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DESIGN OF A PERMANENT MAGNET SYNCHRONOUS MACHINE FOR INTEGRATED STARTER-ALTERNATOR

BY

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Abstract. Due to their high efficiency and reliability, permanent magnet synchronous machines are widely used in automotive applications. The present paper deals with the design and analysis of a special topology of a permanent magnet synchronous machine (PMSM) suited for integrated starter-alternator (ISA). A preliminary design procedure is presented and the results are introduced in FEM based software in order to analyse the performances of the machine.

Key words: PMSM; starter-alternator.

1. Introduction

The power demands from an electric generator in the modern car are more and more increasing in the last years, as a consequence of a higher demand of electric power. There is a worldwide effort in using more and more electrical driven auxiliaries in road vehicles and to replace the hydraulic and mechanical actuators with the electromechanical counterpart. There are two main reasons for this trend: the reduction of the fuel consumption and the increase of the travel comfort. The power of electrical generators is increasing

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in order to deliver the future on-board power demand to approximately 4…10 kW. On the other hand, this increased power demand leads to an electrical machine with a torque that is studied in the range of the starting torque demand of an Internal Combustion Engine (ICE) of a big car (Cai, 2004; Barcaro *et al*., 2008).

The consequence is that both ICE starting and successive power generation features can be performed by a single electrical machine. Such an electrical machine is called *Integrated Starter-Alternator* (ISA). The interest in ISA is continuously growing in order to remove the starter motor from de vehicle, reducing the component cost.

The ISA drive has to deliver a starting torque of some tens of N.m (or more for big trucks), from standstill up to 200…400 rpm, which is the minimum starting speed of an ICE. Duration of the starting phase is normally shorter than 1 s. At higher speed, ISA is asked to operate in generating mode from the minimum ICE operating speed (generally about 1,000 rpm) up to the maximum ICE speed, with a wide constant-power speed range and proper efficiency (Cai, 2004; Barcaro *et al*., 2008)

The ISA can be connected with gasoline or diesel engine either directly trough crankshaft or indirectly trough belt system, and they are accordingly called the *belt-driven alternator* starter (BAS) and *normal* ISA, respectively.

Among the others, the permanent magnet (PM) machine seems to be a competitive choice. It exhibits a high power density, due to PMs, can support high overload, high efficiency due to absence of the field coil losses. From the efficiency point of view, the PM machine with 8…12 poles is preferable. The encased rotor, which can protect permanent magnet from iron dregs in the cooling air and the Nd-Fe-B material from corrosion, is preferred (Barcaro *et al*., 2008; Fodorean *et al*., 2007; Habib-ur, 2008).

The present paper approaches the design and analysis of a special topology of the PMSM (radial-flux machine with outer rotor) suited for automotive application. A preliminary design procedure will be presented and the results will be introduced in Finite Element Method (FEM) based software in order to analyse the performances of the machine: magnetic field density, saturation, induced emf, torque, distribution of magnetic field density in the air-gap.

2. Preliminary Design

An electrical machine design problem 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.

The dimensioning procedure was applied for the following set of key parameters: $P = 4$ kW; rated voltage $U_n = 42$ V; rated speed $n_n = 525$ rpm; pole pair number $p = 4$.

The output power (measured in W) of an electric machine, when the leakage reactance is neglected, is proportional to the number of phases of the machine, n_{ph}, the phase current, $i(t)$, the inducted electromotive force (emf), $e(t)$

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

where: T is the period of one cycle of emf, $E_{\max}$, and $I_{\max}$ represent the peak values of the emf and phase current, respectively, k_p is the power coefficient and η is the estimated efficiency. The peak value of the emf is expressed by introducing the electromotive force coefficient, k_E

$$E_{\max} = k_e N_t B_{\mathrm{gap}} D_{\mathrm{gap}} L_m \frac{f_s}{p}, \tag{2}$$

where: N_t is the number of turns per phase, B_{gap} and D_{gap} are, respectively, the airgap flux density and diameter, L_m – the length of the machine, f_s – the supplying frequency and p – the number of pair poles (Fodorean *et al.*, 2007).

By introducing a geometric coefficient, $k_L = L_m / D_{\mathrm{gap}}$, and a current coefficient (related to its wave form), $k_i = I_{\max} / I_{\mathrm{rms}}$, and defining the phase load ampere-turns

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

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

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

All the other geometric parameters will be computed based on this air-gap diameter. The designer has to choose only the PMs shape and stator slots.

For active parts of the machine it was used good quality PMs material, of Nd-Fe-B type, with 1.2 T remanent flux density. The steel is made of M530-50A sheets.

For motor regime operation of PMSM (with magnetic anisotropy), one can use the typical load phasor diagram, in *d-q* reference frame (Fig. 1). From this phasor diagram one will get the *d-q* axis reactances eqs., function of phase voltage, U_{ph}, phase electromotive force, E_{ph}, phase resistance, R_{ph}, *d-q* axis currents and internal angle, δ:

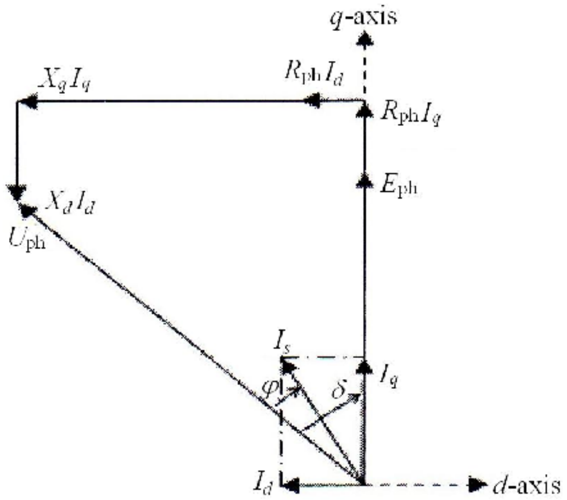


Fig. 1– Phasor diagram for PMSM in motor-load operating (Fodorean *et al*., 2007).

$$\begin{cases} X_d = \dfrac{1}{I_d} U_{\text{ph}} \cos\delta - E - R_{\text{ph}} I_q, \\ X_q = \dfrac{1}{I_d} U_{\text{ph}} \sin\delta + R_{\text{ph}} I_d. \end{cases} \tag{5}$$

Also, it is possible to compute the source current, $I_s = \sqrt{I_d^2 + I_q^2}$, knowing that the direct and quadrature current may be obtained namely

$$\begin{cases} I_d = \dfrac{U_{\text{ph}} (X_q \cos\delta - R_{\text{ph}} \sin\delta) - E_{\text{ph}} X_q}{R_{\text{ph}}^2 + X_d X_q}, \\ I_q = \dfrac{U_{\text{ph}} (X_d \cos\delta + R_{\text{ph}} \sin\delta) - E_{\text{ph}} R_{\text{ph}}}{R_{\text{ph}}^2 + X_d X_q}. \end{cases} \tag{6}$$

The electromotive force is proportional to the frequency, the number of turns, the airgap flux per pole and a demagnetization coefficient (given by the PMs material supplier, usually between 0.8…0.9 for rare earth PMs) (Fodorean *et al*., 2007)

$$E_{\text{ph}} = \sqrt{2}\pi f_s N_t k_{ws} \psi_{\text{gap}} k_d . \tag{7}$$

Next, the usual electromechanical characteristics can also be computed

$$P_{\text{in}} = n_{\text{ph}} U_{\text{ph}} (I_q \cos\delta - I_d \sin\delta) \tag{8}$$

with P_{in} – the input power

$$P_{\text{out}} = P_{\text{in}} - \sum \text{Losses}; \tag{9}$$

– the output power, function of input power and the sum of losses (iron, copper, mechanical and supplementary losses);

$$T_m = \frac{P_{\text{out}}}{\Omega} \tag{10}$$

– the motor torque;

$$\cos\varphi = \frac{P_{\text{in}}}{n_{\text{ph}} U_{\text{ph}} I_s}, \quad \eta = \frac{P_{\text{in}}}{P_{\text{out}}} \tag{11}$$

– energetic performances (power factor and efficiency, respectively).

The resulted main dimensions and the results for operation at rated point are shown in Table1.

Table 1

Main Dimensions and Results for Operation at Rated Point

Stator inner diameter, [m]	0.21
Stator outer diameter, [m]	0.225
Rotor inner diameter, [m]	0.25
Rotor outer diameter, [m]	0.2744
Stack length, [m]	0.18
Air-gap, [m]	0.001
Air-gap flux density, [T]	0.9
Rates speed, [rpm]	525
Phase emf, [V]	23
Rated current, [A]	100
Losses, [W]	1,300
Power factor, [%]	0.92
Efficiency, [%]	0.87
Torque, [N.m]	150

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. This analysis has been carried out using Flux2D software. First, the magnetic behavior of the studied machine will be verified (iron saturation, air-gap flux density). Next, the generator operation in no-load and load condition will be simulated in order to check if the rated emf is obtained. The motor regime operation will be simulated in order to obtain the torque value (Barcaro *et al*., 2008; Fodorean *et al*., 2007; Leonardi & Ionescu, 2005). Also, the iron losses will be computed, in order to have a more comprehensive comparison between the analytical and numerical results. The flux density repartition is shown in Fig. 2. The saturation level can be observed in the stator tooth. The air-gap flux density for in load and no-load generator regime has been plotted, 3-phase sinusoidal currents, 3-phase sinusoidal voltages, as shown in Fig. 3.

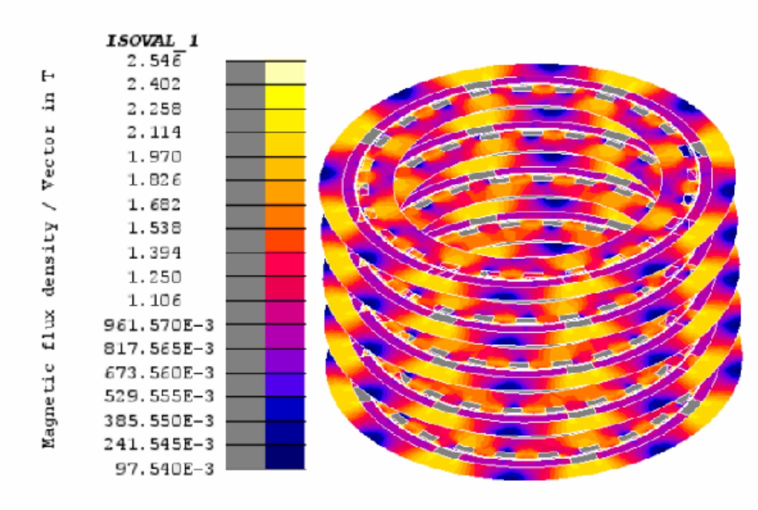
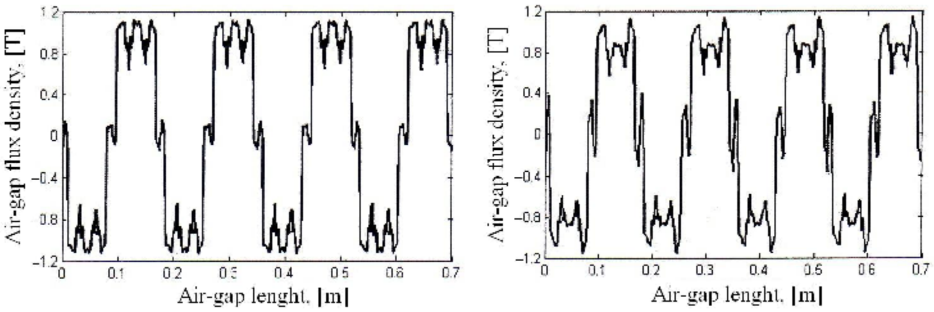


Fig. 2 – Magnetic field density map.



a *b*

Fig. 3– Magnetic field density in the air-gap for no-load (*a*) and load (*b*) generator.

The value of the air-gap flux density obtained in the design process is very close to the one computed in the numeric analysis: 0.9 T from analytical procedure and 0.88 T from numerical computation. Both the value (0.88 T) and the waveform of the flux density in no-load regime are different from the ones obtained when the generator operates with a load connected at its terminals (0.8 T). The same difference can be noted when comparing the voltages obtained in no-load regime (21 V) with in-load situation at nominal speed (15.7 V, Fig. 4).

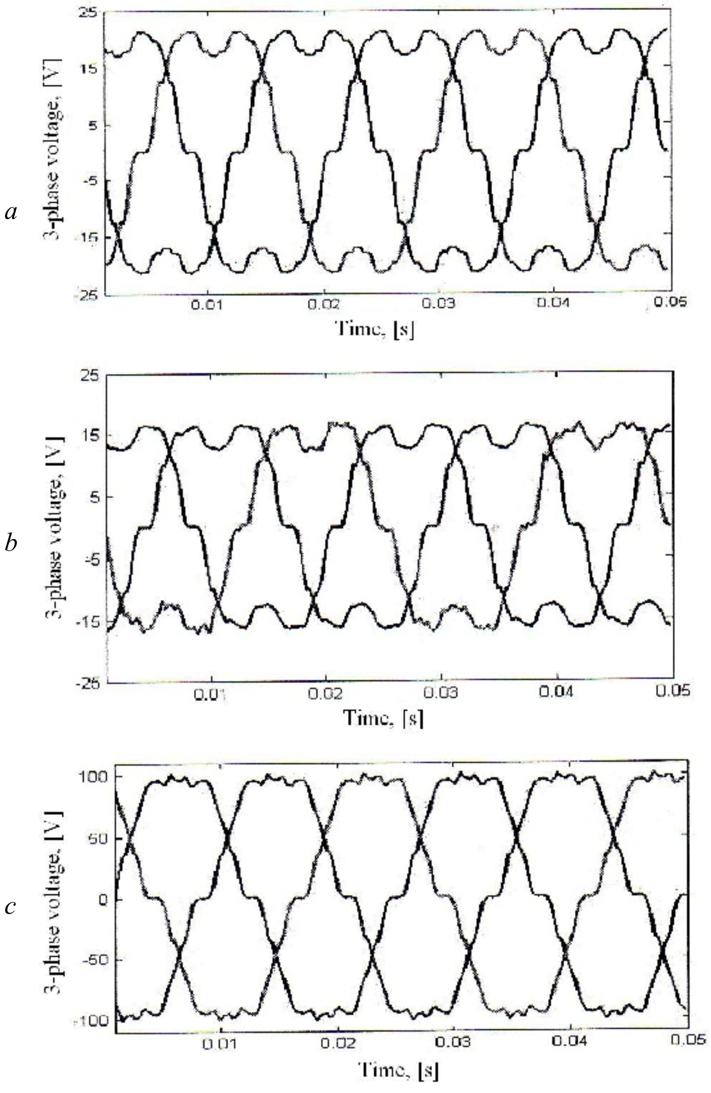


Fig. 4 – FEM results obtained on generator-load and no-load operation: *a* – 3-phase voltage of no-load; *b* – 3-phase voltage of load condition; *c* – 3-phase current.

The behavior of the motor with nominal load is presented in Fig. 5. One of the major problems of the machines with PM's, the existence of the torque ripples, can be noted here (Fig. 5 *a*), but they are relatively small. The mean value of the torque is 153 N.m, very close with the results obtained with the analytical procedure. The value of the iron losses from analytical approach (rel. (12)) is of 1,300 W, while from FEM analysis the mean value is 1,220 W (Fig 5 *b*) and consequently a better efficiency is obtained. This difference can be explained considering the flux density depicted in the active part of the machine (Fig. 2). Its value shows significant variations in the stator iron, while a constant flux density was considered in the analytical approach

$$P_{\mathrm{Fe}} = k_{\mathrm{hyst}} B_m^2 f_s + \frac{\pi^2 \sigma_{\mathrm{Fe}} d_t^2}{6 B_m^2 f_s^2} + k_{\mathrm{exc}} (B_m f_s)^{3/2} f_s , \tag{12}$$

where: k_{hyst}, k_{exc} are, respectively, the hysteresis and supplementary losses coefficients obtained from the supplier magnetic characteristic, B_m – the average flux density (in the analytical approach, a maximum value is used, but in FEM analysis an average value of the flux density repartition is considered!), σ_{Fe} – the iron conductivity (given by the steel supplier – here is 4e6 $\Omega^{-1}.\mathrm{m}^{-1}$) and d_t – the sheet width (0.5e-3 m).

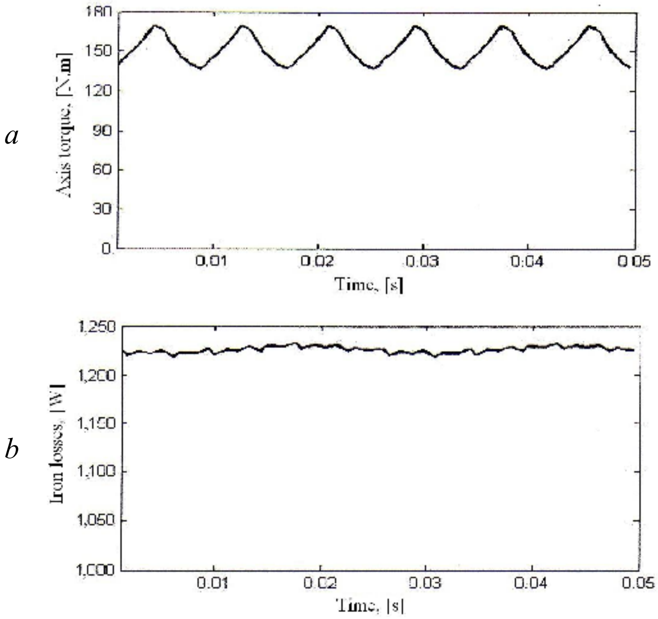


Fig. 5 – *a* – Torque ripple at nominal current (I = 100 A); *b* – iron losses.

4. Conclusions

The paper presents the theoretical approach of a PM radial-flux machine with outer rotor, suitable for automotive application. The preliminary design model of the machine was developed, followed by a simulation carried on by implementing the topology in Flux 2D. The analytical model was validated by numeric computations of the air-gap magnetic field density, voltage for no-load and load regimes, torque and iron losses. Future work will be focused on reducing the torque ripple (as stated, one of the major problems of PM machines) using the fractional pitch winding type, with a proper number of slots to pole pairs ratio.

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PROIECTAREA MAŞINII SINCRONE CU MAGNET PERMANENT PENTRU SISTEME DE TIP STARTER-ALTERNATOR

(Rezumat)

Se prezintă modul de proiectare (calcul analitic şi numeric) pentru o maşină sincronă cu magnet permanent, în construcţie inversă, pentru introducerea într-un sistem de tip starter-alternator. Algoritmul de proiectare este utilizat pentru determinarea principalilor parametrii geometrici ai maşini studiate. Cu ajutorul programului de analiză numerică se validează, în prima etapă, rezultatele algoritmului de proiectare, iar în a doua etapă se urmăreşte studierea comportamentului maşini pentru cele două regimuri de funcţionare considerate: motor şi generator.