In-Wheel Axial-Flux SRM Drive for Light Electric Vehicles

Pere Andrada, Balduí Blanqué, Eusebi Martínez, José I. Perat, José A. Sánchez, Marcel Torrent
GAECE, DEE EPSEVG.
Universitat Politècnica de Catalunya UPC-BARCELONATECH,
Vilanova i la Geltrú, Spain
pere.andrada@upc.edu

***Abstract*— Revenues from global sales of light electric vehicles are expected to grow from $ 9.3 billion in 2017 to $ 23.9 billion in 2025. In order to boost this growth electric drives with better features and lower costs have to be developed. This paper presents a new in-wheel axial-flux switched reluctance motor with double rotor and a particular disposition of the stator and rotor poles that provides short flux path without flux reversal. The magnetic active parts of the stator and the rotor are built using soft magnetic composites. The motor is fed from batteries trough a on purpose designed electronic power controller. Simulation of the whole drive, using Matlab-Simulink coupled with the results of the three dimensional finite analysis of the motor is carried out. Simulation results prove that the proposed in-wheel axial-flux switched reluctance motor drive is adequate for the propulsion of electric light vehicles.**

Keywords*—switched reluctance machines, axial flux machines, soft magnetic composites, electric drives, electric light vehicles.

I Introduction

Light electric vehicles (LEV) are electric vehicles, tricycles or quadricycles, with a limited speed and load capacity (for instance, in the USA 25 mph and 3000 lb.) and two-wheeled electric vehicles such as motorcycles and scooters. Light electric vehicles contribute to improving mobility and reducing the emission of polluting and greenhouse gases, circumstances desired both by government authorities and by citizens. Given their size, they can be parked in small spaces and help reduce traffic congestion; in addition, these vehicles are generally more affordable than cars. As a result of these advantages, they currently lead global sales of electric vehicles. The global market for light electric vehicles is expected to grow from 9.3 trillion dollars in 2017 to 23.9 trillion dollars in 2025. China and especially other countries in Asia (Indonesia, Vietnam, Japan and India) are the markets where the highest growth is expected [1]. In Europe and the USA the growth will be more moderate and will depend on the appearance of more attractive models and political decisions tending to restrict the use of internal combustion vehicles. These vehicles are powered by an electric drive (including motor + electronic power converter + control) of a power comprised between 2-10 kW, through a battery pack (Pb-Acid, Li-Ion) of voltages between 48 and 100 V. There are two different types of electric drives for LEVs: direct drives, in which the motors are located inside the wheel or wheels (in-wheel motor or hub motors) and drives with a mechanical transmission (gears, toothed belts or chains) between the motor shaft and the wheel [2]. Despite in-wheel motor drives have some drawbacks such as the increase of unsprung mass that deteriorates ride comfort they have some advantages such as avoiding mechanical transmission and leaving more useful space in the vehicle.

Nowadays, the most usual in-wheel motors are brushless d.c. motors or permanent magnet synchronous motors with external rotor. Nevertheless, switched reluctance motors due to the absence of permanent magnets and rugged construction are a promising alternative. Usually the rotary switched reluctance machines (SRM) are radial flux machines where the air gap flux is mainly in the radial direction relative to the axis of rotation. This type of SRM, usually have a cylindrical shape with a stator and a rotor that can be internal, the most common disposition, or external. A less usual rotary switched reluctance machine is the axial flux SRM in which the air gap flux is mostly parallel to the axis of rotation. The stator and rotor are in parallel plates arranged perpendicular to the axis of rotation. Some studies carried out in axial flux switched reluctance motors; demonstrate that with this type of machine is possible to obtain higher torque density than in radial flux switched reluctance machines. These better features of the axial flux switched reluctance machine are due to the increase of the air-gap area, which depend on the diameter of the machine, whereas in the radial type machine air-gap area depends on the machine length. Although, a first axial-flux variable reluctance motor was reported by Unnewher and Koch, as early as 1973 [3], recently, some authors have made important contributions to the development of axial-flux switched reluctance machines. Arihara et al. have presented the basic design methodology for the axial counterpart of the classic rotary SRM [4]. Murakami et al, have studied the optimization of an axial-flux 18/12 SRM [5]. Madhavan el al. have contributed to development of the axial counterpart of rotor segment SRM in a machine with two rotor and a stator with a toroidal type winding [6]. Labek et. al.

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have proposed a novel multiphase pancake shaped SRM with a stator composed of a series of C-cores, each with an individual wound coil, perpendicularly disposed to a rotor made with aluminium in which a suitable number of cubes, the rotor poles, of high permeability material have been added. In this machine, the torque production is due to the tendency of any of these cubes to align with the two poles of an energized C-core [7]. Some authors have exposed the manufacturing problems of these machines and proposed to use different materials for building its magnetic circuit as grain oriented electrical steel, Ma et al. [8]; soft magnetic composite, Kellerer et al. [9]; sintered lamellar soft magnetic composite, Lambert et al. [10]. This paper presents a summary of the work developed by the authors [11, 12] about a new axial flux-switched reluctance machine (AFSRM), with a particular distribution of stator and rotor poles that results in short flux paths without flux reversal, specially intended for the propulsion of LEVs.

II DESCRIPTION OF THE PROPOSED AFSRM

A. Basic considerations

In this paper a novel axial-flux SRM (AFSRM) with a stator sandwiched by two rotors has been designed for LEVs, this machine is a particular case for a three phase with multiplicity equal two of the family of axial-flux SRM presented in [12]. In Fig, 1 a schematic view of the proposed AFSRM is shown. The stator and the rotors are disposed in parallel planes that are perpendicular to the rotation axis. Each rotor is separated of the stator by an air-gap. Both rotors are formed by a number of poles, N_R, that are all joined, on the opposite side of the air-gap, by means of an annular flat piece. The rotor poles and the annular flat piece are made of ferromagnetic material. The stator is formed by a number of poles, NS, protruding at both ends and with the same length of a structural disk nailed to a hollow shaft. The cross section of a stator pole is triangular but could be of other shapes. The poles are made of ferromagnetic material and the structural disk of a nonmagnetic material.

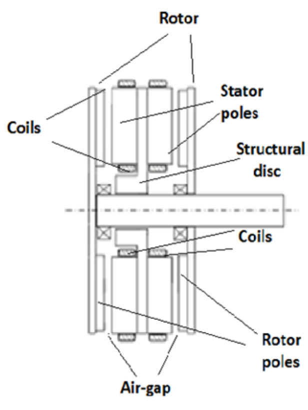


Fig.1 Schematic view of AFSRM

Two coils are wound in both opposite ends of the stator poles and are connected in series. A group of two stator poles, with their corresponding coils and connected between them in such a way that results in a single flux loop, which is closed through two rotors poles is called a double electromagnet, Z. The number of poles and therefore the number of double electromagnets will be given according to the number of phases of the machine, m, by the following relationships:

$$Z = k\,m \quad (1)$$

Where, k, is an integer denominated multiplicity, that is the number of working stator pole pairs. In the case of $k > 1$ the phase windings are obtained by connecting in a proper way the k different double electromagnets of each phase. In any case the terminals of the phase windings are led out of the machine through the hollow shaft.

The number of stator poles, N_S, in consequence is given by:

$$N_S = 2Z = 2k\,m \quad (2)$$

Both rotors have a number of rotor poles, N_R, that have to accomplish the following rule:

$$N_R = k\,(2\,m - 1) \quad (3)$$

The angle, γ, between the axes of two consecutive double electromagnets in the stator is given by:

$$\gamma = \frac{360^{\circ}}{Z} \quad (4)$$

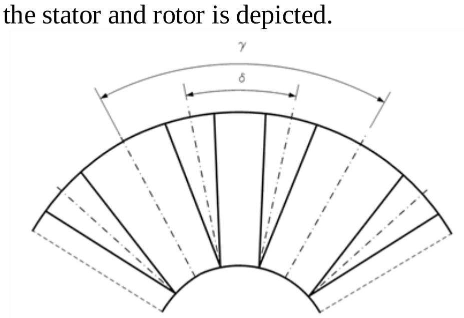
And the angle, α, between two rotor poles is equal to:

$$\alpha = \frac{360^{\circ}}{N_R} \quad (5)$$

Therefore the angle, δ, between the axes of the stator poles of two consecutive double electromagnets is:

$$\delta = \gamma - \alpha = \frac{360^{\circ}\cdot(N_R - (k \cdot m))}{k \cdot m \cdot N_R} \quad (6)$$

In Fig. 2 the disposition of the aforementioned angles (α, γ and δ) in the stator and rotor is depicted.



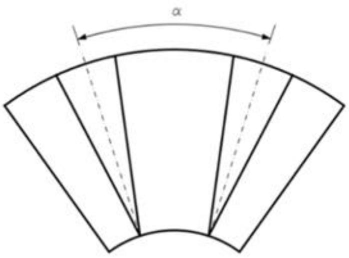


Fig. 2 Disposition of the double electromagnets in the proposed AFSRM, up stator, down rotor

Fig 3 shows the flux path when a current flows through the coils of a double electromagnet. The flux lines link the stator poles of both sides with the poles of the two rotors forcing the alignment of these poles in any case there is flux reversal.

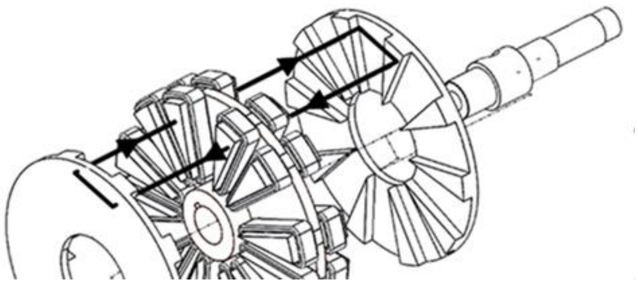


Fig. 3 View of the flux path in one double electromagnet

B. *Magnetic material considerations*

The construction of the magnetic circuit of the proposed AFSRM is difficult to make using silicon iron laminations. The magnetic parts of the stator and the rotors of this machine were made of SMC (Soft Magnetic Composites) [13-15]. SMC are iron powder particles separated with an electrically insulated layer. SMC offer: unique combination of magnetic saturation and low eddy current losses, 3D-flux carrying capability and cost efficient production of 3D-net shaped component by the powder metallurgy process.

However, SMC has low induction of saturation and higher specific losses than the silicon iron steels commonly used in high-performance electric machines, for instance M250-35A. Two different SMC materials were considered: first Somaloy P, material specially intended for prototypes and SMC 700 3 P. In Fig. 4 the B-H curves of both SMC materials are compared with the B-H curve of M235-35 A and table II shows the values of iron losses at different frequencies of these materials. From this comparison it follows that both types of SMC have lower magnetic properties than silicon iron M235-35 nevertheless the use of magnetic short circuits without flux reversal as has been described before, can minimize these problems greatly because the iron losses are roughly proportional to the length of the magnetic flux loop.

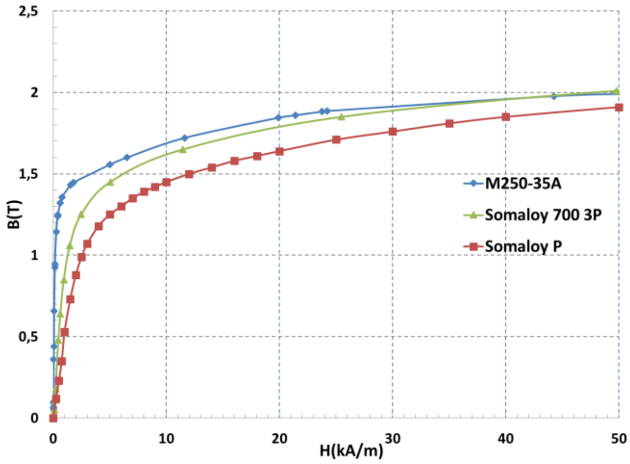


Fig 4 Comparison of manufacturer's B-H curves between M250-35 A and two types of SMC: Somaloy P and Somaloy 700 3P

TABLE I. CORE LOSSES OF THE MAGNETIC MATERIAL CONSIDERED

Core losses (W/kg)	M235-35A	Somaloy P	Somaloy 700 3P
1.5T, @ 50/60 Hz	2,35	11/13	10/12
1.5T, @ 200 Hz	19.6	45	43

C. *Description of the prototype of AFSRM*

A prototype of this in-wheel AFSRM with natural cooling was designed with the goal to be able to propel a direct traction, without transmission, light electric scooter with wheels of 13´´. A maximum torque of 170 Nm is required between 0 to 20 km/h (~220 rpm) and a constant power of 4 kW between 20 km/h (~220 rpm) to 80 km/h (~900 rpm). Due to the machine has to be placed inside a wheel of 13'' the maximum external dimensions are a diameter of the motor frame of 308 mm and an axial length of 116 mm. The machine is powered through a power controller of a battery of 48/72 V. The prototype, a three phase AFSRM with multiplicity two, has the values of the Table II according equations (1-6), in Fig 5 an exploded view of it is shown.

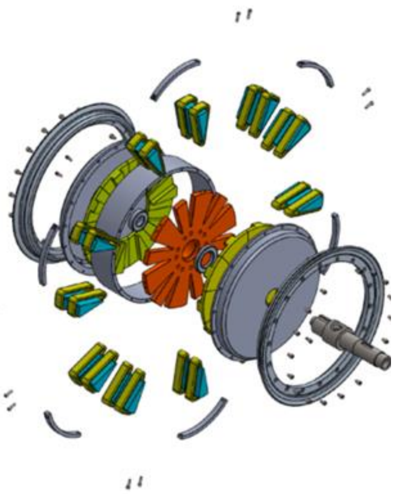


Fig.5 Exploded view of the prototype AFSRM

TABLE II CONFIGURATION OF THE AFSRM PROPTOTYPE

k	m	Z	N_S	N_R	α(°)	γ(°)	δ(°)
2	3	6	12	10	36	60	24

For constructive reasons, as can be observed in Fig. 5, the stator poles were made of SMC and inserted into the supporting disk, in red in the Fig. 5. Otherwise, the rotor poles and the annular flat piece are a set made of N_R parts of SMC and glued to both covers of the machine. The covers and the supporting ring are made of aluminum. In Fig. 6 photographs of the stator pole and the rotor pole pieces are shown. For the winding of the AFSRM prototype, two different alternatives both using insulation of thermal class 180ºC, were considered. First opposite double electromagnets are connected in series, Fig. 7, with *Nc* turns per coil each conductor with two wires in parallel of diameter d. Second opposite double electromagnets are connected in parallel, Fig. 8, with 2*Nc* turns per coil each conductor with a single wire of diameter *d*. Finally, in order to facilitate the construction of the winding the second alternative was chosen each coil with 32 turns, and instead of round wire, rectangular wire was used (2 x 2.39 mm^2). This solution results in a very low skin factor since the maximum expected frequency of the currents in the machine is 200 Hz (corresponding to a maximum speed of 1200 rpm) and, in addition, provides a filling factor of 56.4%. In Fig. 9 a photograph of the stator with the stator poles inserted into the supporting disk and with the disposition of two adjacent pre-wounded coils can be seen. The measured total phase resistance (20ºC) of the winding, including 2 m of output cable (AWG7), was of 60 mΩ.

Fig 6 Stator pole (up) and rotor pole pieces (down) made of SMC

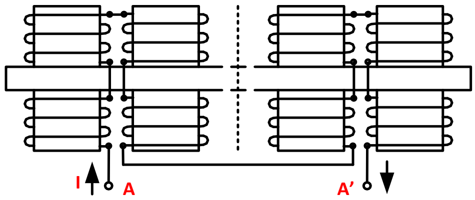


Fig 7 Schematic drawing of one phase of the AFSRM showing the coils arrangement and the series connection of the double electromagnets diametrically opposed

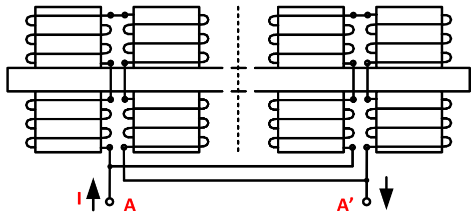


Fig 8 Schematic drawing of one phase of the AFSRM showing the coils arrangement and the parallel connection of the double electromagnets diametrically opposed.

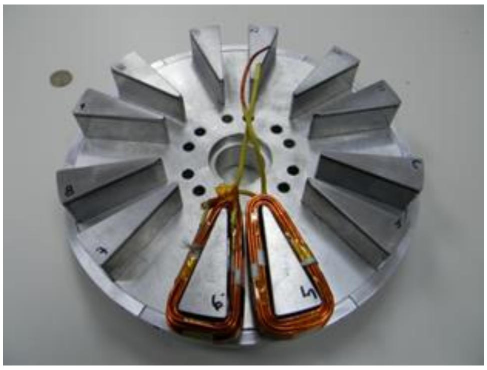


Fig. 9 Stator showing the inserted pole pieces and the disposition of two adjacent coils

Before completing the winding, it is advisable, given the cooling conditions of the prototype, to evaluate the heating of the coils. Four sensors of temperature were disposed in the coils forming one double electromagnet, half phase, as shown in Fig. 10. The coils were crossed by a square waveform of current resulting different values of current density the temperature rise versus time of the hottest sensor T2 for those values of current density are recorded in Fig.11. A thermogram, Fig.12, of the coils taken with an infrared camera shows the homogeneous distribution of temperature of the coils. From the obtained results can be stated that the machine can withstand a current density of 6.28 A/mm^2 for 15 minutes; maintain a current density of 5.23 A/mm^2 for more than 30 minutes and work continuously for a current density of 4.18 A/mm^2.

A view of the complete stator, including winding, and the two covers showing the glued rotor pole pieces can be seen in fig.13.

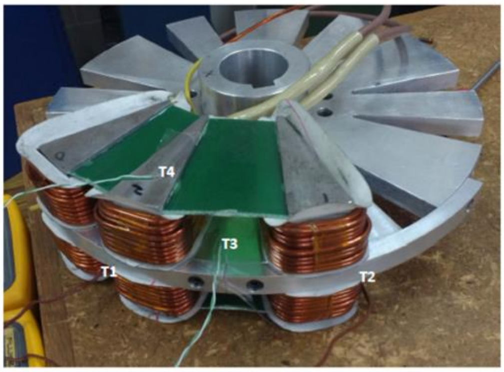


Fig.10 Disposition of temperature sensors

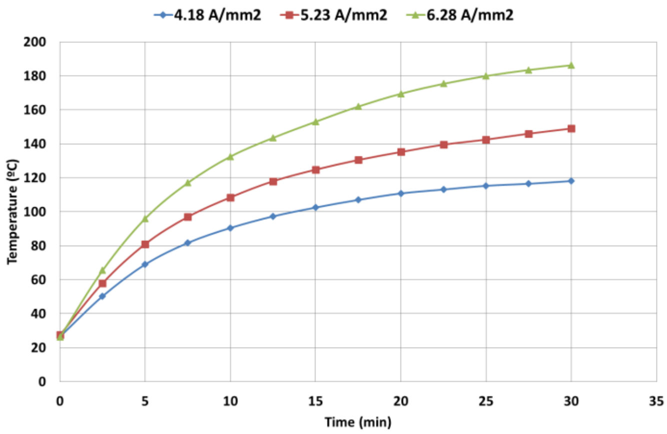


Fig.11 Temperature rise vs time for different values of current density

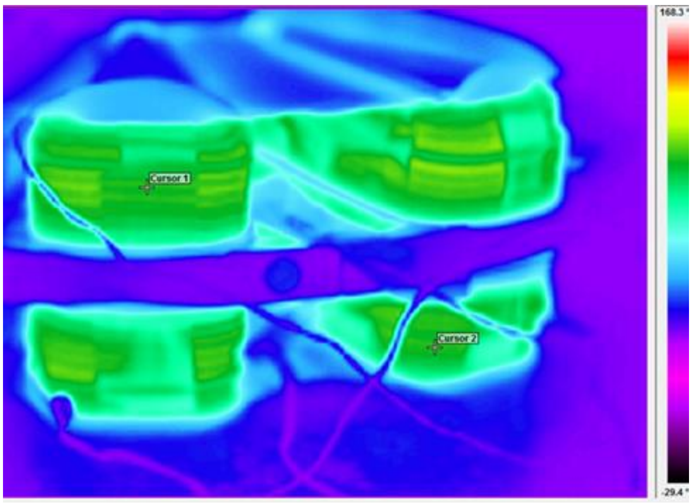


Fig.12 Thermogram of the coils that forms a double electromagnet for a current density 6.28 A/mm^2 (after seven minutes) cursor 109.5ºC cursor 2 109.7ºC

Fig. 13 Stator and the two covers, showing in the middle cover the SMC rotor pieces mounted

III ELECTROMAGNETIC ANALYSIS OF THE AFSRM

The electromagnetic analysis of the prototype of AFSRM was performed using the well-known 3D finite element package, Flux 3D [12,16]. The study considered the use of Somaloy P and Somaloy 700 3P as magnetic material for the stator poles and rotor pieces. A map of the flux densities of the AFSRM prototype, omitting the aluminum frame and covers, for the aligned position and a current of 100 A can be seen in Fig.14. As results of this electromagnetic analysis in Fig.15 the magnetization curves for the aligned and unaligned position are depicted and in Fig. 16 static torque curves are shown. From these results is clear that better performances can be obtained using Somaloy 700 3P, therefore this was the material used in the construction of prototype. For practical and economic reasons the stator pole and rotor pole pieces of the AFSRM prototype were manufactured by tooling pre-fabricated blanks of Somaloy 700 3P instead of by sintering.

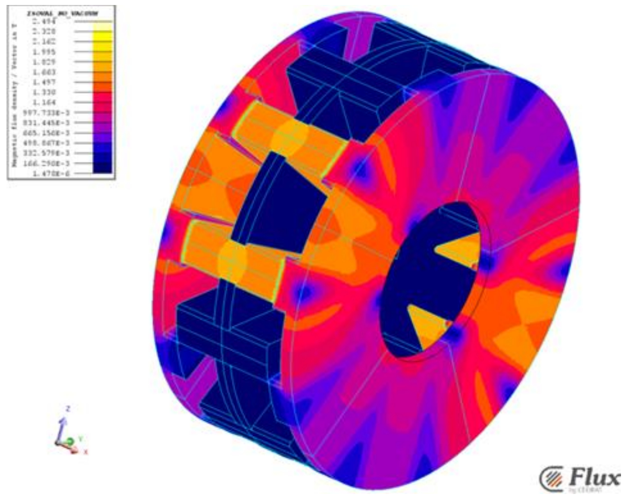


Fig.14 Map of flux densities of the prototype of AFSRM for the aligned position for a current of 100 A

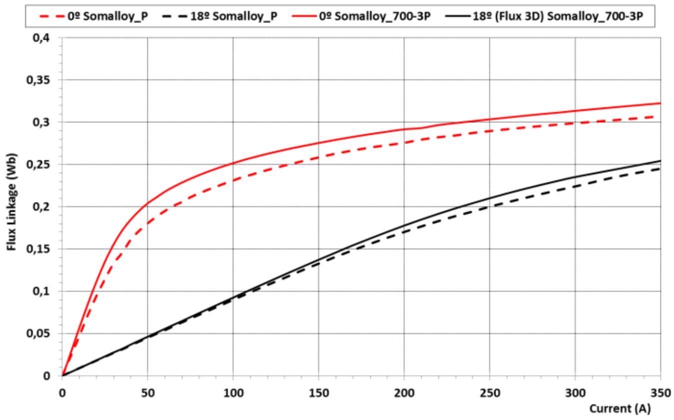


Fig.15 Magnetization curves in the aligned (0º) and unaligned (18º) position the prototype of AFSRM using Somaloy P and Somaloy 700 3P

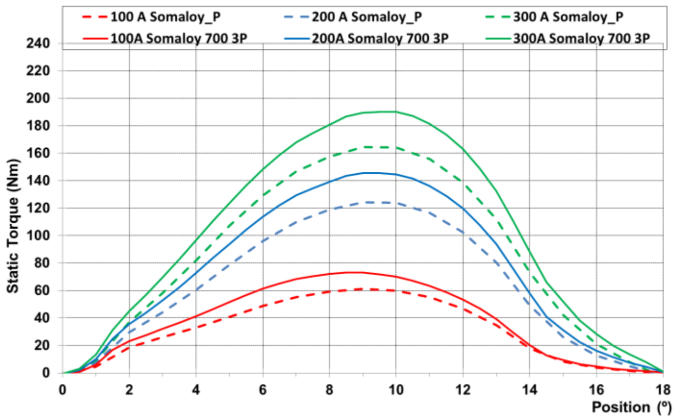


Fig. 16 Static torque curves for the prototype of AFSRM using Somaloy P and Somaloy 700 3P

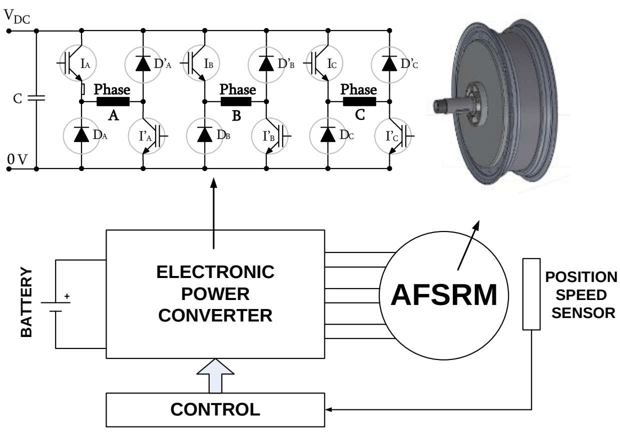


Fig. 17 Block diagram of the prototype of AFSRM drive

IV SIMULATION OF THE AFSRM DRIVE

A block diagram of the whole drive, including the battery, the power converter, the control and the prototype of AFSRM is shown in Fig. 17. The battery ($LiFePo_4$, LFP) is of 72 V. The power converter is an asymmetric or classic converter for SRM specially designed to power SRM for LEVs. As a first option of control, the hysteresis control with variable turn-on and turn-off angles is used for the lower range of speeds and single pulse with variable turn-on and turn-off angles for upper values of speed. The model of simulation is implemented in Matlab-Simulink using the results of the finite element analysis of the prototype of AFSRM. The Simulink block diagram of the axial-flux SRM drive is shown in Fig. 18. The simulation results allow obtaining the waveforms of the electrical magnitudes of the drive, as well as the internal electromagnetic torque. Thus, in Fig. 19 the waveforms of phase voltage, phase current, bus current and total torque for an average torque of 120 Nm at 300 rpm with hysteresis control and a turn-on angle of ϑ_{ON} = - 5º and a turn-off angle of ϑ_{OFF} = 15º are shown. In Fig 20 the same waveforms for an average torque of 40 Nm at 900 rpm with single pulse control and a turn-on angle of ϑ_{ON} = -8.5º and a turn-off angle of ϑ_{OFF} = 10º are represented. Therefore, with this model is possible to predict the behavior of the whole drive for the intended application. Thus, as it can be seen in Fig. 21 the proposed drive is able to work inside the torque-speed envelope required for the E-scooter that has to propel.

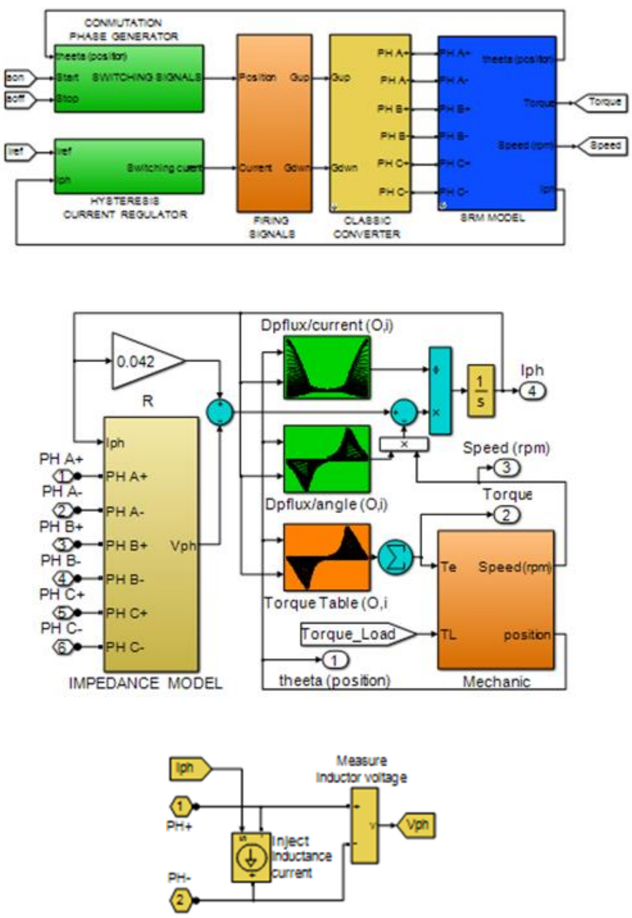


Fig.18 Matlab-Simulik block diagram of the whole AFSRM drive with detail of the Simulink model of the AFSRM.

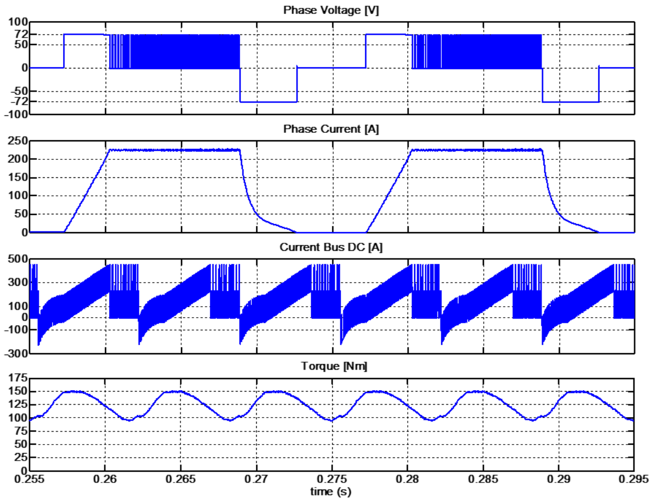


Fig.19.- Waveforms of phase voltage, phase current, bus current and total torque for an average torque of 120 Nm at 300 rpm

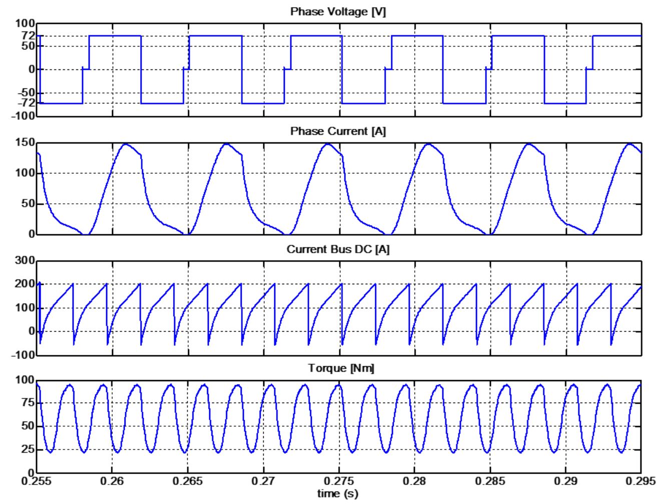


Fig 20 Waveforms of phase voltage, phase current, bus current and total torque for an average torque of 40 Nm at 900 rpm

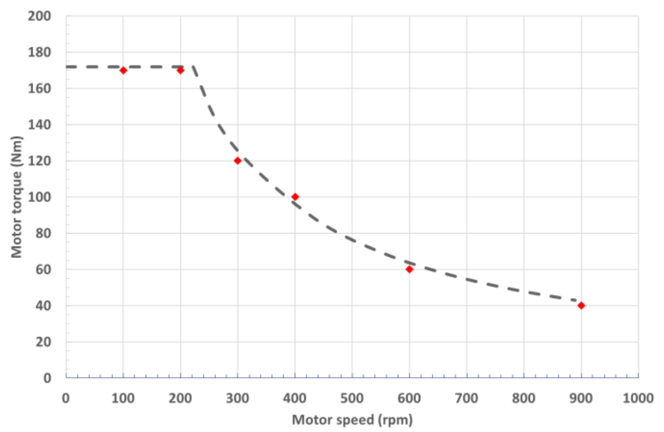


Fig. 21 Comparison between the expected values of torque-speed envelope (dotted line) with the simulated values with 72 V of battery voltage using Somaloy 700 3P (markers in red)

V CONCLUSIONS

In this paper a new in-wheel axial-flux switched reluctance motor, AFSRM, drive, specially intended for the propulsion of light electrical vehicles, is presented. This motor is constituted by a stator sandwiched by two rotors. The particular arrangement of the stator and rotor poles gives rise to short flux paths without flux reversal. Due to the difficult to manufactures the magnetic circuit using laminated silicon iron it was made of soft magnetic composites. The complete electromagnetic analysis of the prototype is performed using 3D-FEA. The simulation of the whole drive, taking into account the AFSRM, the power converter and the control strategies is implemented in Matlab-Simulink using the results obtained from the electromagnetic analysis. Simulations show that the performances of the drive, match pretty well the requirements of the LEVs.

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Pere Andrada (M'91) was born in Barcelona (Spain) in 1957. He received the M.Sc. and the PhD. degrees in Industrial Engineering from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain, in 1980 and 1990 respectively. In 1980 he joined the Department of Electrical Engineering, Universitat Politècnica de Catalunya UPC, where he is currently Associate Professor in the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSVG). He is member of the Electronically Commutated Drive Group (GAECE). His teaching activities and research interests include design, modelling and control of electrical machines and drives.

Balduí Blanqué was born in Reus (Tarragona, Spain) in 1970. He received the B.S. degree in Telecommunications, the M.S. degree in Telecommunications, and the Ph.D. degree from the Universitat Politècnica de Catalunya (UPC), in Barcelona, Spain, in 1996, 1999, and 2007, respectively. Since 1996, he has been with the Department of Electrical Engineering, Universitat Politècnica de Catalunya (UPC), where he is currently Associate Professor in the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSVG). He is member of the Electronically Commutated Drives Group (GAECE). His teaching activities cover digital design and electronics applications and his research interests include modelling, simulation and control of electrical machines and drives.

Eusebi Martínez was born in Barcelona (Spain) in 1960. He received the Engineer degree in Industrial Engineering from Universitat Politècnica de Catalunya in 1984. He is currently an Assistant Professor, in the Department of Electrical Engineering, Universitat Politècnica de Catalunya, in the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSVG). He is member of the Electronically Commutated Drives Group (GAECE). His teaching activities and research interests include design and finite element analysis of electrical machines.

José I. Perat was born in Tamarite de Litera (Huesca, Spain), in 1965. He received the B.Sc., M.Sc. and PhD. degrees in Industrial Engineering from the Universitat Politècnica de Catalunya (UPC), in 1989, 1998 and 2006 respectively. He is currently an Associate Professor in the Department of Electrical Engineering, Universitat Politècnica de Catalunya, in the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSVG). He is member of the Electronically Commutated Drives Group (GAECE). His teaching activities and research interests include power electronics and control of electric machines and drives.

José A. Sánchez was born in Vilanova i la Geltrú (Barcelona, Spain), in 1953. He received the B.Sc., M.Sc. degrees in Industrial Engineering from the Universitat Politècnica de Catalunya (UPC), in 1976 and 1998 respectively. He is currently an Assistant Professor in the Department of Electrical Engineering, Universitat Politècnica de Catalunya, in the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSVG). He is member of the Electronically Commutated Drives Group (GAECE). His teaching activities and research interests include industrial automation and fault diagnostic techniques for electric machines and drives.

Marcel Torrent was born in Menàrguens (Lleida, Spain) in 1965. He received the B.Sc., M.Sc. and PhD. degrees in Industrial Engineering from the Universitat Politècnica de Catalunya (UPC), in 1988, 1997 and 2004 respectively. He is currently an Associate Professor in the Department of Electrical Engineering, Universitat Politècnica de Catalunya, in the Escola Politècnica Superior d'Enginyeria de Vilanova i la Geltrú (EPSVG). He is member of the Electronically Commutated Drives Group (GAECE). His teaching activities and research interests include design, modelling and testing of electric machines and drives.