Steady-state Analysis of Permanent Magnet Synchronous Machine for Integrated Starter-alternator Applications

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Abstract— In the last decade due to their high efficiency and reliability, permanent magnet synchronous machine are widely used in automotive applications. There are two main reasons for this trend: the reduction of the fuel consumption and the increase of the travel comfort. In this study we consider the approaches of electromagnetic design of a special topology of permanent synchronous machine (radial flux machine with outer rotor) suited for automotive applications. The study design requires some analytical analysis, followed by a numerical one in order to attain the performances of the proposed machine in all three cases (starter-alternator-booster). A thermal analysis is required in order to determine the thermal requirements for the automotive applications.

1. INTRODUCTION

Current research efforts related to electric cars have problems mainly related to the accumulation of electricity. In this context (low autonomy, lack of fast charging stations) the use of this type of machine is limited to urban trails. Initially considered as a transition between conventional vehicles and the electric ones, the hybrid vehicles remain an alternative that is gaining more ground by combining the advantages of both types of vehicles. Of the two types of series and parallel hybrid vehicles, alternative series provides a simpler connection between the two engines and transmission power train. Passing to the present path of development of hybrid vehicles involves increasing the role in the operation of the electrical machines by increase its power and "responsibility" (starter-alternator-booster). The first steps were be made by using a single electric machine as a generator (alternator) and motor (starter) for starting the internal combustion engine, but for a hybrid car a second electrical machine is used for the electric propulsion. The simplification of this structure involves the use of a single electric machine incorporating three operating modes: starter-alternator-booster (ISAB). In this case ISAB will initially be able to start internal combustion engine, then when turned on will switch to a generator and will supply the electricity consumers and the electricity storage system. Due to the control strategies used, electrical machine is capable to move quickly from generator to motor (booster) and back to help the internal combustion engine for a short period of time (maximum 2 minutes), in situations where additional mechanical energy is necessary (overruns, ramps etc.) [1, 2].

The ISAB can be connected to a gasoline or diesel engine either directly through crankshaft or indirectly through belt drive, and they are accordingly called the belt-driven starter alternator (BAS) and normal ISAB, respectively. The permanent synchronous machine with outer rotor is an innovative solution of direct connection to the internal combustion engine in both cases in the context of minimal mechanical losses. Comparative whit other types of electrical machines, the permanent magnet (PM) synchronous machines have some important advantages like high power density, high efficiency and the possibility to work in high overload [3].

The present paper approaches the design and analysis of a special topology of the permanent magnet synchronous machine (radial-flux machine with outer rotor) suited for automotive application. A preliminary design procedure will be presented and the results will be implemented in a FEM based software in order to analyze the performances of the machine: magnetic field density, induced emf, torque and current. After that a thermal analysis is required because the thermal behavior can drastically influence the machine's performances. Thus a special attention should be paid on the heat transfer within the active and non-active parts of the machine.

2. PRELIMANARY DESIGN

The main problem at the electrical machine design is to find a set consisting of topological structure, materials, and geometry for a specific application. The selection of the proper machine topology for a specific application is a difficult problem to be solved during the design process.

In order to improve the electrical machines performances, several winding topologies will be analyzed. The output performances of the studied motor are: P — 6 (kW); rated voltage U_n — 72 (V); rated speed n_n — 400 rpm; pole pair number p — 15.

The output power of the electric machine, when the leakage reactance is neglected, is expressed by the number of phases of the machine, n_{ph}, the phase current, $i(t)$, the inducted electromotive force (emf), $e(t)$ [4]:

$$P_{out} = \eta \cdot \frac{n_{ph}}{T} \cdot \int_0^T e(t) \cdot i(t)dt = \eta \cdot n_{ph} \cdot k_p \cdot E_{\max} \cdot I_{\max} \tag{1}$$

In the previous equation, T is the period of one cycle of emf, $E_{\max}$, and $I_{\max}$ represent the peak value of the emf and phase current, η is the estimated efficiency, k_e — the electromotive force coefficient.

$$E_{\max} = k_E \cdot N_t \cdot B_{gap} \cdot D_{gap} \cdot L_m \cdot \frac{f_s}{p} \tag{2}$$

Using the coefficients $k_L = L_m/D_{gap}$ (geometric coefficient), $k_i = I_{\max}/I_{rms}$ (current coefficient) and the phase load ampere-turns [4],

$$A_t = \frac{2}{\pi} \cdot N_t \cdot \frac{I_{rms}}{D_{gap}} \tag{3}$$

it is possible to define the air-gap diameter of the machine:

$$D_{gap} = \sqrt[3]{\frac{2 \cdot p \cdot P_{out}}{\pi \cdot n_{ph} \cdot A_t \cdot k_e \cdot k_i \cdot k_p \cdot k_L \cdot \eta \cdot B_{gap} \cdot f_s}} \tag{4}$$

The power and the voltage coefficients are defined according to the type and current wave form, in this case the sinusoidal wave form is $k_i = \sqrt{2}$, $k_p = 0.5$ [4, 5].

By choosing the type of permanent magnet and the number of slots, and also using the expression of the air-gap diameter, the designer can determine all other geometrical parameters.

The air-gap flux density is computed based on the following formula:

$$B_{gap} = \frac{h_m \cdot B_{rm}}{\frac{D_{gap}}{2} \cdot \left(\ln\left(\frac{R_{scr}-gap}{R_{so}}\right) + \ln\left(\frac{R_{cr}}{R_{cr}-gap}\right)\right)} \tag{5}$$

For active parts of the machine, it was used good quality PMs material, of Nd-Fe-B N48 type, with 1.4 T flux density. The steel is made of M270-35A sheets.

The frequency, the number of turns, the air-gap flux per pole and a demagnetization coefficient (usually between 0.8–0.9 for rare earth PMs) make up the expression of the electromotive force:

$$E_{ph} = \sqrt{2} \cdot \pi \cdot f_s \cdot N_t \cdot k_{ws} \cdot \Psi_{gap} \cdot k_d \tag{6}$$

Next, the usual electromechanical characteristics can also be computed [5]:

$$P_{in} = n_{ph} \cdot U_{ph} \cdot (I_q \cdot \cos(\delta) - I_d \cdot \sin(\delta)) \tag{7}$$

$$P_{out} = P_{in} - \sum \text{Losses} \tag{8}$$

P_{out} — the output power, function of input power and the sum of losses (iron, copper, mechanical and supplementary losses).

$$T_m = \frac{P_{out}}{\Omega} \tag{9}$$

$$\cos(\phi) = \frac{P_{in}}{n_{ph} \cdot U_{ph} \cdot I_s}, \quad \eta = \frac{P_{in}}{P_{out}} \tag{10}$$

The obtained main dimensions and the results for the operation at rated point are shown in Table 1. The obtained structure with winding distribution is presented in Figure 1.

Stator outer diameter [m]	0.186
Rotor inner diameter [m]	0.201
Rotor outer diameter [m]	0.230
Shaft diameter [m]	0.130
Stack length [m]	0.280
Air-gap [m]	0.0015
Air-gap flux density [T]	1
Rates speed [rot/min]	400
Phase emf [V]	42
Rated current [A]	72
Power factor [%]	0.9
Efficiency [%]	0.87
Torque [N*m]	150

Table 1: The obtained results for the designed electrical machine.

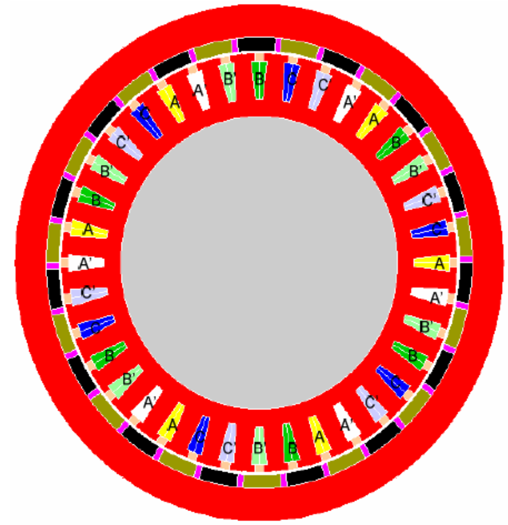

Figure 1: Studied electrical machine.

3. MAGNETIC FIELD ANALYSIS

The finite element method (FEM) is a powerful tool for the design of the electrical machines and others electromagnetic devices. FEM is a simple, robust and efficient widely used method of obtaining a numerical approximate solution for a given mathematical model of the machine. For the proposed machine FEM was used in order to observe the behavior of the machine in all operating regimes (starter-alternator-booster). Thus, we accomplished a simulation scenario in which the proposed machine is analyzed in the three considered operating regimes. In order to do this the circuit presented in Figure 2 was implemented.

The behaviour of the machine in all three regimes is presented (starter-alternator-booster) in Figure 3 (torque profile), 4 (phase voltage and current on the machine), 5 (dc voltage and current obtained on the load).

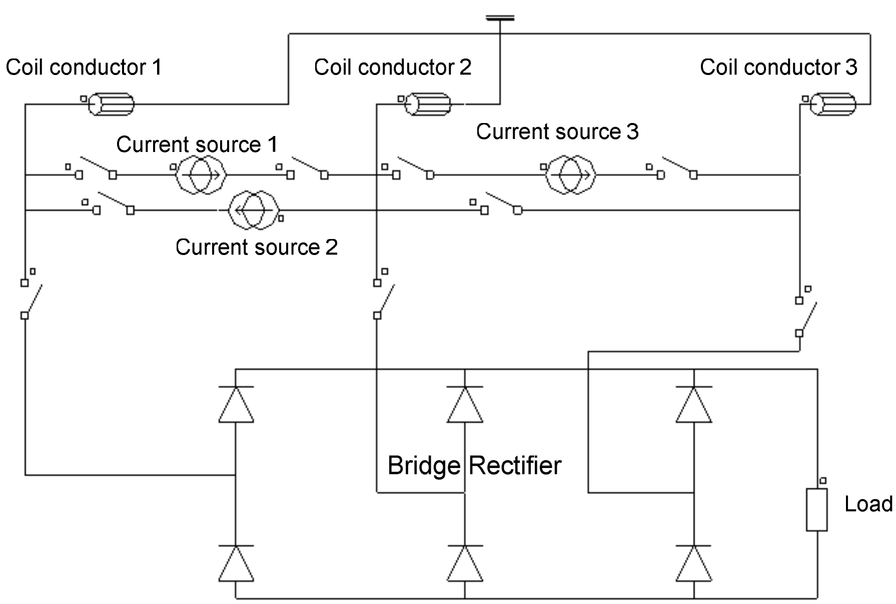

Figure 2: The circuit model of ISAB regime.

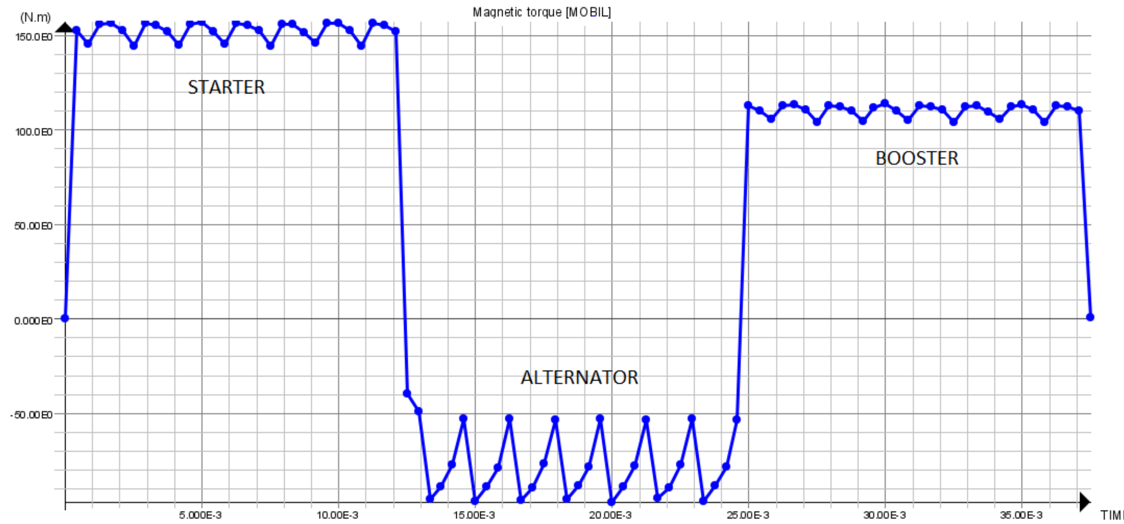

Figure 3: ISAB torque profile.

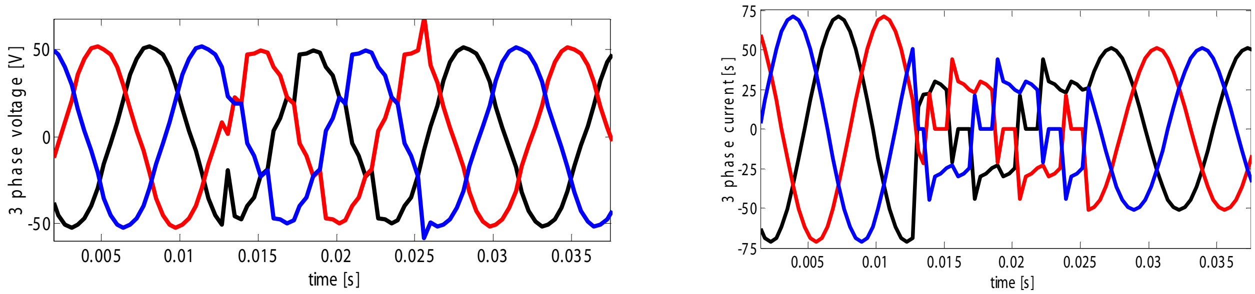

Figure 4: Three phase voltage and current obtained in ISAB regime.

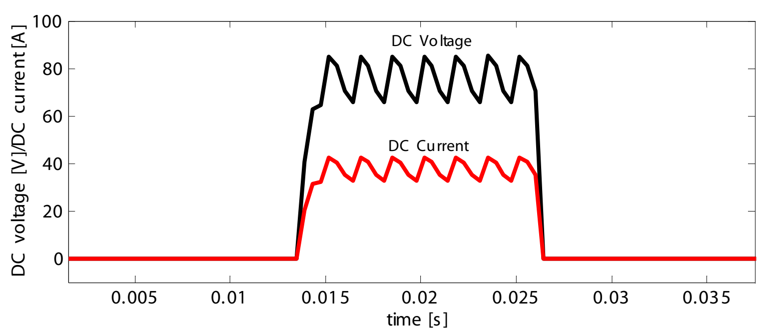

Figure 5: DC voltage and current obtained in alternator regime.

4. THERMAL ANALYSIS

In automotive applications with combustion engine, the thermal behaviour can drastically influence the machine's performances. Thus a special attention should be paid on the heat transfer within the active and non-active parts of the machine. The heat sources on the machine are: the cooper loss, the iron loss and the mechanical loss. The thermal analysis for the proposed machines was carried out using dedicated software Motor-CAD. After implementing the geometry, the winding, the materials, iron and joule losses, the cooling condition and torque profile depending on time are defined. In our case we consider the self-ventilation depending of speed for the proposed integrated starter-alternator-booster.

Usually the starter procedure lasts about 1 second, so in Motor-CAD we have set it to 10 second in order to obtain relevant results about the obtained temperature in the machine in starter mode (Figure 6). For starter mode we have considered 15 second in condition of variable load, and for

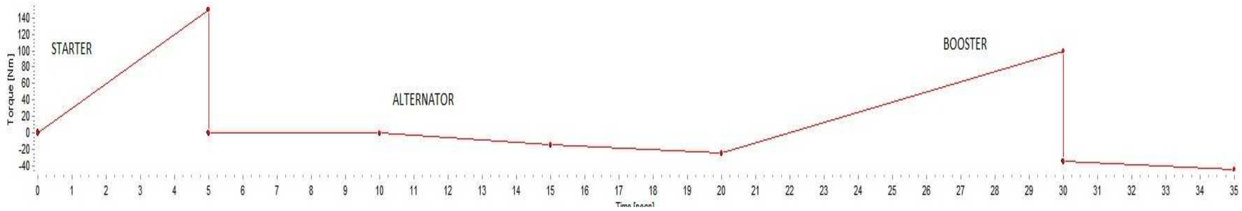

Figure 6: Duty cycle configuration.

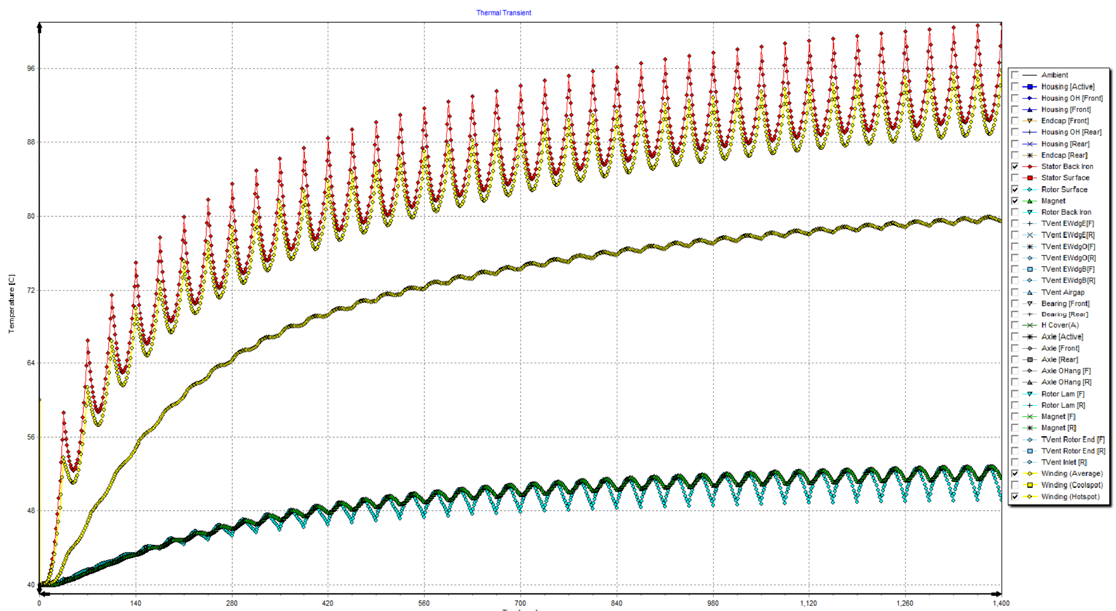

Figure 7: Thermal analysis of the proposed machine, with Motor-CAD: temperatures variation on duty cycle's.

booster we set 10 second. The analysis was made for 40 duty cycles. Highest temperatures were obtained the winding and stator back iron (96 C°), while in the permanent magnet the temperature is around 48 C°.

5. CONCLUSIONS

In this paper a structure of permanent magnet synchronous machine with outer rotor, suitable for automotive application (integrated starter-alternator-booster) is presented. The preliminary design model of the machine was developed followed by a simulation with finite element method in Flux 2D for ISAB regime. The results obtained here provide valuable information on the machine's behavior in all three operating mode. The thermal analysis for the proposed machines was carried out in order to evaluate the thermal stress of the ISAB.

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REFERENCES

1. Cai, W., "Comparison and review of electrical machine for integrate starter-alternator applications," *IEEE Industry Applications Society Annual Meeting (IAS)*, 386–393, 2004.
2. Barcaro, M., A. Alberti, L. Faggion, M. Sgarbossa, M. Dai Pr'e, and N. Binachi, "Expereimental tests on a 12-slot 8-pole integrated starter-alternator," *Proceedings of the 2008 International Conference on Electrical Machines*, 1–6, 2008.
3. Mirahki, H. and M. Moallem, "Design improvement of interior permanent magnet synchronous machine for integrated starter alternator application," *2013 IEEE International Elec-*

tric Machines & *Drives Conference (IEMDC)*, 382–385, IEEE Conference Publications, DOI: 10.1109/IEMDC.2013.6556279, 2013.

4. Fodorean, D., A. Djerdir, I. A. Viorel, A. Miraoui, and A. Double, "Excited synchronous machine for direct drive application — Design and prototype tests," *IEEE Transactions on Energy Conversion*, Vol. 22, No. 3, 656–665, Sep. 2007, ISSN 0885-8969.
5. Jurca, F. and D. Fodorean, "Axial flux interior permanent magnet synchronous motor for small electric traction vehicle," *International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM*, 365–368, Sorrento, 2012, ISBN: 978-1-4673-1299-8.