Integrated Starter Generator: Need of an optimal design and control approach. Application to a permanent magnet machine

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***Abstract*- Automotive applications impose very constrained conditions (temperature, current density, high saturation level, high power mass ratio…). Optimisation procedures may allow efficient design and control. This paper proposes to apply such approaches to the design and control of a buried permanent magnet machine. Experimental results are described and discussed.**

I. INTRODUCTION

Integrated Starter Generator (ISG) is a solution for mild hybrid vehicles. High efficiencies, low cost and easy implementation are required. Various types of electric machines have to be considered and leads to make comparisons between different machines structures : induction machine, wound rotor synchronous machine, reluctant and permanent magnet machine. All these machines must respect very strong rules and specifications (low size, high torque, speed and efficiency). In this context, Internal Permanent Magnet (IPM) structure owns lots of advantages : high specific power, brushless, no losses in the rotor. IPM particularities, associated to ISG contraints (wide speed range, battery supply and highly variable temperature) impose a precise control. [1]–[10] After a presentation of an optimal machine design associated to specific constraints, and an optimal control, experimental results will be presented and discussed.

II. IPM FOR STARTER GENERATOR APPLICATIONS

The fig. 1 shows a cross-section of a classical IPM adapted to flux-weakening operation.

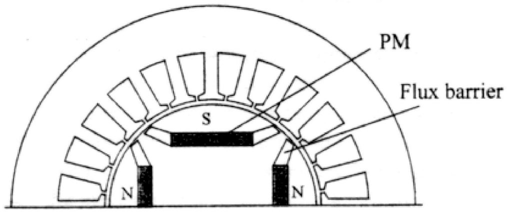

Fig. 1: IPM cross-section

This structure cumulates the characteristics of permanent-magnet and reluctant machines : torque is a combination of hybrid and reluctant torque ; the induced voltage, due to the presence of permanent-magnet excitation, is constant and must be reduced by flux-weakening at high speed.

Starter-generator, as others automotive applications, is very constrained :

These constraints create specific behaviours (high magnetic saturation) and limitations (current, voltage, power, energy). Moreover, terminal voltage, equal to the battery voltage, varies with the state of charge and the consumed power.

A precise model needs to take into account all these specificities.

III. OPTIMAL DESIGN

The optimisation of electric machine design is a difficult problem and a mathematical approach may simplify the work of the researcher and allows to find a real optimal solution [11].

A general problem of optimisation consists in a selection of n design optimal variables (OV) expressed in a vector X and to obtain the optimal values $\bar{X}$ which :

- minimise the objective function ;
- agree with required constraints.

A. Definition of the design optimisation variables (OV)

The choice of the design optimisation variables is the first part of the problem. In electric machines, OV are of two types : discrete or continuous. Classical optimisation algorithms need continuous differentiable variables. So, in our study , discrete variables (pole number, slot number) are determined by classic ways [12] and remain constant during the optimisation procedure.

Nevertheless, number of turns of the winding which is difficult to determine for low voltage applications (very low number) has been treated in two steps: In a first step this variable has been considered as continuous and in a second step, this variable has been kept constant and a second optimisation computing has been made for other continuous values.

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These optimisation variables are geometric (for example length), electric (turns number) or control (current space vector).

B. Definition of the objective function

In integrated starter application, the objective is to reduce the length of the electric machine to be integrated to a classical motor with no modification of the vehicle. The objective function is expressed by :

$$F[x] = \frac{L_{zf}(x) + L_{ztb}(x)}{L_{ref}} (1)$$

with : L_{zf} : active length of the machine
L_{ztb} : length of the end windings
L_{ref} : reference length to normalise the objective function

C. Definition of the constraint function

Constraint function is of various types :

- *torque-speed characteristics*
- *efficiency characteristics*
- *thermal characteristics*
- *geometric constraints*
- *supply constraints*

Torque-speed characteristics :
. starter mode (M_1) : 215 mN from 0 to 110 rpm
. generator mode (G_1) : P_{elec} = 1 500 W 850 rpm
. generator mode (G_2) : P_{elec} = 2 500 W 2 000 rpm
. generator mode (G_3) : P_{elec} = 1 000 W 6 000 rpm

Efficiency characteristics :
80% (including power converter efficiency) for G_1, G_2, G_3
For M_1 no minimum efficiency is required. Nevertheless, the battery current has to be limited to a maximal value.

Thermal characteristics :
For this project, the thermal model has not been developed, because it is very linked to the implantation of the ISG in the vehicle. Thermal constraints have been taken into account by the limitation of the current density in the windings :
50 $A/mm^2{}_{max}$ for starter mode (M_1)
10 $A/mm^2{}_{max}$ for generator mode (G_1,G_2,G_3)

Geometric constraints :
The maximal external diameter is 255 mm and minimal internal diameter of 134 mm.
Length has to be minimised with a maximum allowed value of 53 mm.
Supply constraints :
The ISG is supplied by a 42 V (Edc) Pb battery with an 20 mΩ (Rdc) internal resistance. Ni MH batteries are under investigations
Classically, constraints limits have been defined to avoid unrealistic optimal solutions and reduce computing time.

D. Model analyse

A model has to be used to compute magnetic, electric and thermal states, to evaluate for each iteration, the values and the gradient (required for the optimiser) of the constraint function. Theoretically, these three states are linked, but in our study we have chosen a simplified approach, which consists in decoupling the 3 phenomena in a such way :

- Thermal state:

As previously described, no thermal model has been developed. Thermal aspects have been taken into account by a limitation of the current density.

- Magnetic state :

The power converter delivers sinusoidal voltages (chopping is not taken into account). So for a given temperature and applied voltage, the magnetic state may be defined as long the stator current space vector is known (amplitude and torque angle).
The model used for the determination of the magnetic state is based on a decoupled reluctant circuits (one variable reluctance model for d axis and one model for the q axis). Saturation is classically taken into account by an iterative process.

- Electric state *:*

In our analyse model machine, voltage and current waveforms are sinusoidal (rectangular supply is not investigated). So, in motor mode, the maximum value of U_S (RMS) is limited to Vdc/sqrt(2) (Delta coupling).
In generator mode, all values of U_S between 0 and Vdc/sqrt(2) will be considered as correct.
The computation of Idc is based on the conservation of power between the two sides of the converter. The efficiency of the power supply is considered as unity.

$$I_{dc}.V_{dc} = \sqrt{3}\ U_S\ I_S \cos\varphi_S \quad (2)$$

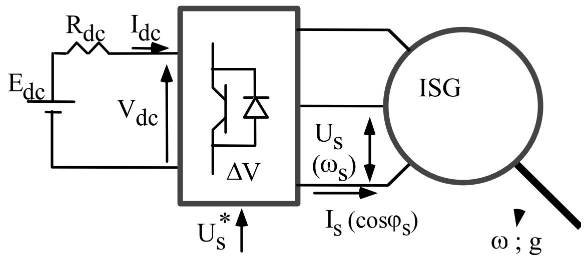

Fig. 2: electric model

E. Definition of the design variables and implementation of the optimisation.

The optimisation process is based on two types of optimisation variables:
- geometric optimisation variables (GOV)
- electrical optimisation variables (EOV)

The figure 3 shows the different geometric design variables which have been defined.

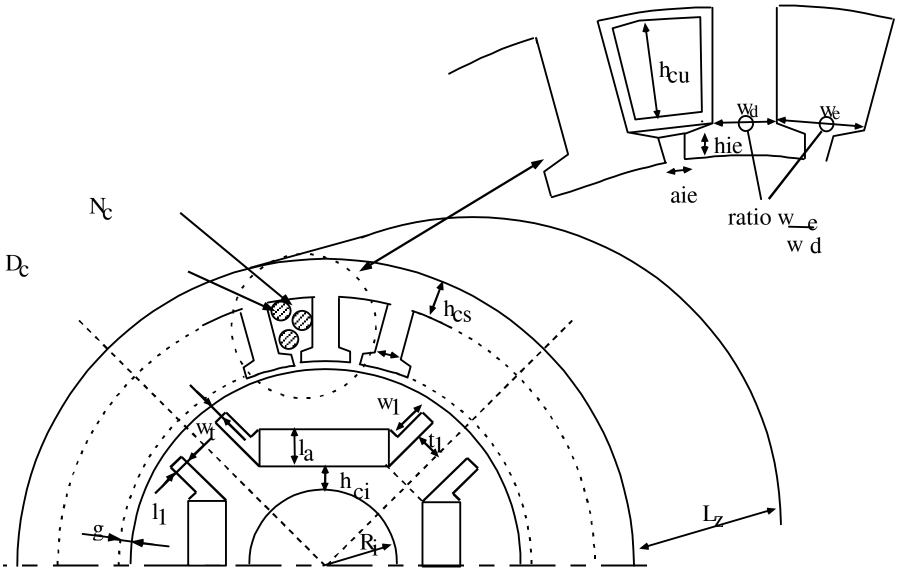

Fig. 3: geometric optimisation variables

GOV definition (see fig 3):
- *Rotor variables:*
R_i, h_{ci}, l_a, t_l, l_1, w_1, w_t.
- *Stator variables:*
w_e/w_d ratio, h_{cu}, a_{ie}, h_{ie}, h_{cs}
- *Other variables:*
L_z, g, S_{cond}, N_c

EOV definition

The electrical optimisation variables correspond to the minimization of the current amplitudes for the four torque speed constraints previously described (M_1, G_1, G_2, G_3). They are treated by the optimiser in the same way as GOV.

F. Optimisation procedure

The approach previously described has been implemented in FORTRAN and the optimiser is a classic commercial Sequential Quadratic Programming (SQP) from IMSL lib.

The initial model determination is based on the main geometric constraints and the use of simple and classic "rules of the art" for a first "manual design".

IV. OPTIMAL CONTROL PROCEDURE

Once the machine designed, we need to apply optimal currents for maximising the efficiency in the whole torque-speed plane. The same optimal approach can be applied.

A. Definition of the control optimisation variables (OV)

Control a IPM is equivalent to inject the currents i_d , i_q which minimise the total losses with respect to different constraints (torque, current, voltage and power).

$$\forall(T^*,\Omega),\quad (i_d{}^*,i_q{}^*)\setminus min_{id^*,iq^*}\Sigma P_{losses}$$

with:

$$\begin{aligned} T_m &= T^* \\ V_{rms} &\leq V_{disp} \\ I_{rms} &\leq I_{lim} \\ P_e &\leq P_{bmax} \end{aligned}$$

B. Definition of the objective function

The objective function is here the total losses:

f = total losses

Cooper losses have been determined in a traditional way. Iron losses have been computed by commercial FE software (Flux 2D) for different magnetic states of the machine (currents and speeds) and results have been saved in a table.

Mechanical losses have been measured by a special test on the prototype.

Mechanical and iron losses have been tabulated and are called for each optimisation step.

C Definition of the constraint function

The constraints functions are :

Mechanical torque is equal to the torque requirement:

$g_t=|T_m-T^*|-[epsilon]|T^*|$

[epsilon] is a percentage (0<[epsilon]<1) which defines precision.

Current is less than the limit:

$g_i=I_{rms}-I_{lim}$

across voltage is less than the available voltage

$g_v=V_{rms}-V_{sup}$

In starter mode, electrical power is limited by the battery maximum power :

$g_p=P_e-P_{bmax}$

D. Model of analysis

One of the main problem for the optimisation procedure is the need of an accurate model do determine performances for each optimisation step. IPM machine is particularly difficult to model because of its rotor structure and highly variable saturation level.

Saturation and cross saturation need to be taken into account. As previously described, cross saturation has not been taken into account in the model used for the machine design. Once the given machine its possible to obtain a more accurate model based on a FE method.

A such model has been described in [16] and is used in our procedure.

E. Optimal control

The optimal values for id and iq are computed in a traditionnal way as described on the fig. 4.

The optimiser is the Matlab function "fmincon" [15] which allows the use of tabulated data. In our case the tabulated data are:

- ψ_d, ψ_q computed by a commercial FE software (FLUX 2D) for different values the space vector current. These solutions are tabulated, linearised and used for the torque determination.
- Iron losses from the FE software for different values of speeds and space vector current.
- mechanical losses from a special test on the prototype.

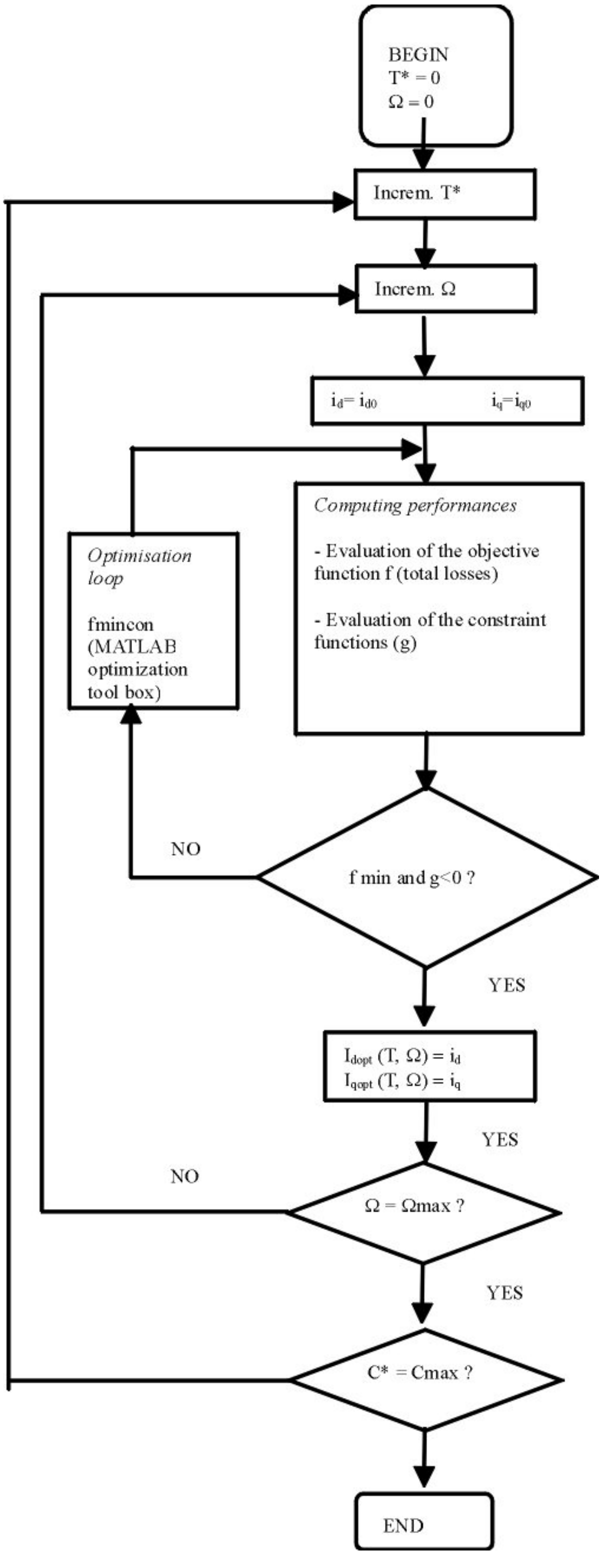

Fig. 4: Optimal currents determination.

The results of the optimisation are shown on the figure 5

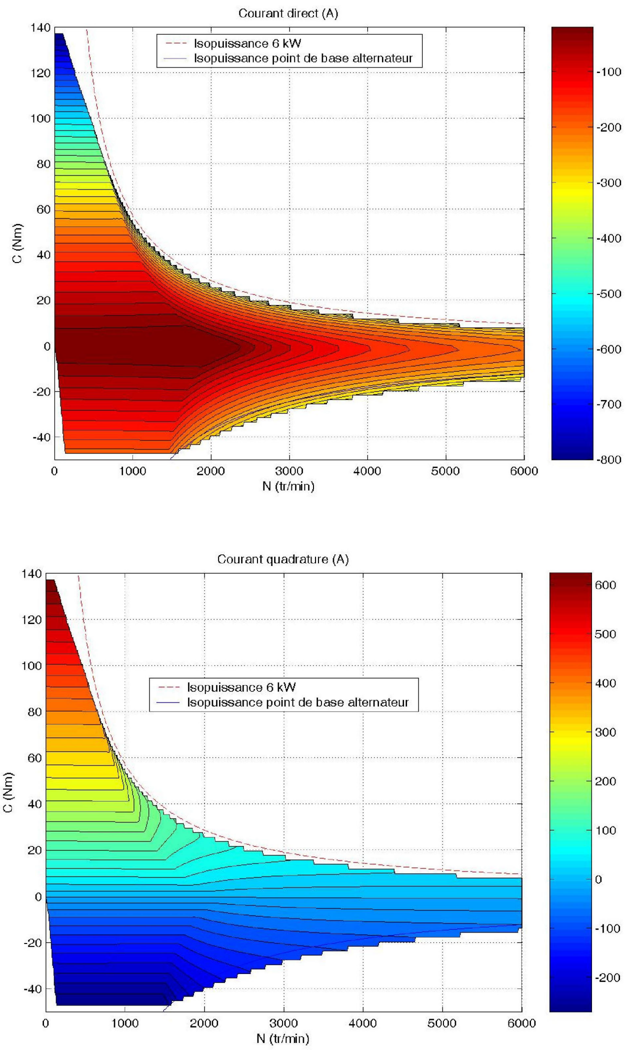

Fig. 5: Optimal currents (id and iq)

V. APPLICATION AND RESULTS

The both optimisation procedures (design and control) have been applied and a prototype has been tested.

The fig. 6 shows the ISG on the test rig.

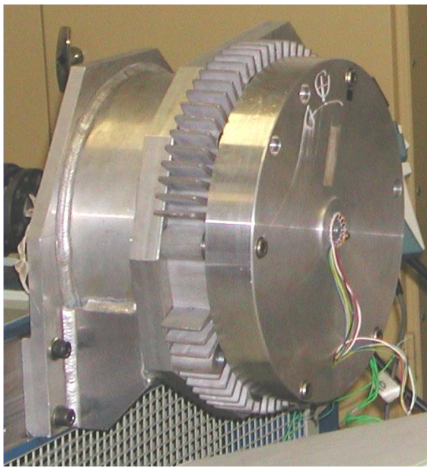

Fig. 6: Permanent magnet ISG on a test rig

The figure 7 and 8 show a comparison between the simulations obtained with the control model (grey arrays) and measures (dots). This comparison shows the high accuracy of the developed model.

Starter mode.

Injected currents have been limited to 200A peak for limiting the machine temperature during the measures, so, maximum experimental torque is limited to 30 Nm.

Nevertheless, simulations show that the required starting torque (140Nm) is reached for the maximum temporary current (600A RMS).

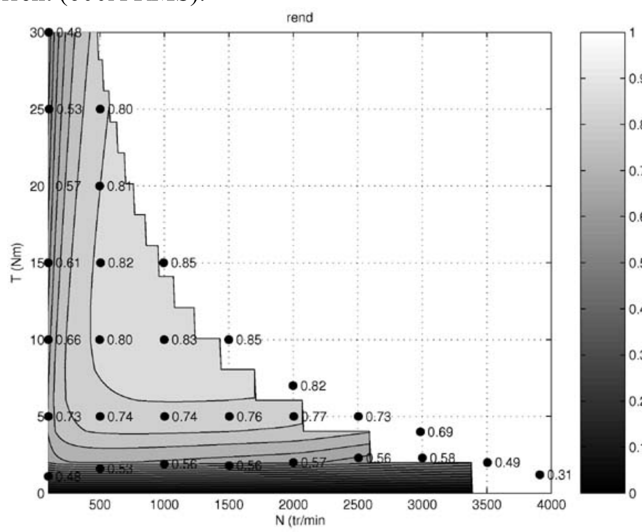

Fig. 7: ISG performances in starter model

Generator mode

Figure 8 shows a very high efficiency on a wide zone of the torque speed space (compared to the classic claw pole generators).

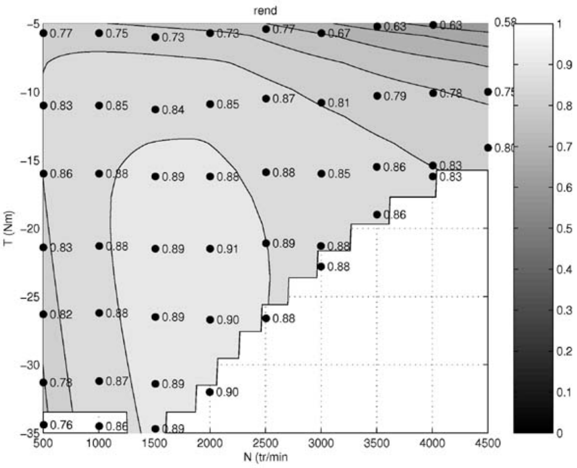

Fig. 8: ISG performance in generator mode.

The efficiency remains higher than 80% in a wide zone of the torque-speed space. Due to the optimal design of the machine, the high value of the negative id current for high speeds (see fig 5), (flux weakening mode) don't reduce significantly the efficiency: it remains greater than 75% for a delivered power of about 4500W (4500rpm, 10Nm).

VI. CONCLUSION

An optimal design associated to an optimal control applied to an IPM machine for ISG application may give excellent results.

The efficiency remain high even for high field weakening operation.

The rotor has no internal losses (in comparison with the induction machine) and don't require slipping contacts (in comparison with claw pole machine). Its construction is very simple and permanent magnet prices become affordable.

The IPM seems to be a good choice for ISG applications, its main problem remains its high output voltage for high rotation speeds in the case of a power electronic failure.

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