Optimal Design of a PMSM Using Concentrated Winding for Application Urban Hybrid Vehicle

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Abstract—**This paper deals with a design method of an external permanent magnet (PM) synchronous motor (PMSM) using concentrated winding (wound around one tooth). The machine is used for the electrical motorization of a small urban hybrid vehicle. Such an application leads to strong design constraints, such as weight limitation, high starting torque, compactness etc. To achieve the design of the machine, an optimization software using SQP method (Sequential Quadratic Programming) is used. The PM synchronous in-wheel motor using concentrated winding is successfully designed: the in-wheel motor, integrated in a standard 15'' rim, is able to provide a peak torque of 240 N.m, a peak power of 4,5 kW and a maximal speed of 616 rpm without reduction gear. The optimized motor validation with the finite-element method (FEM) and the discussions about the results are finally presented.**

Keywords– **Optimization, PM, PMSM, concentrated winding, in-wheel motor.**

I. INTRODUCTION

The design problem of an in-wheel PMSM for the motorization urban hybrid vehicle is addressed in this paper. The motor has a reverse structure with an outer rotor, since it is used as in-wheel motor [1-2] in the back wheels of the vehicle (see Figure 1). A design of a PMSM using distributed winding has been already presented for this application in [3]. In this paper, we investigate the design of a machine using concentrated windings, which are wound around one tooth [4-6] (see Figure 2). The use of concentrated windings in PMSM has several advantages: the back electromotive force (EMF) is rather sinusoidal, the cogging torque is small and the slight volume of copper makes it possible to reduce the copper losses. Otherwise, it can also be noticed that PM machine using concentrated windings have some drawbacks compared to a traditional machine with overlapped windings: the eddy-currents losses in the magnets and the variations of magnetic forces on the stator teeth can be potentially high. The last point can be at the origin of excessive vibrations and acoustic noise in the motor.

Concerning the motor design, a classical optimization algorithm is used: the SQP (Sequential Quadratic Programming) method [3, 7]. This algorithm is applied by the way of the commercial software Pro@Design. The main interest of this software is that the input is simply an analytical model of the system to design (in our case the electrical motor). Then the software calculates *automatically* the *symbolic* expressions of the gradients of the parameters, leading to precise evaluation of these last and avoiding the classical numerical problem of convergence obtained when the gradients are numerically evaluated.

Thus an analytical model of PMSM is required. Since the constraints are various, the model should be rather a multi-physical one and it is easier to elaborate such a model with an analytical approach than with a numerical one.

In this paper, first, the use of in-wheel motor for the electrical motorization of a small hybrid vehicle is introduced. A brief description of the PMSM analytical model, which has been used for the design, is presented next. Then, the motor design using SQP method is carefully described. Finally, the motor performances are confirmed with 2D FEM simulations. The discussions of the results are also presented.

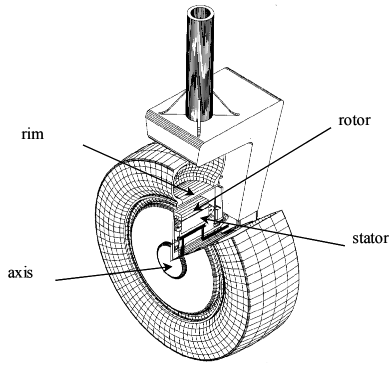

Figure 1. An example of a 18 kW brushless DC in-wheel motor (prototype Novelté Systeme/ENISYS Departement).

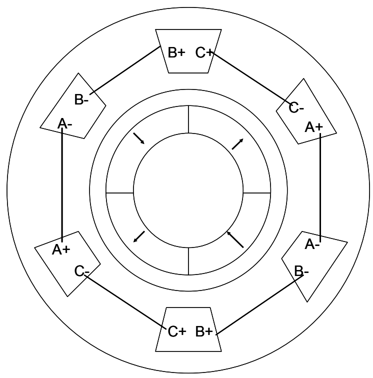

Figure 2. An example of concentrated windings with double layer.

II. Characterization of Electrical In-wheel Motor

The use of in-wheel motor for the electrical motorization drives has been presented in [1, 2]. It is possible to integrate the motor directly in one or several wheels, with or without a gear box. This solution is named *in-wheel motor* or *hub-motor* (see Figure 1).

The small hybrid vehicle considered in this paper has a simple structure. Two electrical motors are integrated in both back wheels, and ensure the propulsion of the rear wheel axle. A heat engine ensures the traction of the front wheel axle. A pack of ultra-capacitors and batteries is used as power/energy supply and the energy management is achieved with an electronic control.

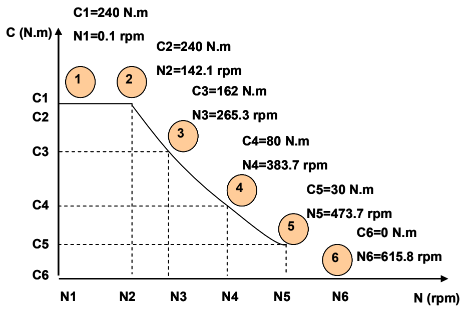

Figure 3. Characteristic electromagnetic torque versus speed of electrical motor.

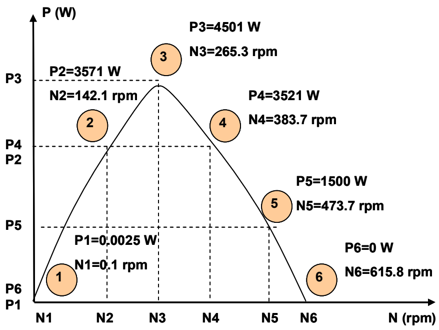

Figure 4. Characteristics power versus speed of electrical motor.

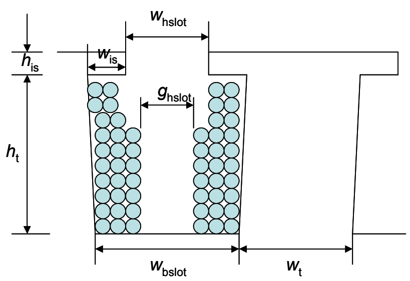

Figure 5. Geometric dimension of one slot in concentrated winding.

The Figures 3 and 4 present the mechanical characteristics of the two in-wheel electrical motors, i.e., the electromagnetic torque and the power versus speed. Theses curves come from a complete simulation of the vehicle for specific profiles given by the vehicle manufacturer. For example, the following characteristics are required:

- Acceleration from 0 to 45 km/h on flat ground needs to be achieved in at least at 10 sec;

- Acceleration from 0 to 10 km/h on a slopping road of 16 % needs to be achieved in less than 6 sec;

- The vehicle is able to start on a sloping road of 8 % and to achieve the speed of 30 km/h on the same slope;

- Etc.

III. Analytical Model of the PMSM using Concentrated Winding

In this section, we describe shortly of the analytical model of PMSM using concentrated winding. The model is elaborated for a machine with an outer rotor motor. The analytical model contains geometrical, electrical, thermal and magnetic equations of the PMSM.

Geometrical Equations:

These equations calculate the geometrical parameters and the mass of different parts of the machine. For example, the space between two parts of conductor in one slot of machine is computed by:

$$g_{bslot} = w_{bslot} - 2 \cdot n_{lay} \cdot S_{cond} \tag{1}$$

where w_{bslot} is the width on the bottom of a slot (see Figure 5), n_{lay} is the number of layer in the winding and S_{cond} is the conductor surface.

The surface of the copper in a slot is computed by:

$$S_{cop} = 2 \cdot ns \cdot S_{cond} \tag{2}$$

where ns is the number of turns in series in one phase.

The mass of the copper in one slot is:

$$m_{cop\_s} = 2 \cdot l_{iron} \cdot S_{cond} \cdot Nt \cdot mv_{cop} \tag{3}$$

where l_{iron} is the length of stator iron, Nt is the number of teeth and mv_{cop} is the copper specific mass.

The mass of copper in the winding overhang is:

$$m_{cop\_ew} = l_{ew} \cdot S_{cond} \cdot ns \cdot Nt \cdot mv_{cop} \tag{4}$$

where l_{ew} is the length of winding overhang in the axial direction of the stator.

The total copper mass is then computed as:

$$m_{cop} = m_{cop\_s} + m_{cop\_ew} \tag{5}$$

The filling factor of the copper in one slot is expressed as following:

$$Eff\_r\_cop = \frac{m_{cop\_s}}{m_{cop}} \tag{6}$$

The weight of the other parts of the machine is also computed. For example, the magnets weight is computed as a function of the outer and the inner radius Rr, Ra the magnets length l_{mag} and the specific mass of the magnets mv_{mag}:

$$m_{mag} = p \cdot \pi \cdot \alpha_m \cdot \left(Rr^2 - Ra^2\right) \cdot l_{mag} \cdot mv_{mag} \tag{7}$$

where p is the number of pole pairs in the machine.

The motor total weight is the sum of all parts in the motor:

$$m_{mot} = m_t + m_{cop} + m_{stat} + m_{rot} + m_{mag} \tag{8}$$

where m_t, m_{stat} and m_{rot} are respectively the mass of the teeth, the stator and the rotor of the machine.

Magnetic Equations:

Magnetic equations describing the magnetic behavior of the machine are also computed. The basic of those equations is the resolution of the Maxwell equations in the air-gap and the PM using the variable separation. Then all the magnetic parameters can be deduced form the knowledge of the vector potential. For example, the magnetic flux through the stator surface is calculated knowing the expressions of the vector potential created by the PMs:

$$\Phi_{stat}(Ta) = 2 \cdot l_{iron} \cdot \left(A^I_{mag}\left(Rsc, 0, \frac{\pi}{p}, Ta\right) - A^I_{mag}\left(Rsc, \frac{\pi}{p}, \frac{\pi}{2p}, Ta\right)\right) \tag{9}$$

where Ta is the temperature in the PMs, A^I_{mag} is the vector potential in the air-gap created by the PMs, Rsc is the stator radius corrected by the Carter's coefficient [2].

The flux density in the yoke of stator is then calculated by:

$$B_{stat}(Ta) = \frac{\frac{\Phi_{stat}(Ta)}{2}}{l_{iron} \cdot h_{cs}} \tag{10}$$

where h_{cs} is the stator height.

The flux density in the teeth of stator is also calculated by:

$$B_t(Ta) = \frac{\frac{\Phi_{stat}(Ta)}{2}}{l_{iron} \cdot w_t} \tag{11}$$

where w_t represents the width of a teeth.

Electrical equations:

The electrical equations are also computed. As an example, the resistance of one phase is calculated with:

$$R(Tcu) = \rho_{Cu}(Tcu) \cdot \frac{l_{turn}}{S_{cond}} \cdot ns \cdot N_{bm} \tag{12}$$

where Tcu is the copper temperature, ρ_{Cu} is the copper resistivity, l_{turn} is the length of one turn and N_{bm} is the number of serial turns in one phase.

Then, the copper losses in one phase are calculated with:

$$P_{cop}(Tcu) = 3 \cdot R(Tcu) \cdot Is^2 \tag{13}$$

where Is is the supply current RMS in one phase.

Finally, the motor efficiency is deduced:

$$Eff\_mot = \frac{P_{em}(Tmot, \Omega)}{P_{em}(Tmot, \Omega) + P_{cop}(Tcu, Tmot, \Omega, Ta) + P_{iron}(\Omega, Ta)} \tag{14}$$

where $Tmot$ and Ω are respectively the electromagnetic torque and the rotation speed; P_{em} and P_{iron} are respectively the electromagnetic power and the total iron losses of the motor.

Thermal Equations:

The thermal model is limited to the adiabatic heating of the copper at starting point which is calculated with:

$$\Delta t\_ad1 = \frac{m_{cop} \cdot Cp_{cop}}{P_{cop\_1}(Tcu)} \cdot \Delta T\_ad_{\max} \tag{15}$$

where Cp_{cop} is the thermal specific capacity of the copper, ΔT_ad_{max} is the maximal adiabatic heating of the copper.

IV. The Methodology Used to the Motor Design

A. Methodology of design

The methodology of the PMSM design using concentrated winding is shown in the Figure 6. First, the analytical model of a PMSM shown in the previous paragraph is used to generate input and output variables for the design program. Secondly, the constraints variables and an objective function are chosen, according to the power specification, the speed of the motor, the geometrical constraints, the thermal limitations… Finally, the optimization program try to find an optimal solution, following the constraints given by the designer.

B. The multi-constraints problem

The previously described analytical model is applied for the design of PMSM outer motor with the performances target presented in section II. To minimize the cost of the motor and to maximize the performance, minimum of weight and maximum of efficiency are both required.

Two machines with different number of poles pairs are studied (i.e., p=14 and p=17). The electrical machines have concentrated windings with double layer winding: all the teeth are wound and there are two coils per slot.

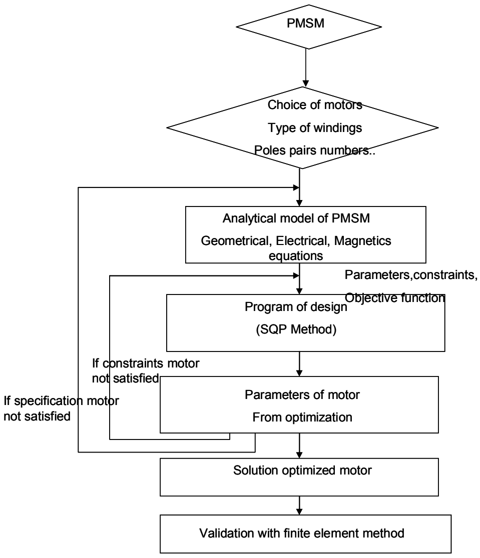

Figure 6. Methodology of the PMSM design.

More precisely, the main design constraints are the following:

- the external diameter *Rext* and the active length of the machine *Liron* are bounded by the dimension of the wheel;
- the magnetic flux densities in the ferromagnetic parts *Bstat* , *Bt* and *Brot* are limited to avoid saturation;
- the RMS current in the PMSM phases is limited due to the power electronic components (IGBT);
- the back EMF E at high speed is limited, to avoid that the recirculation of the current back to the converter through the diodes;
- the copper losses P_{cop} must be limited, in order not to overheat the motor;
- the weight of the PMs m_{mag} must be minimized to mitigate the cost of the motor;
- in order to satisfy dielectric insulation, the space between two coils g_{bslot} has to be higher than a value defined by the winding manufacturer.

C. Design Process

The design results concerning two PMSMs (i.e., p=14 and p=17) are presented in the TABLE I. The Figures 7 to 10 show respectively the iron losses at working point 5 versus the active length, the flux density in the stator versus the height of PMs, the copper loss at working point 4 and the motor efficiency at working point 5 versus the number of turns.

Theses curves show the dependence of the output parameters from analytical model as function of geometrical input parameters of motor. Finally, the machine with the number of poles pairs p=14 has been chosen for the reason of its simplicity of realization: the number of coils is lower and the automatic winding is easier to realize.

TABLE I. PARAMETERS OF DESIGN OF TWO MACHINES (P=14, P=17)

	p=14		p=17	
Variable	Initial value	Final value	Initial value	Final value
Rext [mm]	155	-	155	-
p [-]	14	-	17	-
αm [rad]	0,862	0,837	0,83	0,88
ha [mm]	7,135	3,9	3	4,61
lmag=liron [mm]	41,962	30,5	37	28,02
ns [-]	25	38	28	32
Is2 [A]	47,5	47,26	47,9	48
Pcop4 [W]	376	431	411	417
Pfer5 [W]	29,4	24,92	26	30,13
Pfer6 [W]	44,2	37,51	39,5	45,84
mmag [kg]	1,793	0,7	0,649	0,8
mcop [kg]	1,535	2,27	1,98	1,93
mtot [kg]	8,457	8	8	7,13
Eff_mot3 [%]	71,9	69	70	69,76
Eff_mot4 [%]	89	87,7	88,2	87,98
Eff_mot5 [%]	94,8	94,56	94,8	94,42

Figure 7. Iron losses at working point 5 versus the actif length.

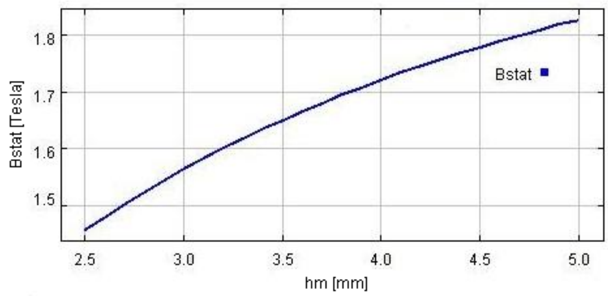

Figure 8. Flux density in the stator versus the height of PMs.

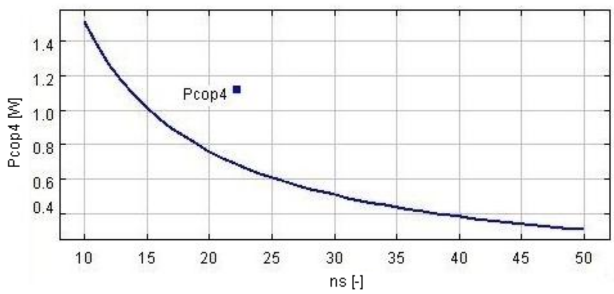

Figure 9. Copper loss at working point 4 versus the number of turns.

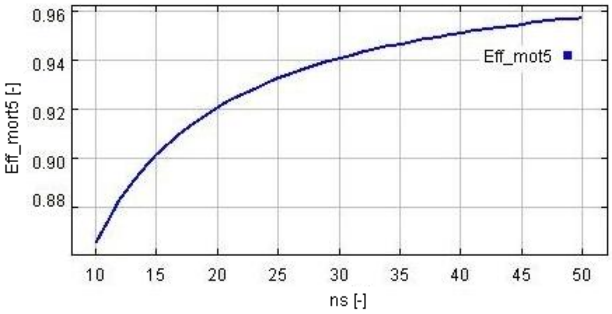

Figure 10. Motor efficiency at working point 5 versus number of turns.

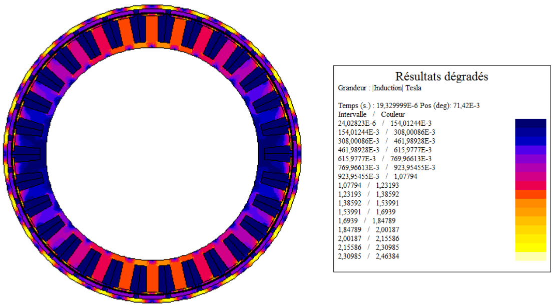

Figure 11. PMSM with p=14 in the finite element simulation.

Figure 12. Electromagnetic torque at the point 2.

Figure 13. Iron and PMs losses on load at the various points.

Radial component of the magnetic force on the stator teeth

at the point 2 at 0° position of stator versus the rotor.

V. Validations of the Results and Discussions

A. Simulation with 2D FEM

The optimal machine is then validated with 2D FEM, in order to confirm the performances of the motor (see Figure 11).

The Figures 12 to 14 present the simulations results:

- electromagnetic torque at the working point 2 (see Figure 12);
- iron and PMs losses on load at different working points (see Figure 13);
- radial component of the magnetic force on one stator tooth for the working point 2 and with a relative position of the rotor versus the stator equal to 0° (see Figure 14).

B. Discussions about the optimization method SQP

The optimization method has some advantages. It is simple and fast. Of course, the optimization solution depends on the constraints given by the designer. The method can handle a problem with numerous equations, such as the PMSM design problem presented in this article. By the way, the method presents also some disadvantages. It needs an analytical model to generate its variable, so that it may be difficult to account for some phenomena such as saturation or slotting effects.

C. Discussions about the concentrated winding machine

The machine designed satisfies the specification requirements for the motor. The program has successfully designed the machine. By the way, some points have to be underlined about the electromagnetic performances of this machine. The machine is compact (integration in a 15’’ standard wheel, active part weight of 8 kg) and has a high torque (240 N.m). But it presents also a high level of the eddy-current losses in the magnets. Because of that, the authors propose to segment the magnets in the transversal axis and/or the circumference axe. The machine also presents a large variation of magnetic forces on the teeth of stator, compared to a traditional machine. So the concentrated machine could lead to vibration and acoustic noise. In our case, the rotor being external, it is necessary to modify its mechanical structure to obtain Eigen frequencies compatible with the forces vibration frequency.

VI. Conclusion

An optimization method (i.e., the SQP method) has been successfully investigated for the PMSM design using concentrated windings. The designed machine satisfies the performances which are necessary for the motorization of back wheels of a small hybrid vehicle. The design method is simple and generic. It can be used with many other problems where multi-physical constraints are required. Although the PMSM presents some interesting performances (30 N.m per kg of active part and 0.6 kW per kg of active part for example), it can be noted that this motor presents some drawbacks. The eddy-current losses in the PMs are high, needing a segmentation of the magnets in the transversal and/or circumference axis. Moreover the designed machine presents a large variation of magnetic forces applied on the stator teeth. They could generate larger vibrations and higher noises in the machine, than the ones obtained with traditional machines using overlapped windings.

Acknowledgment

This work is subscribed within PHEBUS project supported by the ADEME (Environment and Energy Mastery Agency) and ANR (National Agency of Research) in Franche-Comté Region, France. The authors thank all financial and technical partners involved in this project.

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