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Comparison between a surface permanent magnet synchronous motor and a segmented stator switched reluctance motor with aluminum windings for light electric traction

Pere Andrada,
GAECEQS, DEE, EPSEVG.
Universitat Politècnica de Catalunya UPC-BARCELONATECH,
Avinguda Victor Balaguer 1, 08800, Vilanova i la Geltrú, Spain
Phone:34 938967732
Fax:34 938967700

Abstract. Nowadays, light electric vehicles are usually powered by drives with motors that use rare-earth permanent magnets. Nevertheless, due to the problems these materials present, light electric vehicle manufacturers are open to considering other alternative drives free of permanent magnets. This paper raises a comprehensive comparison between a surface permanent magnet synchronous motor and a segmented stator switched reluctance motor with aluminum windings for light electric traction, specifically for a motorcycle similar to the Super Soco TCmax.

Key words. Light electric vehicles, Power-train, Permanent magnet synchronous drives, Switched reluctance motor drives.

1. Introduction

E-Mobility means forms of movement that use an electric motor. This definition, given by the German government [1], encompasses: bicycles and motorcycles, cars, buses, trucks, trains, ships, and small airplanes that are powered by batteries or fuel cells. E- Mobility is a key technology for developing a clean and efficient transportation system that outstrips the fossil fuel era. Light electric vehicles (LEVs are those vehicles included in category L in the European Union, Directive 2007/46 /EC [2]. This category of vehicles comprises two, three, and four-wheeled vehicles with limited weight (maximum 550 kg) and power (maximum 15 kW). LEVs contribute to improving mobility and reducing the emission of polluting and greenhouse gases, which are circumstances desired by both government authorities and citizens [3-4].

Usually these vehicles are powered by an electric drive (including motor + electronic power converter + control) of a power comprised between 2 and 15 kW, fed by a battery pack (Pb-Acid, Li-Ion) of voltages between 36 and 100 V. It is necessary to distinguish between direct drives, in which the motor or motors are located inside the wheel (in-wheel motor or hub motors), or drives with a mechanical transmission (gears, toothed belts or chains) between the motor shaft and the wheel (central motors) [5-6].

The motors used in LEVs are, generally, motors with high performance permanent magnets (brushless DC motors, BDCM, or synchronous motors with permanent magnets, PMSM). Nevertheless, nowadays, these high-performance permanent magnets have a high content of rare-earth materials, mainly Neodymium and small amounts of Dysprosium, and present the following drawbacks:

- The high environmental impact of rare earth mining [7]
- The fact that the complete chain of production of permanent magnets (from raw material to final product) comes from China.
- The increase of the demand for rare earth magnets in the wind generation and electric traction industries.
- The uncertainty of its price and the high percentage of the cost of the magnets on the motors that use them.

These drawbacks have favored the tendency to research electric motors with less mass of permanent magnets or even without permanent magnets (PM-less) [8-13], such as induction motor drives (IMD), synchronous reluctance motor drives (SyncRELD), and switched reluctance motor drives (SRMD). The main advantages and disadvantages of the different types of PM-less drives can be found in Chapter 1 of the reference [14].

This paper deals with the powertrain selection for a motorcycle with specifications similar to those of the Super Soco TCmax, Figure 1, which are listed in Table 1. To meet these specifications, the motor should be able to provide the torque-speed characteristic of Figure 2. Two central drives with two different electric motors, were proposed to achieve this objective, both motors with natural cooling: a surface permanent magnet synchronous motor SPMSM) and a segmented stator switched reluctance motor with aluminum windings (SSSRM Al).

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Fig.1. Photograph of Super Soco TCmax

Table I. – Super Soco TCmax main data

Motorcycle type	Performance similar to a $125cm^3$ motorcycle
Motor type	PMSM, central motor with toothed belt
Motor power (peak/rated)	5.1/3.9 kW
Maximum rear wheel torque	180 Nm
Maximum Climbing Angle	17º
Transmission ratio	1:3.8
Front wheel	90/80-17”
Rear Wheel	110/70-17”
Maximum loading weight	150 kg
Battery type	Li-ion
Battery voltage	72 V
Battery capacity	45 Ah
Battery energy	3.24 kWh
Battery weight	22 kg
Maximum range (homologated)	96 km
Maximum speed	95 km/h

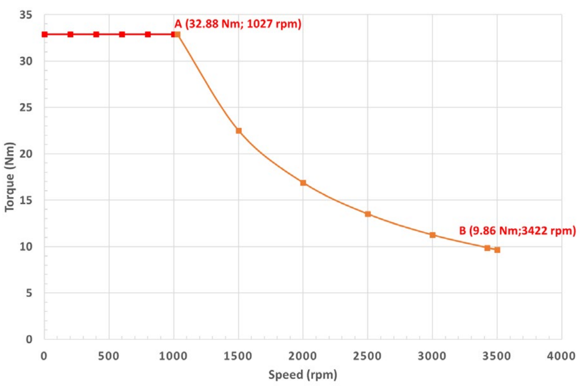

Fig.2. Motor torque-speed characteristic

2. Description of SPMSM drive.

The Super Soco TCmax uses a permanent magnet synchronous drive that was purposely developed. Given the impossibility of carrying out the benchmarking of this drive, it has been decided to design a new one with similar characteristics. Then, a three-phase SPMSM with 10 poles and 12 stator slots was designed [15]. The motor was powered by a 72 V battery of Li-ion, through a three-phase inverter controlled by field-oriented control. The maximum phase voltage is about 30 V. The winding is concentrated with a number of slots per pole and phase of 0.4. The permanent magnets were NdFeB magnets (N35 UH). Figure 3 shows the cross-section of the designed SPMSM.

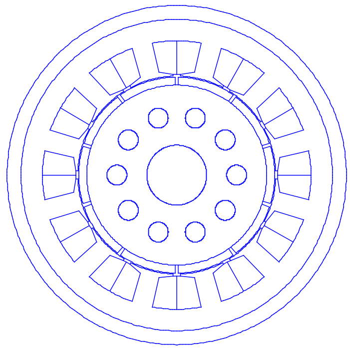

Fig.3. Cross-section of the designed SPMSM

A finite element analysis (FEA) of the SPMSM was performed. Figure 4 shows the distribution of field lines when the currents are $\hat{I}_a$ = 76.37 A and $\hat{I}_b = \hat{I}_c$ =38.18 A. From FEA the main parameters of the motor were obtained. The normal component of the airgap magnetic flux density is given in Figure 5. Static torque versus load angle curves is depicted in Figure 6. The phase resistance, $R_{20ºC}$; phase inductances (magnetizing inductances in d and q axis L_{md}, L_{mq}, and leakage inductance of end-winding L_{σ}); and the induced voltage per speed are listed in Table II.

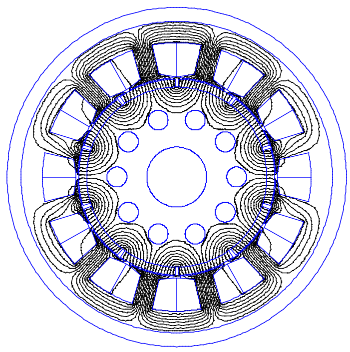

Fig.4. Distribution of magnetic field lines in the SPMSM

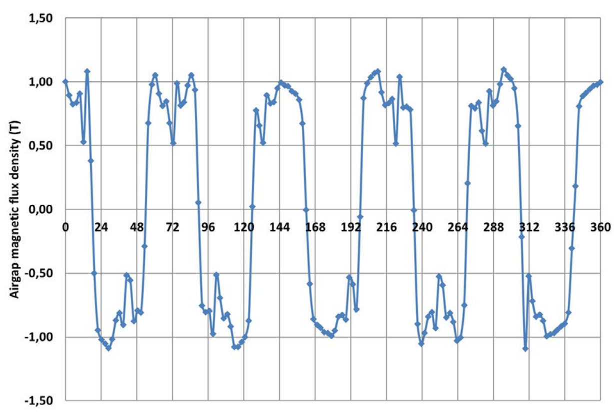

Fig.5. Airgap magnetic flux density (T) versus position (elec º) without currents

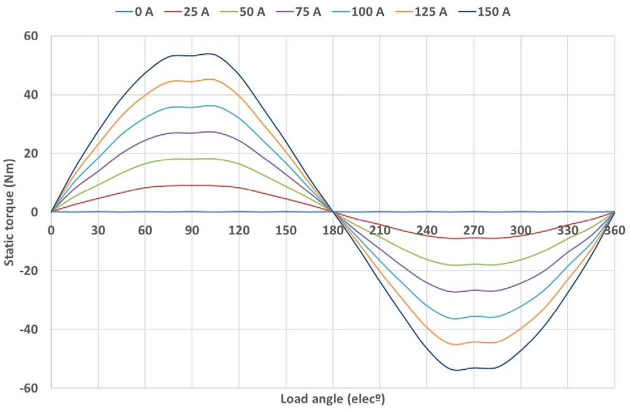

Fig. 6. Static torque curve vs load angle (elecº) SPMSM

Table II SPMSM parameters

$R_{20^\circ C}$ (mΩ)	20
L_{md} (µH)	229
L_{mq} (µH)	229
L_{σ} (µH)	11.09
E(V) @ 1000 rpm	17,55

3. Description of SSSRM drive.

In previous papers, authors presented a segmented stator switched reluctance motor (SSSRM) drive for light electric vehicles [16-17]. It was a three-phase 12/10 SSSRM with multiplicity 2 with the stator formed by 6 independent U-core with 12 stator poles while the rotor had 10 poles, Figure 7. In each U-core, there were two coils wound on each of their legs and connected in series. The parallel connection of the diametrically opposite U-core coils formed a motor phase. The conductors were of copper with a rectangular section.

In this paper a three-phase12/10 SSSRM drive but with aluminum windings is considered

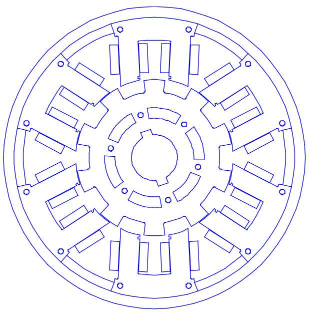

Fig. 7. Cross section of the 12/10 SSSRM with copper winding

In electrical engineering, aluminum is used as line conductors (aluminum cable steel-reinforced) in overhead line transmission, in distribution isolated cables, and in squirrel-cage of small and medium asynchronous motors. In the USA, a high percentage of dry transformers rated 15 kVA or larger, and some fractional motors use aluminum windings. Copper is the most commonly used conductor in electrical machine windings, mainly due to its high electrical conductivity (1.64 times greater than aluminum). However, there are some considerations, such as lower density (0.3 lower than copper), and lower cost (the ten-year average copper aluminum price ratio was of 3.5, Figure 8) that favor aluminum. From the environmental impact of each, even when considering the 62% additional amount of aluminum needed for equal resistivity, aluminum has much less environmental impact than copper. In addition, aluminum windings are easier to separate from electric steel in the scrapping process. All these arguments make aluminum attractive in machines that require a high power/mass ratio and low costs [18-19].

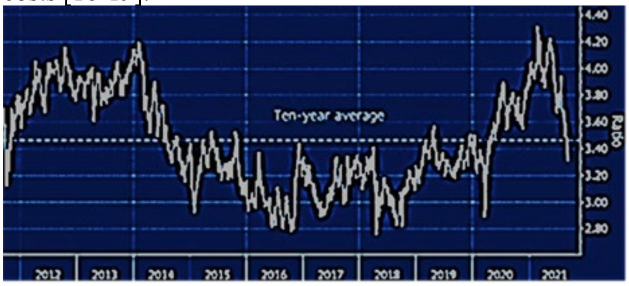

Fig.8. Evolution ratio Cu /Al price (source LME)

The SSSRM proposed in this paper has the same stator and rotor structure of that of Figure 5 but with the coils of aluminum arranged toroidally, Figure 9. The aluminum wire has rectangular section (3.55x2.24 mm^2) and is taped with Nomex T410 CTE.

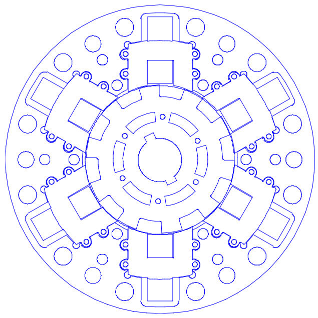

Fig.9. Cross section of the designed 12/10 SSSRM Al

The motor was powered by a 72 V battery of Li-ion, through an asymmetric half-bridge converter (with two switches and two diodes per phase) controlled by hysteresis and single pulse control with variable turn-on and turn-off angles. FEA of the SSSRM was performed. Figure 10 shows the distribution of the field lines for a flat-topped current of 200 A. Figure 11 depicts the magnetization curves, and Figure 12 the static torque curves versus position. The phase resistance at 20ºC is 17 mΩ.

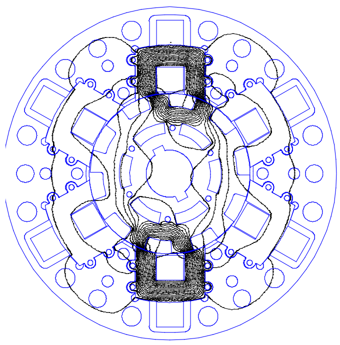

Fig.10. Distribution of magnetic field lines in the SSSRM Al

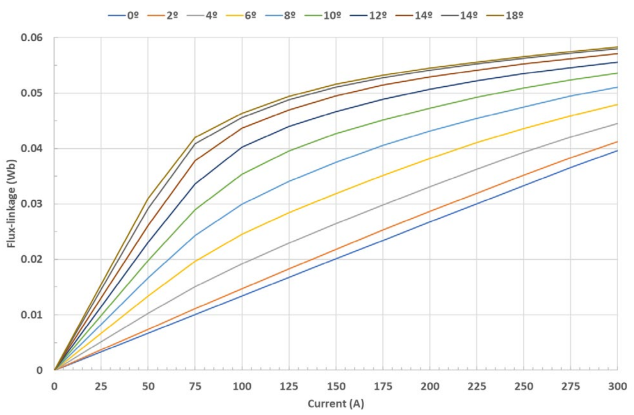

Fig.11. Magnetization curves SSSRM Al

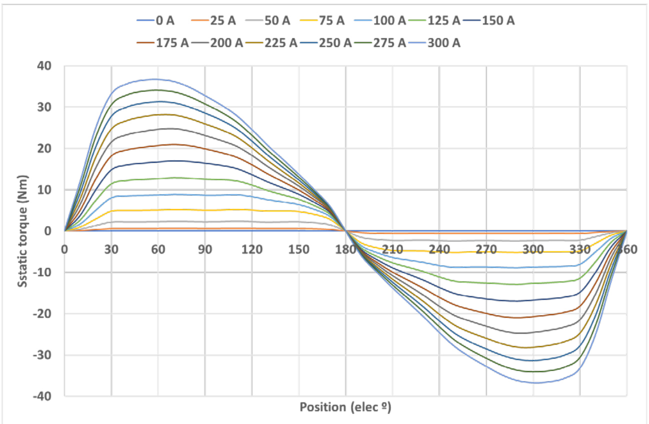

Fig.12. Static torque vs position (elecº) SSSRM Al

4. Comparison and discussion

In general, the main advantage of the SPMSM drive is its high-power density. In contrast the main advantage of the SSSRM is its constructional simplicity and the complete absence of permanent magnet. The main recognized drawbacks of both drives are listed in Table III.

Table III. Main drawbacks of SPMSM and SSSRM

SPMSM	SSSRM
Use of permanent magnet	Asymmetric half-bridge power converter (it has a lack of commercial availability [20])
Cogging torque	Large DC-link capacitors must be used as buffers because of the huge amounts of energy stored and transferred back and forth between the DC source and the motor
	Each phase winding requires two external cables
	High torque ripple and acoustic noise

In the specific case of the proposed SPMSM and SSSRM drives, the comparison should consider the following aspects:

A. Dimensions

The main dimensions of both motors are outlined in Table IV. The SSSRM Al boasts a high output diameter as a result of its modular construction and toroidal disposition of its coils. After constructing the SSSRM Al, it was found that the axial length support pieces of the U-cores could be decreased. This would enable a significant reduction in the volume of the motor (dimensions marked with*).

Table IV. Main dimensions

Main dimensions	SPMSM	SSSRM Al
D, inner stator diameter (mm)	99.2	120
L, stator axial length (mm)	80	60
δ, airgap (mm)	0.5	0.5
D_o, output stator diameter (mm)	170	248
L_o, output stator axial length (mm)	160	160 (130)*
Motor volume (dm^3)	3.63	7.73 (6.28)*

B. Mass of active materials

The mass of active materials is shown in Table V. The mass of electric steel is more or less the same. On the other hand, the mass of copper is almost 2 kg in the SPMSM while that of aluminum in the SSSRM is barely one kg. Obviously, the choice of the SSSRM drive means significant savings of NdFeB.

Table V. Mass of active materials

Mass of active materials	SPMSM	SSSRM Al
Mass of electric steel M270-50A	7.50 kg	7.67 kg
Mass of PM, N35 UH (180ºC)	0.68 kg	-
Mass of copper	1.98 kg	-
Mass of aluminum	-	0.99 kg

C. Performance

The SPMSM and the SSSRM drives meet with the required specifications. In Table VI are shown the values obtained in each case.

Table VI. Performance

Performance	SPMSM	SSSRM Al
Torque (Nm) @ 1027 rpm	33	32.21
Torque (Nm) @ 3422 rpm	9.83	9.81
Efficiency @ 20 Nm and 2000 rpm	90.3	88.70

Apart from these considerations, it is important to keep in mind that in the SSSRM, the maximum phase voltage, because it is fed through an asymmetric half-bridge converter, is equal to the battery voltage, while in the

SPMSM, it is equal to the maximum inverter output phase voltage. Furthermore, a look at Figures 5 and 11 shows that in the SPMSM the torque is obtained with a much lower current value, because in this motor, there are always three phases conducting while in the SSSRM there is usually only one active phase.

To complete this comparison a study of noise, vibration, and harshness (NVH) should be conducted.

5. Conclusions

In this paper, an SPMSM drive and an SSSRM Al drive were compared, and both demonstrate that are able to meet the specifications required to propel an electric motorcycle. It is difficult to respond to which of these two options is the best. It depends on the starting goals. If the most important is the highest power density with high efficiency in the short term the answer is SPMSM. If some other arguments are placed on the table, SSSRM has more options, although, in many aspects, it is a technology that still has a long way to go.

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