented the proposed solution and after that the performances for this structure will be evaluated.

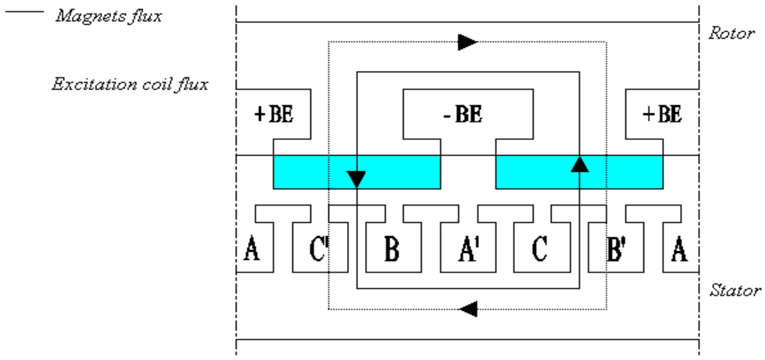


Fig. 1. The proposed double excitation solution

In figure 4 is given the proposed double excitation solution, with the outer rotor. Supplying the excitation coil with a current that creates a flux who flows against the permanent magnets flux, the flux-weakening regime is obtained. The stator and the rotor armature are made of quality steel. Because of a series excitation circuit, the air gap flux weakening is local and global also. The iron losses for a first harmonic model are decreasing, which is an advantage for this solution.

3. ANALITYCAL MODEL

It is generally recognized that the sizing equation for designing an electrical machine is given by the air gap diameter equation.

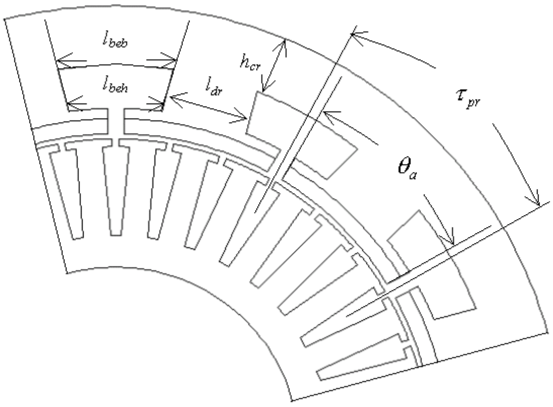


Fig. 2. Motor's geometry

Starting from the designing data, the output power P_2=*550 W*, the speed *n=200 tr/min*, supply voltage from a 36 V battery, using a proper magnet for such an applications, *Nd-Fe-B* (B_r=*1,15T*, μ_r=*1,05*, H_c=*880 kA/m*), and choosing the proper electrical loading, A_s=*7500 Am* , we can develop the geometry of the studied synchronous double excited in-wheel motor:

- *air gap diameter*:

$$D_g^3 = \frac{2 \cdot p \cdot P2}{\pi \cdot m \cdot As \cdot Ke \cdot Ki \cdot Kp \cdot Kl \cdot \eta \cdot Bg \cdot f_s} \tag{1}$$

where K_e, the emf factor, K_i, current wave form factor K_p, electrical power wave form factor, K_l aspect ratio coefficient.

- *effective air gap*:

$$g_{ef} = g + \frac{h_m}{\mu_{ra}} \tag{2}$$

- *Carter's coefficient*:

$$k_c = \frac{\tau_d}{\tau_d - \frac{4}{\pi} \cdot \left[\frac{l_{so}}{2 \cdot g_{ef}} \cdot \arctan\left(\frac{l_{st}}{2 \cdot g_{ef}}\right) - \ln\left(\sqrt{1 + \left(\frac{l_{so}}{2 \cdot g_{ef}}\right)^2}\right) \right] \cdot g_{ef}} \tag{3}$$

where l_{so} and l_{st} represents the width of a stator slot opening and slot top respectively, τ_d, is the stator tooth pitch.

- *the air gap for calculus* :

$$g_c = g + (k_c - 1) \cdot g_{ef} \tag{4}$$

- *flux density in the air gap*:

$$B_{gc} = \frac{B_r \cdot \frac{h_m}{\mu_r}}{g_c + \frac{h_m}{\mu_r}} \tag{5}$$

where h_m is the permanent magnet's height.

- *phase resistance and excitation coil resistance*:

$$R_{ph} = \frac{\rho_{cu} \cdot l_{ph} \cdot N_{ph}}{S_c} \tag{6}$$

$$R_{ec} = \frac{\rho_{cu} \cdot l_{ec} \cdot N_{ec}}{S_{cec}}, \qquad (7)$$

where l_{ph}, l_{ec}, and N_{ph}, N_{ec} are the length for the stator and the excitation coil respectively and the number of turns.

- *stator and rotor leakage reactance*:

$$X_{\sigma s} = 4 \cdot \pi \cdot f_s \cdot \frac{N_{ph}^2}{q} \cdot \mu_0 \cdot L_s \cdot \Sigma \lambda_s \qquad (8)$$

$$X_{\sigma r} = 4 \cdot \pi \cdot f_s \cdot \frac{N_{ec}^2}{q} \cdot \mu \cdot L_r \cdot \Sigma \lambda_r \qquad (9)$$

where λ_s and λ_r are the stator and rotor permeances respectively.

- *the iron losses*: $$p_{fer} = p_{hys} + p_{ed} \qquad (10)$$

where p_{hys} and p_{ed} are the hysteresys and eddy current losses.

- *Joule effect losses*: $$P_J = m \cdot R_{ph} \cdot I_{ph}^2 + R_{ec} \cdot I_{ec}^2 \qquad (11)$$

- *the electrical power*: $$P_1 = mV_{ph}\left(I_{qs}\cos\delta - I_{ds}\sin\delta\right) + V_{ph}\left(I_{qr}\cos\delta - I_{dr}\sin\delta\right) \qquad (12)$$

where δ is the load angle.

- *the mechanical power*: $$P_2 = P_1 - \sum P \qquad (13)$$

where ΣP represents the total losses.

The main design data, the main dimensions and the performances of the designed machine are given in Table 1:

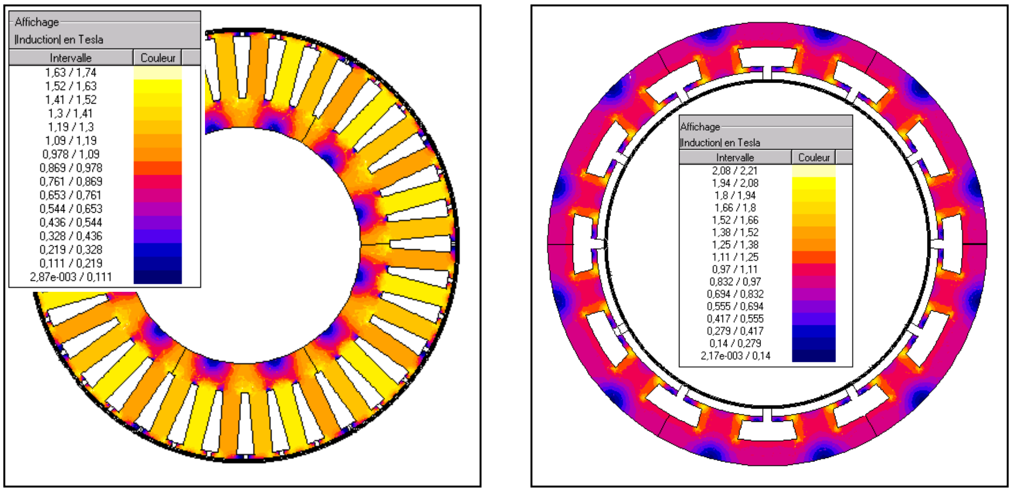
Table I.

1	Output power	550 W
2	Mechanical speed	200 RPM
3	Battery voltage	36 V
4	Nominal current	10.8 A
5	Nominal torque	26 Nm
6	Number of phases	3
7	Outer rotor's diameter	210 mm
8	Outer stator diameter	170 mm
9	Air gap	1 mm
10	Magnet height	3 mm
11	Stator phase resistance	0.303 Ω
12	Excitation coil resistance	0.97 Ω
Flux-weakening regime		
13	Motor's efficiency	67.8 %
14	Power factor	0.83
Without flux weakening		
15	Motor's efficiency	73 %
16	Power factor	0.68

4. FEM RESULTS AND CONCLUSIONS

For the validation of the analytical model the magnetic field computation software*Flux2D* has bees used. After creating the geometry, defining the material properties for each part of the machine and starting the solving process the following results has been obtained:

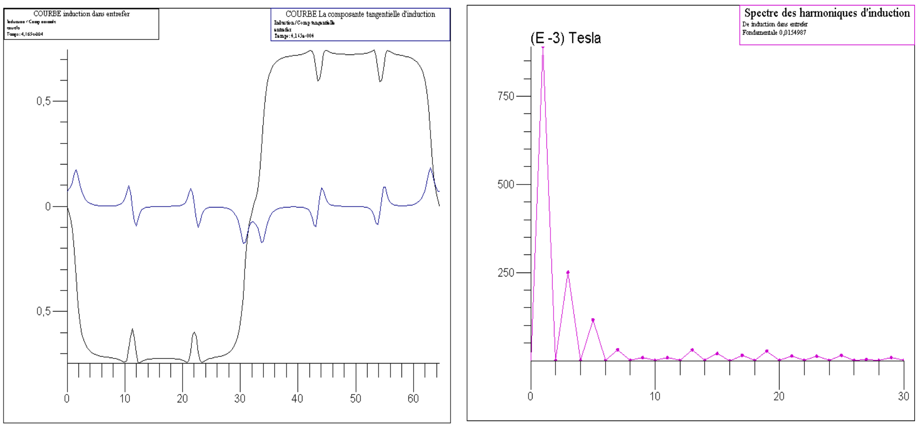
- *flux density repartition in different parts of the machine*:



(a) (b)

Fig. 3. Flux density in stator(a), rotor(b)

- *normal and tangentia* *y in flux-weakening regime*:



(a) (b)

Fig. 4. Normal and tangential component (a) and the harmonics of flux density in the air gap (b)

- *motor torque for the sixth part of the machine, on the flux-weakening regime*:

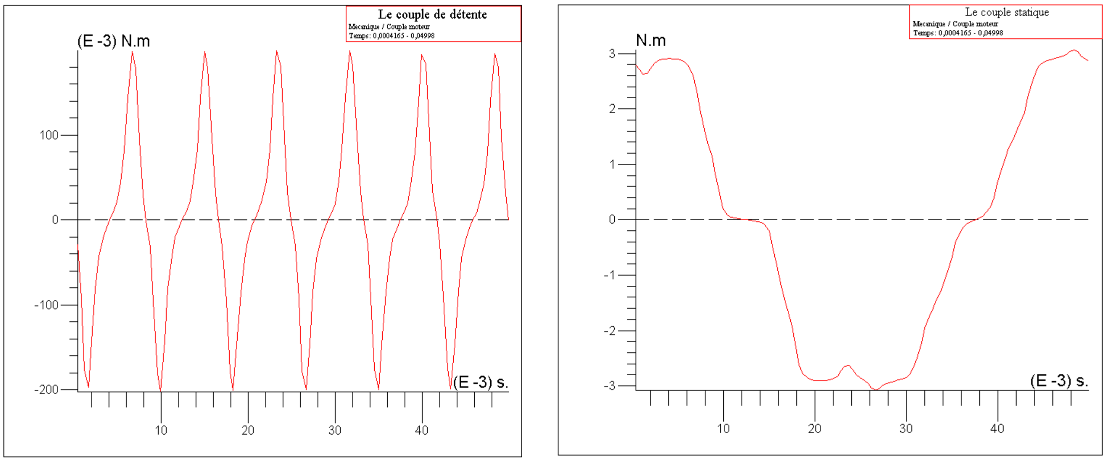


Fig. 5. Motor torque on no load (a) and on rated load (b)

- *speed-torque characteristics*:

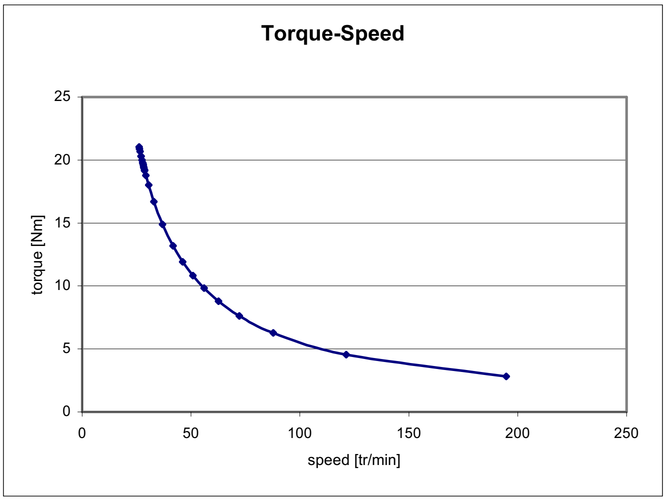


Fig. 6a. Speed-torque characteristic on normal operating

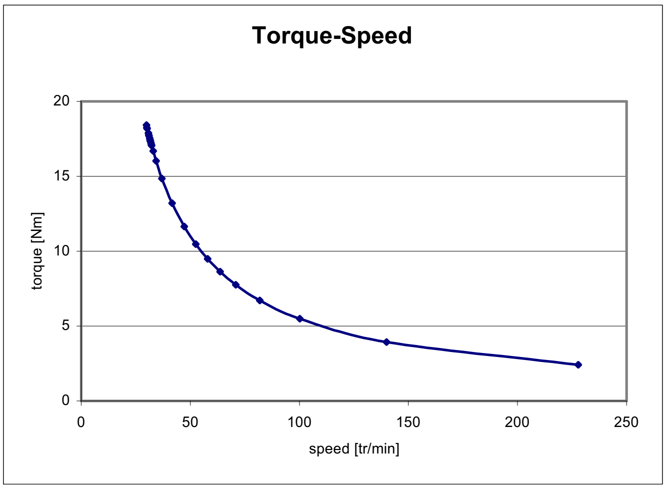


Fig. 6b. Speed-torque characteristic on flux-weakening operating

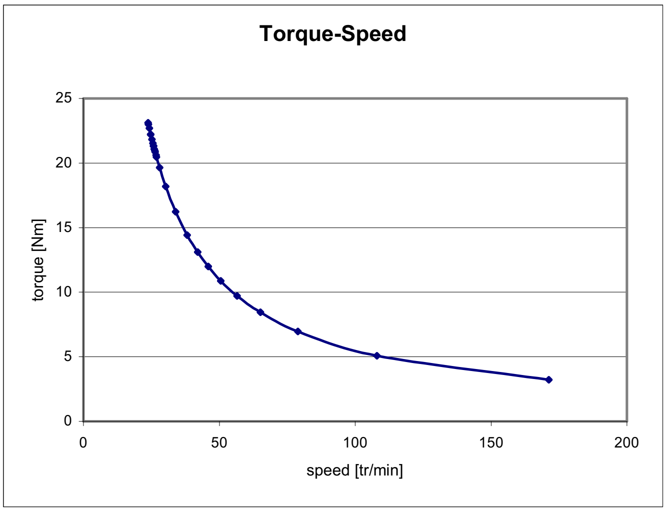


Fig.6c. Speed-Torque characteristic on flux strengthening

The FEM analysis shows a good concordance with analytical results. The air gap flux density value, in the case of analytical model is 0.84T, and from FEM model resulted a maximum value of 0.85T. In safe operating conditions, eliminating the demagnetization effect, is obtained a plus of 13% speed in the flux-weakening regime. One can see also that in the case of flux weakening, the motor's efficiency decreases, because of joule losses, which are increasing.

In conclusion, the double excited machines can be a good choice for a direct drive system. The flux-weakening regime benefits of the advantage of permanent magnets motors efficiency and of the possibility to extend the speed domain by using an excitation coil.

5. REFERENCES

[1] Y. Amara: *Contribution à la conception et à la commande des machines synchrones à double excitation. Application au véhicule hybride*, Thèse de Doctorat, Université de Paris, 2001.

[2] C. Espanet: *Modélisation et conception optimale de moteurs sans balais à structure inversée. Application au moteur-roue*, Thèse de Doctorat, Université de Franche-Comté, 1999.

[3] G. Henneberger – J. R. Hadji-Minaglou – R. C. Ciorbă: Design and test of permanent magnet synchronous motor with auxiliary excitation winding for electric vehicle application, in:*Proceedings of the European Power Electronics Chapter Symposium*, Lausanne, October, 1994, pp. 645-649.

[4] S. Huang – J. Luo – F.Leonardi: *A general approach to sizing power density equation for comparison of electrical machines*

[5] A. Lange, W.– R. Canders – F. Laube: Comparison of different drive systems for a 75 kW electrical vehicle drive, in: *Proceedings if the ICEM '2000 International Conference*, Helsinki (Finland), August, 2000, vol. 2, pp. 1308-1312.