Comparison of two optimal machine designs for integrated starter-generator applications

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Abstract — **The proposed paper presents experimental results of a comparison between the performances of an induction machine (IM) and a wound rotor synchronous machine (WRSM) in an Integrated Starter Generator (ISG) application. The two machines have been designed with exactly the same required performances: high torque associated to low speed for the starter operation and same output power for the high speed generator operation. These operation conditions have to respect various constraints such as maximum temperature, efficiency, external diameter and minimum length.**

1. Introduction

This study is a part of a more ambitious research program between a University (UTC) and an automotive supplier (VALEO). The aim of this research program is to compare various electric machines for an ISG application.

The proposed paper presents experimental results of a comparison between the performances of an induction machine (IM) and a wound rotor synchronous machine (WRSM) in a starter generator application. Nevertheless, an interior permanent magnet machine is under investigation.

The two machines have been designed with exactly the same required performances: high torque associated to low speed for the starter operation and high efficiency constraints for the generator operation. These operation conditions have to respect various constraints such as maximum temperature, external diameter and minimum length.

Principles used for the design optimization have been already published [1], [4] and the corresponding prototypes have been realised with the same active length. The presented paper deals with the presentation of the principle of the optimization used and compare the experimental results of the machines

2. Formulation of the optimisation problem applied to a starter generator design

The optimization 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. Various papers, which describe the approach used in the « Laboratoire d'Electromécanique de Compiègne » (LEC), applied to various machines (permanent magnet (AC and DC) and induction machine), have already been published and we remind in this paper the application of such methods to the starter-generator design. A more comprehensive description of the optimization procedure may be found in [1] applied to a DC permanent magnet brushless machine.

A general problem of optimization 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 optimization variables (OV)

The choice of the design optimization variables is the first part of the problem. In electric machines, OV are of two types : discrete or continuous. Classical optimization algorithms need continuous differentiable variables. So, in our study , discrete variables (pole number, slot number) are determined by classic ways [2], [3] and remain constant during the optimization procedure. Nevertheless, number of turns of the winding have been considered as continuous and rounded for the prototype realisation.

The choice of the optimization variables may be founded in [4] for the induction machine. These optimization variables (16 for the IM) are geometric (for example length), electric (turns number) or control (slip and applied voltage or current).

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 (figure 1).

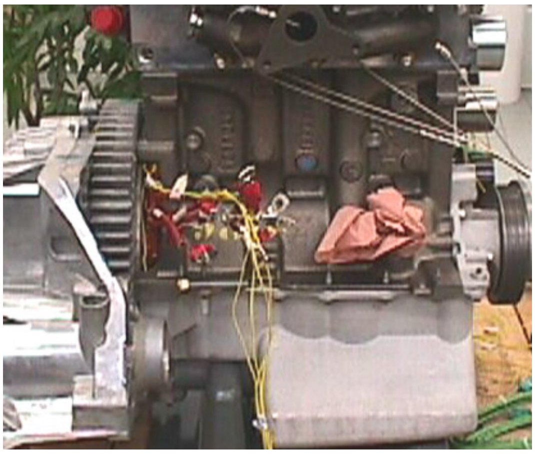

Figure 1: ISG integration

The objective function is expressed by :

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

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 imposed to 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 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 as slip is known for the IM, or torque angle and field current for the WRSM. The parameters of the electric machine are computed by a classical way of machines design described in [2].

- *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).
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.

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

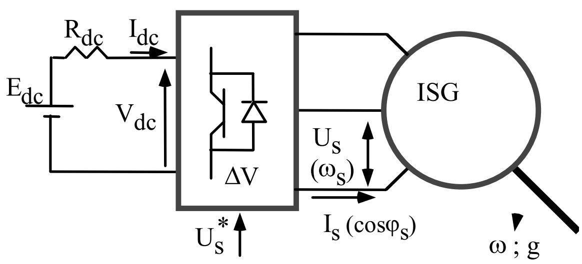

Figure 2: electric model

3. Control laws

. Control laws :

The optimization procedure, by principle, do not require the determination of control laws. (optimization design procedure gives optimal supply conditions only for the specified torque-speed constraints).

Nevertheless, their determination become of the prime importance for an optimal operation in the full torque-speed plane.

For the both machines, control laws are based on the « static flux control » :

- Slip and current amplitude control for IM.
- Torque angle, field current and stator current amplitude control for the WRSM.

The structure used is reminded on figure 3 and control laws have already been described in previous papers [5] for the IM and [6] for the WRSM.

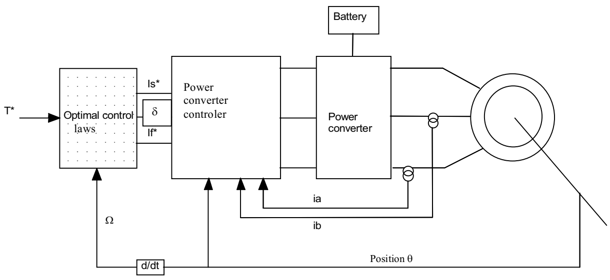

Figure 3 : control structure (WRSM)

Nevertheless, our application imposes a very important variation of the saturation level. So, analytic precise magnetic models remain difficult to establish. The presented experimental results have needed an on site calibration of the controllers.

4. Experimental results

All the required performances have not been reached by the optimization procedure. The required starting torque has been impossible to reach in respect with the imposed constraints. The presented results are based on 53mm length machines.

In a first part, we present the WRSM performances and in a second part, we present the comparison with the IM performances.

All the presented results have been obtained in a permanent operation and with a stabilised machine temperature for generator mode and in 'impulse mode' (<3 seconds) in starter mode.

A. WRSM performances

1). Starter mode

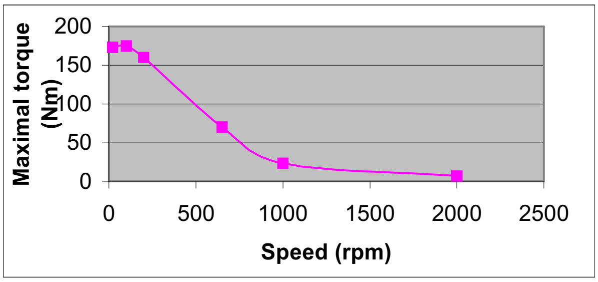

figure 4: WRSM starter performance

Figure 4 shows the torque speed characteristics in the starter mode. The maximum delivered torque reaches 170 mN (500A peak or 353 A RMS) but remains under the desired value. The base point is at about 200rpm and higher speeds are reached in a "flux weakening mode".

In spite of the required constraints, the starter torque cannot be reached in the maximum allowed length.

Nevertheless, performances are greatly sufficient for starter applications

2) Generator mode

Pure rectifier mode (PRM)

One of the most interesting feature of the WRSM on ISG applications is its ability to operate in generator mode without a PWM control. All switches of the converter remain open, so, the system can operate only on the fly wheel diodes which act as a classic three phase rectifier. The voltage output is controlled by the field current. This mode reduces component stress, improve efficiency (no switching losses) and may improve EMC performances.

Of course, as the IM, the WRSM is able to operate in PWM mode to enlarge its working zone (speed inferior to the base point).

Figure 5 shows very good efficiency performances in a wide range of operations. The allowed performances are better than the required one. This is due to the optimisation procedure because, in our case, the constraints are more difficult to reach in motor mode than in generator mode.

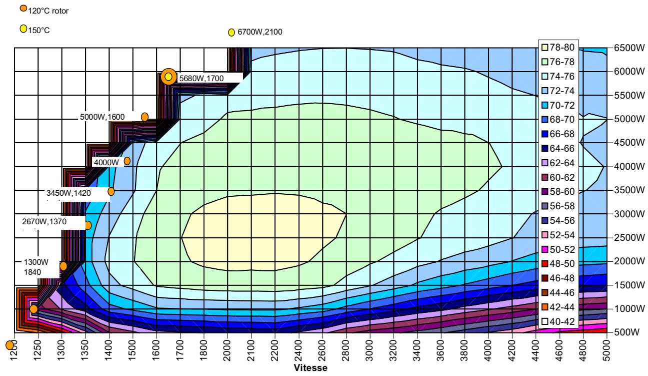

figure 5: Efficiency map of the WRSM (Pure Rectifier Mode)

PWM mode

In this mode, we have not measured an efficiency map. Nevertheless, the delivered power reaches 2,5kW@850 rpm with an efficiency of 80% for a 1,5kW power output.

B. IM WRSM comparison

The evaluation procedure is the same for the two machines

1) Starter mode

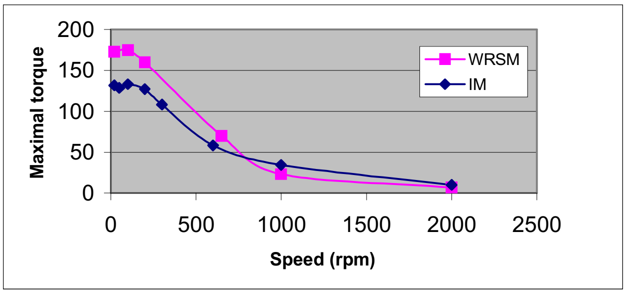

figure 6: performance comparison in starter mode

For the same injected currents (in the constant torque zone), the low speed IM torque is about 20% smaller than the available torque of the WRSM. The "base point" appears at the same speed (200rpm). Figure 6, as previously said on figure 4, shows that the maximum torque is limited by the maximum length imposed by the application. The WRSM shows better performances for the same injected current, nevertheless, the IM torque remain sufficient for the investigated application.

Generator mode

The comparison has been limited to the PRM (WRSM).
Figure 7 shows the comparison of the accessible working zones for the IM and WRSM. We can see that the WRSM delivers a more important power than the IM especially for high rotation speeds. At5000rpm the delivered power is roughly double for the WRSM compared to the IM (6500W for the WRSM and about 3000W for the IM.)

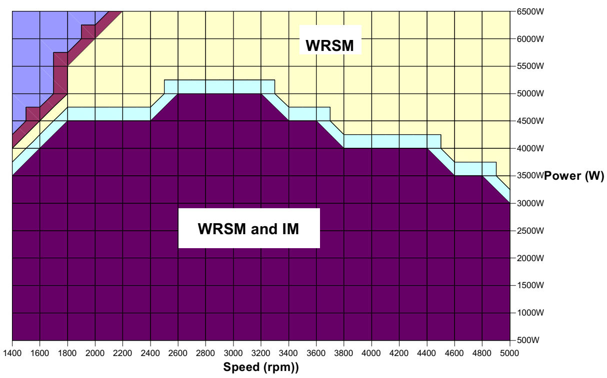

figure 7: comparison of the generator power output

Figure 8 shows the difference of efficiencies between the two machines expressed in their common torque-speed space (limited by the IM). We can notice a wide zone where the energetic performances remain similar (between -4 and +4 points of efficiency). For high powers, WRSM takes a real advantage because the difference of efficiency reaches up to 16 points. Once more, this shows a better adaptation of the WRSM for high power ISG applications.

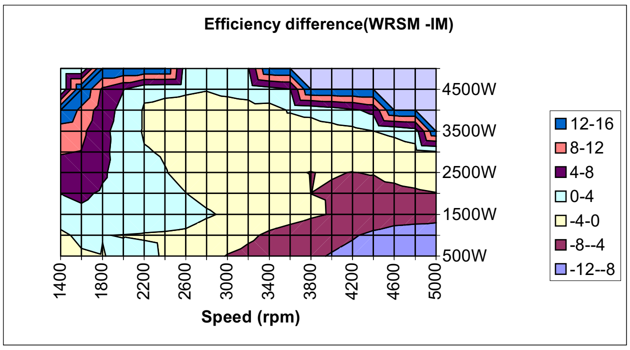

figure 8: comparison of efficiencies

5. Conclusion

Experimental results based on a same optimisation machine design have been presented. The two machines have exactly the same external dimensions. The WRSM presents higher performances as well as on the maximum delivered power or the efficiency point of view.

The IM don't require any system for the rotor supply and so, may reduce the cost and improve the fiability of the electric machine, nevertheless, the generator mode requires a permanent chopping of the power converter.

On the other hand, the WRSM allows working in generator mode without any chopping and so may improve the reliability of power electronics and reduce EMC but requires a rotor supply.

This rotor supply remains the main default of the WRSM, nevertheless, specific constraints taken into account during the optimal design, associated to a mechanical study made by VALEO lead us to a very compact and high reliability system of gliding contacts which has been implemented on the prototype.

The two machines principles are well fitted to starter generator applications and the WRSM seems more adapted to high power applications (> 6 KW) and so will be able to respond to the ever growing electric consumption required on modern vehicles

Our investigations now deal with an internal permanent magnet synchronous machine which could avoid the problems due to the rotor supply of the WRSM with the same intrinsic synchronous machine qualities

6. References

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