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ANALYSIS OF A FLUX SWITCHING AND A SWITCHED RELUCTANCE MACHINE USED IN AUTOMOTIVE

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Abstract: *The paper details a theoretical approach comparing two types of electrical machine suitable for automotive traction applications. The two compared machines are the flux switching and the switched reluctance one. The comparison is carried out starting from the same requirements and comparing their behavior in the same motor regimes. The performances of each machine are highlighted concluding with the advantages and drawbacks of each of them.*
Keywords: *comparison, flux switching, switched reluctance, performances*

1. Introduction

The choice of the motor for electric propulsion system application is a very important issue that requires special attention. In order to choose the most suitable motor, one should consider the key features that are required for this application. Besides the specifications on torque and speed, the main demands in the case of HEV are: high efficiency, high torque density, small installation room and weight, mechanical robust structure, high reliability at low cost, and so on [1].

The motor choice also depends on the hybrid systems and their demands [2]. In a series hybrid system, the electrical motors should be designed for the maximum vehicle power and the full speed range while in a parallel hybrid system the speed range is restricted to low speeds.

Two topologies were considered to be compared, respectively the permanent magnet flux switching motor and the switched reluctance motor, Figure 1. For both of them, it has been performed the analytical design and a numerical analysis in oder to determine which is the most suitable motor for HEV propulsion system.

2. The design results and the studied motors

The main dimensions of the studied motors were obtained based on an analytical design algorithm developed for each motor.

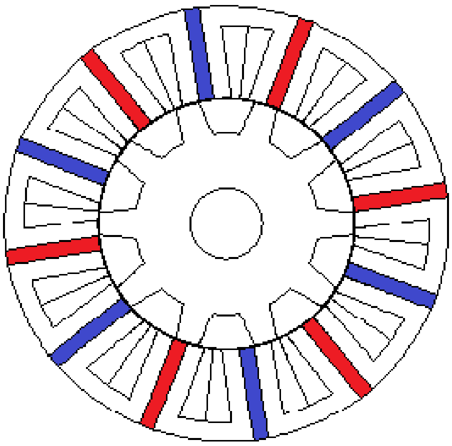
The proposed motors were designed for the same main dimensions, such as the air-gap diameter, air-gap length, stack length, and the same ratings, such as the phase voltage, number of turns per phase, phase number and rated speed.

The main dimensions of the proposed motors are listed in Table 1. As it can be seen, the PMFSM has the biggest outer diameter. The outer diameter of the PMFSM is bigger than the one in case of SRM [3] because of the large width of stator poles in case of PMFSM. This fact has led to the increasing of the stator coil height, respectively of the outer diameter of the motor.

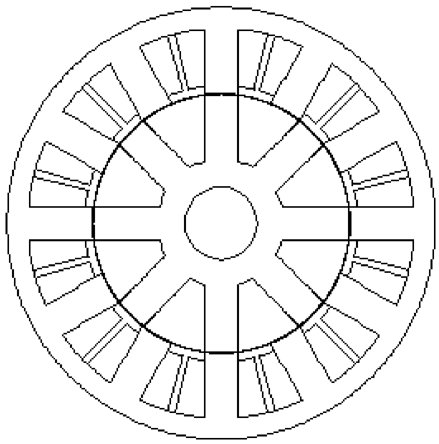
The studied machines are also designed for the same output power, respectively for 30 kW.

The main dimensions and the most important parameters are evinced in Table 2.

It can be observed from Table 2 that the PMFSM has the biggest torque density.



a)



b)

Figure 1. Cross section of a: a) PMFSM, b) SRM

3. Performance comparison

In order to have a better comparison in terms of performances, five key factors including the torque density, efficiency, power factor, mass of the active parts and the material cost of the proposed motors, are compared in order to establish which is the most suitable motor for the proposed application. As follows, the main guidelines for sizing a PMFSM and a SRM [4],[5],[6] are presented in order to have a more transparent comparison.

3.1. Design breviary for the PMFSM

The mean air-gap diameter:

$$D_g = \sqrt[3]{\frac{P_{out} \cdot Q_s}{\sqrt{2} \cdot \pi^3 Q_R \eta \cdot k_L k_E \cos\phi \cdot n_N \cdot B_{g\max} \cdot A_S}} \quad (1)$$

Where, P_{out} is the output power, Q_s and Q_R are the stator and rotor number of poles, k_L and k_E are the aspect coefficient and the emf coefficient, B_{gmax} is the maximum air-gap flux density and A_s is the electrical loading.

The active length will be:

$$L_{st} = k_L \cdot D_g \quad (2)$$

The number of turns per phase:

$$N_t = \frac{Q_S \cdot E}{\sqrt{2} \cdot \pi^2 \cdot k_L \cdot Q_R \cdot D_g^{\,2} \cdot n_N \cdot B_{g\max}} \quad (3)$$

Where E is the induced emf.

The stator pole pitch is computed function of the mean diameter and the number of stator poles:

$$\tau_S = \frac{\pi \cdot D_g}{Q_S} \quad (4)$$

The permanent magnet's width is imposed to a standard value:

$$b_{PM} = 0.0084 \quad (5)$$

The stator tooth width is computed function of the stator slot opening, the permanents magnet's width and the stator pole pitch:

$$b_{pS} = \frac{\tau_S - b_{slS} - b_{PM}}{2} \quad (6)$$

Like in the case of the stator, the sotor pole pitch is given by:

$$\tau_R = \frac{\pi \cdot D_g}{Q_R} \quad (7)$$

The shaft diameter is imposed to a standard catalog value:

$$d_{ax} = 0.045 \quad (8)$$

The height of the rotor poles is given function of the mean diameter, the air-gap length and the shaft diameter:

$$h_{pR} = \frac{D_g - g - d_{ax}}{2} \quad (9)$$

Now the rotor yoke height can be established:

$$h_{yR} = h_{pR} - h_{tR} \quad (10)$$

The cross section of the used wire is function of the phase current and the current density imposed:

$$A_{cond} = \frac{I_f}{J_c} \tag{11}$$

The stator slot area is computed function of the total area occupied by the conductors and the fill factor:

$$A_{slot} = 2 \cdot \frac{A_C}{k_{fill}} \tag{12}$$

Hence, the stator slot height will be:

$$h_{slS} = \frac{A_{slot}}{b_{slS}} \tag{13}$$

The permanent magnet height is computed function of the stator yoke height and the stator slot height:

$$h_{PM} = h_{yS} + h_{slS} \tag{14}$$

Now the outer diameter of the motor can be determined:

$$D_{out} = D_g + 2 \cdot h_{PM} + g \tag{15}$$

3.2. Design breviary for the SRM

In order to be able to compare the two structures, and as the first sized one is the PMFSM, for the SRM, the main dimensions will be imposed to the values obtained for the latter sized machine. All the values are represented in meters (m).
Hence, the air-gap diameter is:

$$D_g = 0.159 \tag{16}$$

and the active length will be:

$$L_{st} = 0.159 \tag{17}$$

The number of turns per phase are imposed to:

$$N_t = 36 \tag{18}$$

The output power will be computed using:

$$P_{out} = \frac{Q_R}{Q_S} \cdot \pi^2 \cdot \eta \cdot k_L \cdot n_N \cdot B_{g\max} \cdot (1 - \frac{1}{k_{CR}}) \cdot A_S \cdot D_g^{\ 3} \tag{19}$$

Where k_{CR} is Carter's factor.
The rater phase current is computed function fo the output power, the supply voltage, the power factor and the machine's efficiency:

$$I_f = \frac{P_{out}}{U_f \cdot \cos\varphi \cdot \eta} \tag{20}$$

Function of the output parameters of the machine, the required electromagnetic torque should be:

$$T = \frac{P_{out}}{2 \cdot \pi \cdot n_N} \tag{21}$$

The SRM's stator pole pitch:

$$\tau_S = \frac{\pi \cdot D_g}{Q_S} \tag{22}$$

The width of the stator pole for the SRM is usually considered, from experience, to be half of the stator pole pitch:

$$b_{pS} = round(0.5 \cdot \tau_S) \tag{23}$$

Hence the stator slot opening will be:

$$b_{slS} = \tau_S - b_{pS} \tag{24}$$

Usually the stator yoke height is considered at the level of compromise between increased saturation and unsaturated core. Hence, from experience, 60% of the stator pole's width is a fair enough value for it:

$$h_{yS} = round(0.6 \cdot b_{pS}) \tag{25}$$

Like for the stator, the sotor pole pitch will be:

$$\tau_R = \frac{\pi \cdot D_g}{Q_R} \tag{26}$$

For a SRM the rotor pole width is usually about 40%-50% of the rotor pole pitch. For this particular case, 40% is considered to be used. Hence:

$$b_{pR} = round(0.4 \cdot \tau_R) \tag{27}$$

The rotor slot opening can now be computed:

$$b_{slR} = \tau_R - b_{pR} \tag{28}$$

As for the stator, the rotor yoke height is percent of the rotor pole width:

$$h_{yR} = round(0.7 \cdot b_{pR}) = 0.017 \tag{29}$$

The shaft diameter is imposed to the same standard value as for th PMFSM:

$$d_{ax} = 0.035 \tag{30}$$

The rotor pole height can now be computed:

$$h_{pR} = \frac{D_g - g - d_{ax}}{2} - h_{yR} \tag{31}$$

Like for the PMFSM the conductor cross section area will be computed using the same eq. 11.

Table 1.
Main dimensions and specifications of the motors.

	Item		Value	
		M.U	PMFSM	SRM
Design	Air-gap	m	0.159	

specification	diameter			
	Active length	m	0.159	
	Air-gap length	m	0.0007	
	Rated phase voltage	V	230	
	Rated speed	rpm	3000	
	Phase number	-	3	
	Number of turns per phase	-	36	
	Stator/Rotor pole number	-	12/10	12/8
Analytically obtained results	Rated output power	kW	30	30
	Phase current	A	58	103.5
	Stator pole pitch	m	0.042	
	Rotor pole pitch	m	0.05	0.062
	Stator pole width	m	0.0114	0.021
	Rotor pole width	m	0.0145	0.024
	Stator slot opening	m	0.0104	0.021
	Rotor pole opening	m	0.0355	0.038
	Stator pole height	m	0.0626	0.042
	Rotor pole height	m	0.0218	0.046
	Stator yoke height	m	0.0125	0.013
	Rotor yoke height	m	0.0347	0.016
	Coil height	m	0.0501	0.037
	Motor's outer diameter	m	0.285	0.2695

The conductor insulation thickness is imposed to a certain standard value:

$$w_{insulation} = 3 \tag{32}$$

The winding for such machine is placed into the slot in layers. The number of layers can be computed:

$$N_{layer} = ceil(\frac{l_{coil} - w_{insulation}}{1.05 \cdot d}) \tag{33}$$

Where 1.05 is a factor, which considers the displacement of one layer on top of the other. Each layer is compound of a certain number of turns. Hence the number of turns per layer:

$$N_{coil\_layer} = ceil(\frac{N_t}{4 \cdot N_{layer}}) \tag{34}$$

The insulation between the coil's lower side and the rotor poles, is imposed to the height of the nonconducting material used:

$$h_{\lim} = 0.005 \tag{35}$$

The stator pole height is computed function of the height of the insulation and the actual height of the winding:

$$h_{pS} = h_{coil} + h_{\lim} \tag{36}$$

The outer diameter of the motor can be now sized:

$$D_{out} = D_g + 2 \cdot (h_{pS} + h_{yS}) + g \tag{37}$$

The value of electromagnetic torque [7],[8] in each case is an important performance indicator to evaluate these motors from Table 1. A motor with a higher electromagnetic torque can reach the desired speed in a shorter time than the one with a lower electromagnetic torque.

The variation of electromagnetic torque versus rotor position at constant phase current, using the numerical analysis, is illustrated in Figure 2.

In all two cases the rotor was moved over a complete electric period, the corresponding electric period being different in each case. The results are closely related to the structure of motors and to the size of permanent magnets in case of the PMFSM.

Figure 2 shows that the highest electromagnetic torque value is obtained for the PMFSM, followed by the SRM witch has the lowest value, respectively 40 Nm [8]. After computing the electromagnetic torque and the active mass of all considered motors, it is easy to determine the torque density.

The corresponding torque density, efficiency, power factor, mass of the active parts and the material cost of the proposed motors are given in Table 2.

Table 2.
Main calculated parameters of the proposed motors

Item		Value	
	M.U	PMFSM	SRM
Total losses	kW	3.05	2.678
Efficiency	-	0.911	0.822
Power factor	-	0.854	0.632

Active mass	Kg	22.38	26.3
Material costs	USD	802	133
Torque density	Nm/Kg	**4.5**	**1.52**

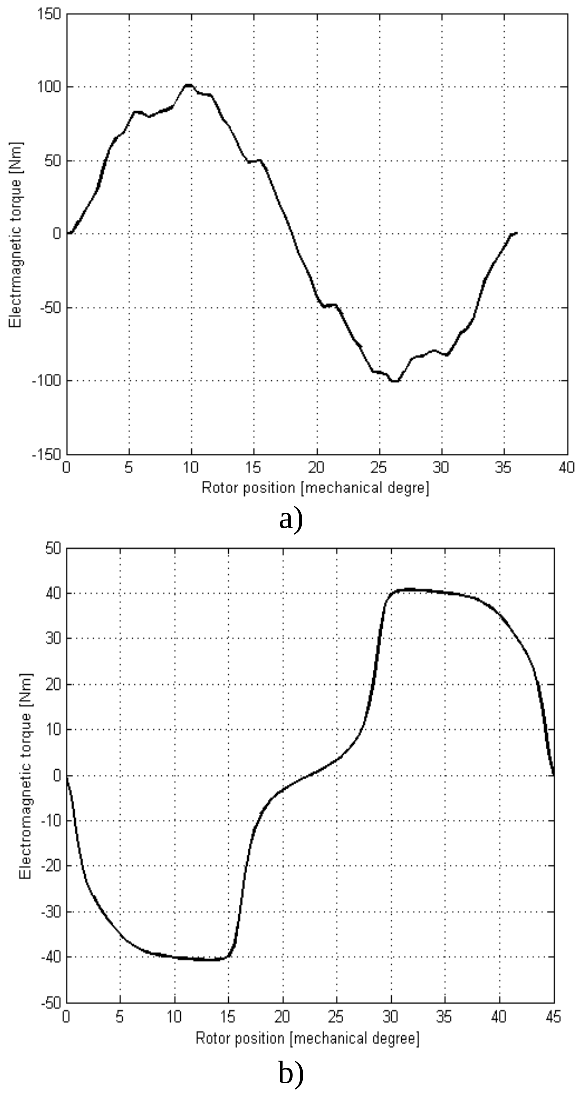


Figure 2. Electromagnetic torque of: a) PMFSM, b) SRM

Analyzing Table 3, it can be observed that the PMFSM has the biggest torque density, the obtained value being 4.5, approximately three times more than the one in case of SRM.

Even if the volume of the PMFSM is bigger than that of the PMSM and the SRM, the PMFSM active mass is the lowest, respectively 22.38 Kg. The mass of the PMFSM is lower compared to that of PMSM due to the reduced weight of the rotor part.

The total weight of rotor part in case of PMFSM is 5.127 Kg. However, the PMFSM is the most expensive due to the necessity of a large quantity of permanent magnets, respectively 7.26 Kg, the total price of materials being 802 USD.

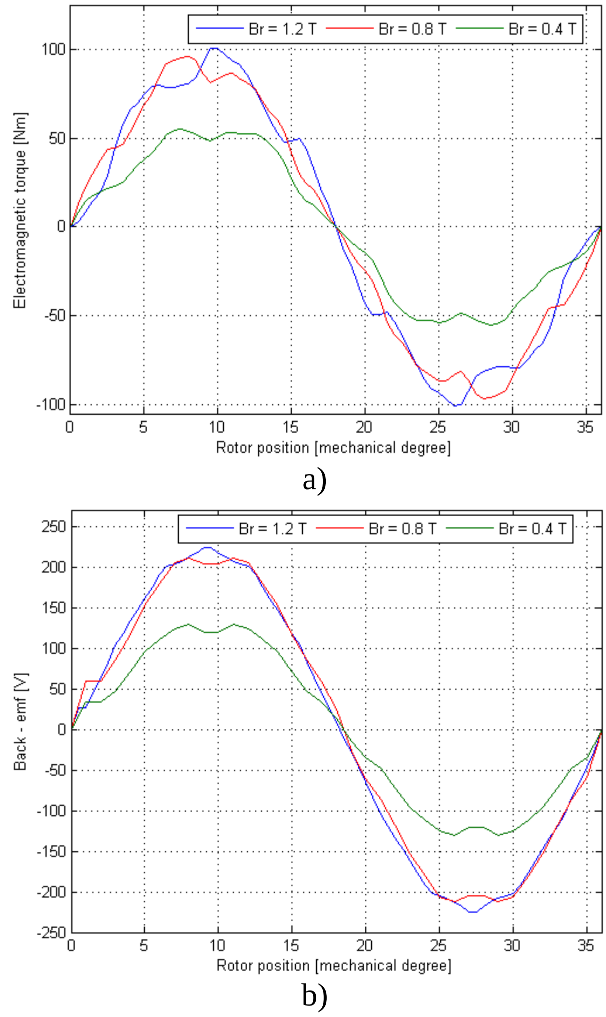


Figure 3. PMFSM electromagnetic torque for different values of Br (a) and back-emf (b)

4. CONCLUSIONS

The necessity of a large quantity of permanent magnets and the high price of the permanents magnets used, respectively of NdFeB with the remanence flux density Br = 1.2 T and the coercive field intensity HC = 910 kA/m, made the permanent magnet motor to be more expensive comparatively with the SRM. The influence of different remanent flux densities values (1.2 T, 0.8 T, 0.4 T) on PMFSM's performances is illustrated in Figures 3a-3b. In conclusion, even if the PMFSM is the most suitable and the possible future applied motor type in HEV applications the SRM has its advantages as low cost and robustness, which makes it an alternative.

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Analiza motorului cu flux variabil şi a motorului cu reluctanţă variabilă folosite în industria de automobile

Rezumat: *Lucrarea detaliză o abordare teoretică, analizând două tipuri de mașini electrice folosite în industria auto. Cele două mașini comparate sunt cele cu flux variabil și cu reluctanță variabilă. Comparația se efectuează pornind de la aceleași cerințe, comparând modul de comportare în regimul motor. Performanțele fiecărei mașini sunt evidențiate pe baza avantajelor și dezavantajelor fiecăreia.*

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