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Switched reluctance motor controller for light electric vehicles

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Acknowledgements

This research was supported by Spanish Ministry of Economy and Competitiveness (DPI 2014-57086-R).

Keywords

«Power converters for EV», «Switched reluctance drive», «Converter circuit», «Converter control», «Traction application».

Abstract

Nowadays, switched reluctance motor drives are one of the most promising alternatives for the elimination of permanent magnets in the electric traction systems, due to their well-known advantages such as simple and rugged construction, high efficiency, speed torque characteristic well adapted to traction needs and despite their drawbacks high torque ripple and high acoustic noise. Unfortunately, nowadays, the lack of commercial controllers intended for switched reluctance motors slows down its use as power traction unit. This paper tries to overcome this barrier proposing a specific controller, understood as the assembly of electronic power converter and control unit, for electric light vehicles. First, the specifications of the controller will be exposed then a comprehensive description of the architecture of the controller and details about the choice of its components will be given. Finally, experimental results will be shown in order to demonstrate its suitability as a SRM controller for light electric vehicles.

Introduction

Light electric vehicles 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. Because 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.

Usually these vehicles are powered by an electric drive (including motor + electronic power converter + control) of a power comprised between 2 -10 kW, powered by a battery pack (Pb-Acid, Li-Ion) of voltages between 48 -100 V. It is necessary to distinguish between direct drive drives, in which the 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 [2].

The motors used in the light electric vehicles are, generally, motors with permanent magnets (Brushless DC motors, BDCM, or synchronous motors with permanent magnets). In addition, there are commercial controllers, electronic power converter and control unit, of many manufactures, such as Sevcon [3], Curtiss-Wright [4] and Kelly Controls [5], that can easily adapt to these motors.

Nowadays, circumstances such as:

- ✓ The increase of the demand for rare earth magnets (especially Neodymium) in the wind generation and electric traction industries.
- ✓ The fact that 95% of the production of raw material comes from China.
- ✓ The uncertainty of its price and the high percentage of the cost of the magnets on the total cost of the motors that use them.

Have favored that there is a tendency to reduce the mass of the permanent magnets and even to dispense of them [6-7]. For these reasons there is a great interest in the development of magnet-less electric drives, the most relevant drives in this category are induction motor drives, synchronous reluctance motor drives and switched reluctance motor drives.

The switched reluctance motors have as main advantage their constructive simplicity and robustness; traditionally they have been classed as motors with high torque ripple and noisy. As far as power density and efficiency are concerned, they reach values slightly higher than induction motors and are below those attributed to synchronous motors with permanent magnets. However, the use of suitable magnetic materials has allowed approaching the power density and performance of synchronous motors to those of permanent magnets [8]. On the other hand, the consideration of constructive structures that tend to increase inductance in the alignment position and reduce it in non-alignment position have managed to improve the characteristics of SRMs [9], specifically motors with segmented rotor [10], structures with segmented stator [11-13] and motors with double stator or double rotor [14, 15]. Axial flux motors are another alternative especially indicated for in-wheel direct drive motors [16, 17].

Unfortunately, nowadays, in the market there is no commercial controller intended for switched reluctance motors. This circumstance is the main cause that slows down its use as a power traction unit for light electric traction vehicles. In this paper, in order to overcome this drawback a controller for the switched reluctance motors specially designed for its application to light electric vehicles is proposed.

Specifications of the SRM controller

The controller, electronic power converter and control unit, is designed for powering any type of low voltage three phase SRM intended for the propulsion of light electric vehicles. Fig. 1 depicts a wiring diagram of the SRM controller showing the connection of the power components (battery pack SRM), of the sensors (speed/position, temperature) and of the driving functions of the vehicle (key switch, throttle, brake, forward/reverse). The controller must handle input voltages, from a pack of batteries, between 24 V up to 100 V and should be able to work with a peak current of 400 A for 2 minutes and 150 A RMS for 60 minutes. The controller has to manage the signals of the SRM sensors (speed/position, current, temperature) and the control inputs/outputs thus special attention has to deserve to communications. The controller should allow to load external software for the control of the SRM or even to connect it to a HIL (hardware in the loop) platform. In addition, it should be small, compact and safe and be prepared for working on board of a light electric vehicle; therefore, regulations related with them should be taking into account. The whole controller should be covered by an enclosure that guarantees a protection IP66.

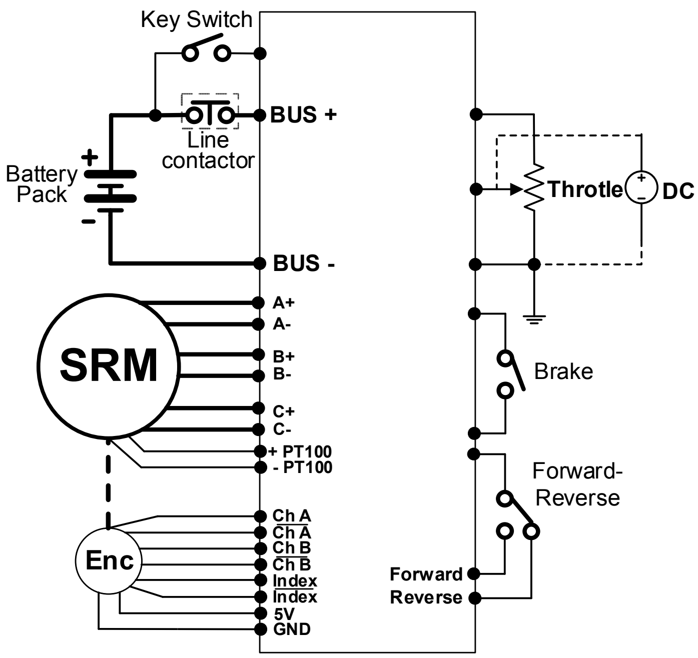


Fig.1. SRM controller wiring diagram

SRM controller architecture

In order to accomplish the before specifications the controller was designed with an architecture according the block diagram shown in Fig.2.

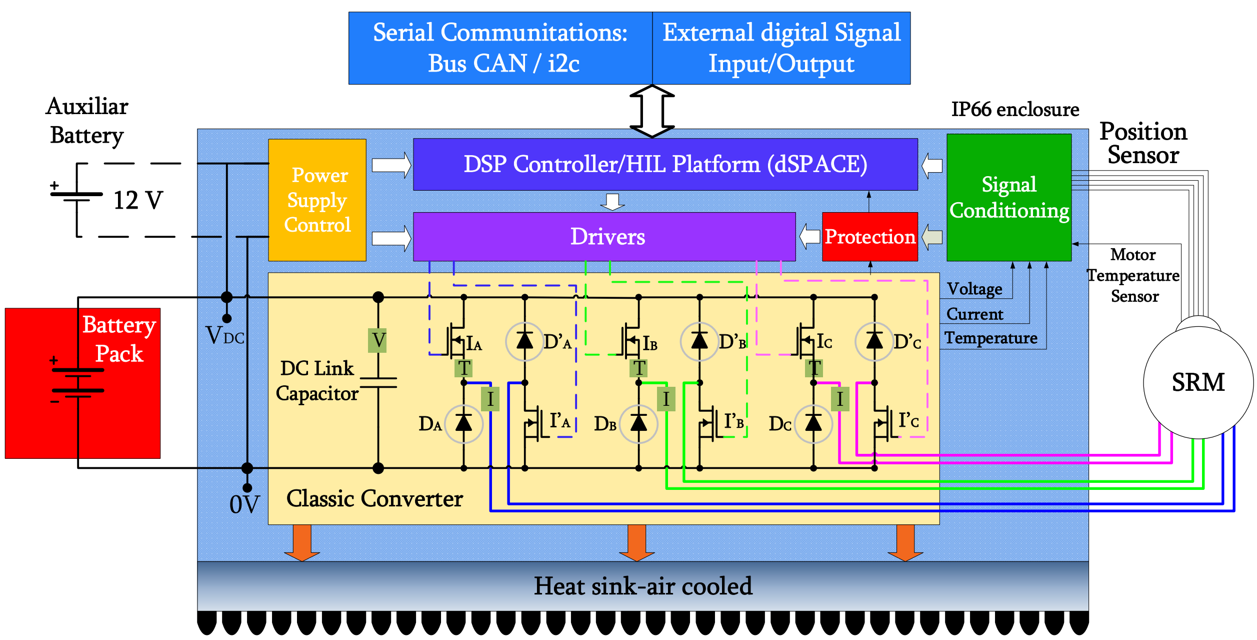


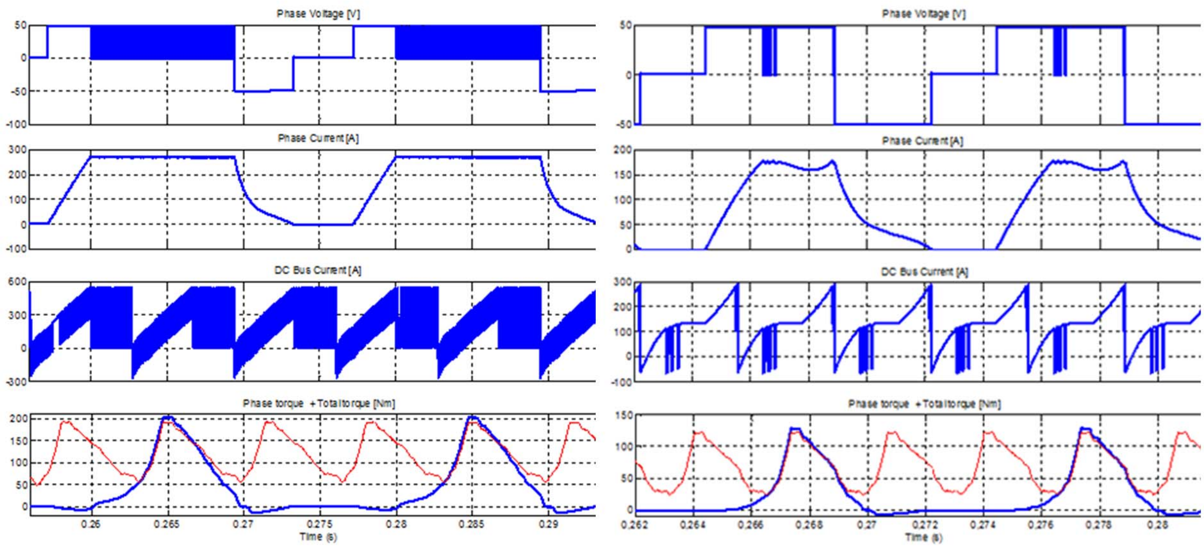
Fig.2 Block diagram of the SRM controller

Electronic power converter

The electronic power converter is the controller's core. Even though a number of phases greater than three can be a good choice for an SRM drive, relieving the reduction of torque ripple and increasing the fault tolerance capability. The minimization of the number of power components advice that usually the best option is a three phase SRM drive, as a consequence the number of phases of the power converter was set to three. Although some efforts have been done to use common three phase inverters for A.C. machines (IM and PMSM), they are not entirely suitable for SRM drives [18-19] since the torque in SRM drives is independent of the current sign and therefore unipolar converters are required. There are several unipolar power converters for SRM [20] but in this case, an asymmetric power converter or classical converter with two power switches and two diodes per phase was selected. It is important to point out that unlike the inverters for permanent magnet synchronous motors drives where there are three output power connectors in the asymmetric power converter for SRM drives six output power connectors are required.

Power switches and diodes

The design of the power converter and specially the selection of the power switches and diodes was based on the specifications of the SRM controller and previous simulations considering the behavior of the whole SRM drive including battery, power converter, SRM and different control strategies. These simulations were performed using a Matlab-Simulink model taking into account the results of the finite element analysis of the SRM [21, 22]. Waveforms of phase voltage, phase current, DC bus current and total torque, for the particular case of SRM a powered from a Li-ion battery of 48 V through a classical power converter are shown in Fig 3. Fig 3 a) for a torque of 122 Nm (average value) at 300 rpm with hysteresis control and variable commutation angles, turn on angle of -5º and turn off angle of 17º; and in Fig 3 b) for a torque of 70 Nm (average value) at 600 rpm single pulse control with turn on angle of -2º and turn off angle of 14º.



a) b)

Fig. 3 Simulation of a SRM: a) Waveforms of phase voltage, phase current, bus voltage and total torque (in red) for hysteresis control. b) Waveforms of phase voltage, phase current, bus voltage and total torque (in red) for single pulse control

Phase leg commercial modules, containing solid state power switches, can be used in the construction of power converters for SRM but twice as many modules as in an inverter for alternating current machines are required (i.e. only half of the components in each module is employed), implying a significantly higher cost for the electronic power converter. In the case under study, due to the high electric requirements, the chosen power switches and diodes were discrete components and respectively: power MOSFETs and high voltage Schottky diodes.

Taking into account the maximum voltage that the converter has to work, 112 V when a 100 V battery pack is considered, the power semiconductors were chosen with a voltage margin of at least 30% higher in order to assure that the voltage peaks caused by switching transients do not damage the power semiconductors.

Considering the electrical specifications of the power converter and previous simulations, the suitable semiconductor packages are SOT-227, or TO-247. Due to the possible imperfection of current sharing of the diodes, SOT-227 package were chosen because it has the diodes with highest rated current, so the least number packages has to be put in parallel in order to improve the sharing of currents.

The power MOSFET selected was Ixys IXFN360N15T2 due to its low $R_{DS,on}$ and the chosen diode was Microsemi APT2X101S20J which has two diodes in parallel inside the same SOT-227 package. These two diodes inside the package share the same case to sink thermal resistance, so, their temperature will be more alike than if they are in separate modules. The SOT-227 package also has bigger thermal capacitances than TO-247, which helps to reduce the ripple of the temperatures, mainly the junction temperature. Unlike the TO-247, the SOT-227 case is electrically isolated from active parts; therefore, no additional insulation film was needed between case and heatsink, which reduces thermal resistance. Another important factor is that the mechanical assembly becomes much simpler with the SOT-227 package requiring a standard flat extruded heatsink on which the semiconductors are screwed.

The power converter has to work in a short period of time (two minutes) under the most demanding thermal conditions; therefore, a transient thermal model was used in order to calculate the reached junction temperature after this period. The thermal system was simulated with an electric equivalent circuit in which resistors represent the thermal resistances and capacitors the thermal capacities as shown in Fig. 4. The thermal circuits of the semiconductors were those provided by the datasheet, but in the case that they were not available then a 4th order RC circuit of Foster type [21] was obtained from the transient thermal response graphs of the datasheets. The thermal resistance from the heatsink was fixed to 0,2 °C/W, and the thermal capacity was calculated from the estimated mass and specific thermal capacity of aluminum.

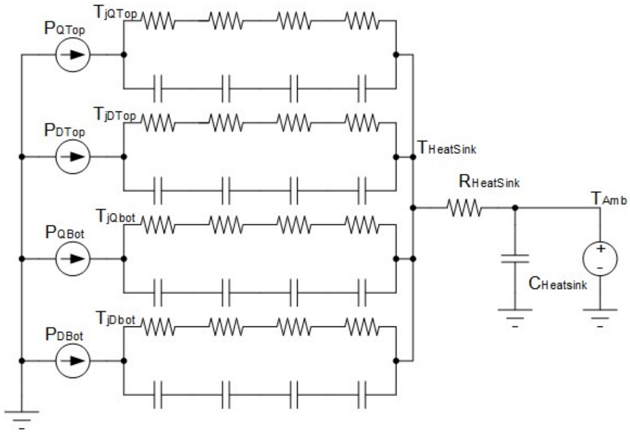


Fig. 4 Transient thermal model

The number of parallel MOSFETs and diodes was decided with the help of the thermal simulation. This was performed considering the worst case, a transient simulation of two minutes, with a 25 °C margin below maximum allowed junction temperature (150 °C). As can be seen in Fig. 5, the temperature in the junction of the semiconductors, did not reach the steady state after this time, but it was below the maximum junction temperature of the semiconductors during this two minutes. Finally, as a result of this simulations it was decided to put 4 MOSFETs modules in parallel and 2 diode modules in parallel.

Capacitor bank

The capacity of the capacitor bank was initially designed using the maximum voltage ripple as input, and taking in account a series resistance of 10 mΩ for the battery and connection cables. The simulations showed that with a 6 mF capacitor the maximum voltage ripple was about 7 V peak-to-peak, which was considered satisfactory. Nevertheless, the current trough this capacitor bank, in the worst case, was of 150 A RMS. From a search in the capacitor market, it was found that for 160 V only MKP/film capacitors can handle these large currents with this capacity, but they occupied a very large area (approximately 560 cm^2 with 28 rectangular capacitors of 220 µF). It was studied if a higher number of electrolytic capacitor in parallel in order to increase the supported ripple current may reduce the occupied area, even if the total capacity was bigger than the initial estimation. The most compact solution was with 66 cylindrical capacitors of 820 µF (Rubycon 160BXW820MEFR18X50) which occupied approximately 210 cm^2 (each capacitor with a diameter of 18 mm). This solution increased the capacity up to 54 mF. One of the main reasons for this reduction of space is the large height of this capacitor (50 mm). The selected capacitor has a specified lifetime of 12000 h at 105 °C, but the actual lifetime depends on the temperature of the capacitor core, which also depends on the cooling and heat generated by the capacitor. The heat generated by the capacitor is function of the current and its frequency spectrum, which is unknown because it is related to the speed of the motor. Therefore, the worst case was considered to be 150 Arms at 120 Hz coinciding with the rated current. Consequently, only ambient temperature modifies the lifetime of capacitor, which was considered at 80 °C of 68000 h.

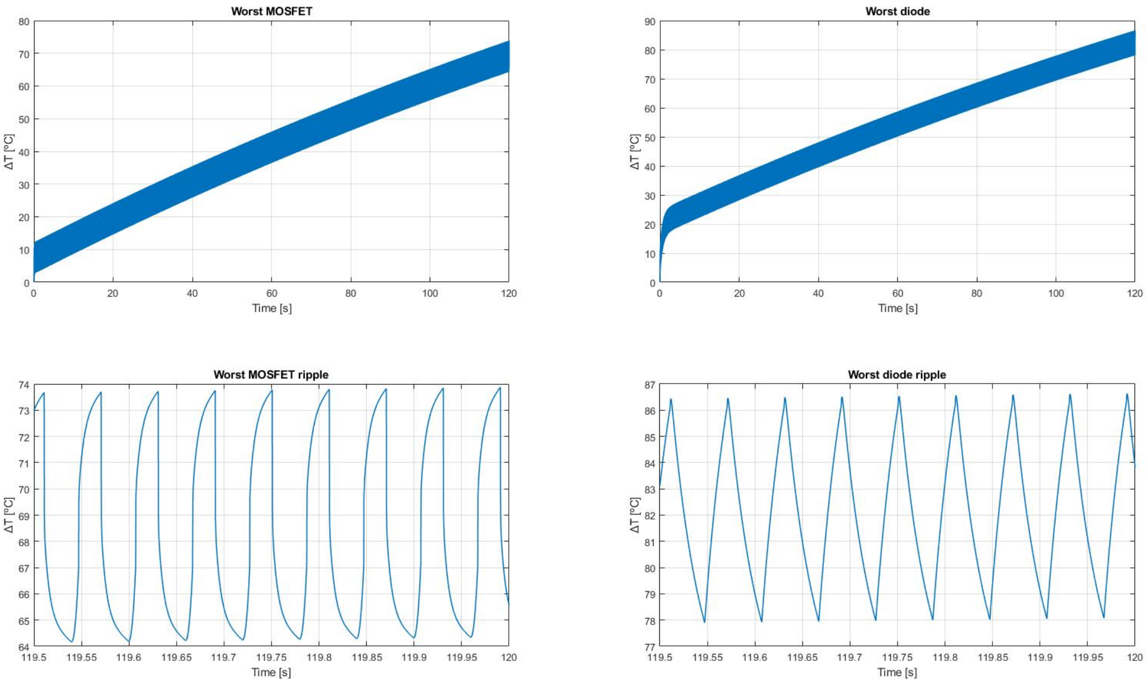


Fig. 5 Results of transient thermal simulation of the power converter semiconductor's (left MOSFETs and right diodes) ambient temperature of 40 °C

DSP Controller and HIL Platform

The SRM controller includes a DSP, TMS320F28335 control CARD from Texas Instruments attached to the main PCB, denominated DSC. The SRM controller was designed to also allow the control of the converter by means of an external HIL platform if required. Figure 6 shows the way how the converter can be controlled and monitored by both DSC and by an HIL platform in this case dSPACE.

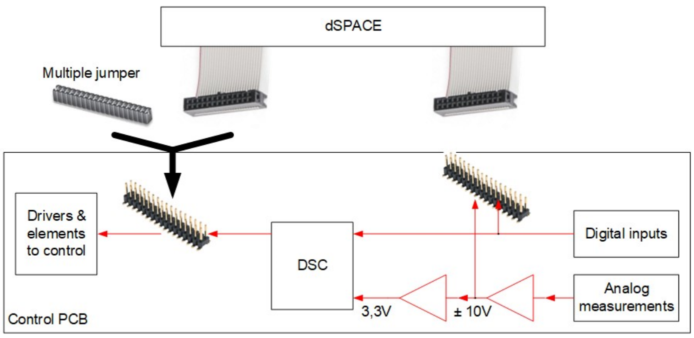


Fig. 6 Control of the power converter by DSC or by dSPACE.

Ancillary parts

Other important parts of the SRM controller, included into the name of ancillary parts, are the control power supplies, the signal conditioning and the gate drivers.

The electronics of the controller was powered from a 12 V rail that must be supplied externally. From this 12 V rail three other auxiliary voltage are generated for internal usage and to supply optional external elements: -12 V for the negative supply of current sensors and the analog circuit conditioning, 3,3 V and 5 V for the supply of other digital components. These auxiliary voltage supplies were implemented with non-isolated step-down converters.

For the measurements of current four open loop Hall effect current sensors were used (LEM HAS 300-P), one for each of the phases and one for the DC bus current. The measurement gain can be configured by two ways: by making one or two turns with the power cable around the sensor or by choosing one of two possible gains of the analog circuitry. For the DC bus voltage measurement, a voltage divider was used with an analog adaptation circuit. This measurement was also configurable with two possible gains.

The signal conditioning was implemented in two stages (Fig. 6). The first adjusts the measure to 0-10 V range if the measure is unipolar, or ±10 V if it is bipolar. After this first stage, the signal is branched into two paths: the first one to the dSPACE, and the second one to another analog stage that adapts to the 0-3 V range required by the DSC analog-to-digital acquisition.

Each of the 4 parallel power MOSFETs were driven by a single gate-driver, which is isolated in order to avoid high frequency interference between power and control. The integrated circuit chosen for this purpose was the ADUM3223BRZ, one for each of the 6 channels. The floating secondary sides were supplied with 9 V by means of 6 standard isolated power supplies (MTE1S1209MC).

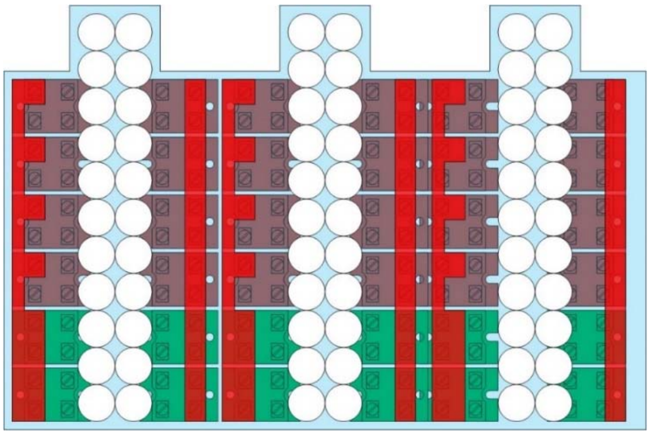


Fig. 7 Conceptual component disposition (white: capacitor, green: diodes, brown: MOSFETS) and conceptual distribution of layers (Red: top/bottom, Blue: 4 inner layers, 2 for positive and 2 negative)

Printed circuit board

The power converter including the capacitors bank, the isolated gate drives, the voltage, current and temperature sensors, the signal conditioning, the control power supplies, the power connectors and the input/output connectors were implemented into a printed circuit board (PCB) of 6 layers and 70 µm copper thickness, the semiconductors (MOSFETs and diodes) mounted on an aluminum heatsink. A great challenge for the design of the power part of the PCB was to get a good thermal performance considering the high currents to be carried. A correct placement of the components and adequate routing of the tracks and conduction planes minimizes the resistance and inductance of the current path which helps in two ways: first, the Joule conduction losses are reduced, facilitating the thermal handling and second, the ringing due to the switching of high currents is reduced. The layout of the power part was designed in order to minimize the current loops of the 6 switching cells (formed by the capacitor, the MOSFET and the diode of each leg). The adopted distribution can be seen in Fig. 7. This layout allows the DC bus to be implemented with 4 continuous copper layers along the 6 legs (2 layers for positive and 2 for negative), thus minimizing the DC bus inductance and enhancing the heat dissipation. The midpoints of each arm, which also are the outputs to the motor, were only routed on the bottom layer to contact the power semiconductors and on the top layer where they were reinforced with copper bars, which were screwed onto the PCB. For a better spreading of the currents from the battery to the PCB

(400 A during 2 min), additional copper bars where implemented connecting the legs of the 3 phases, see bottom of Fig. 8.

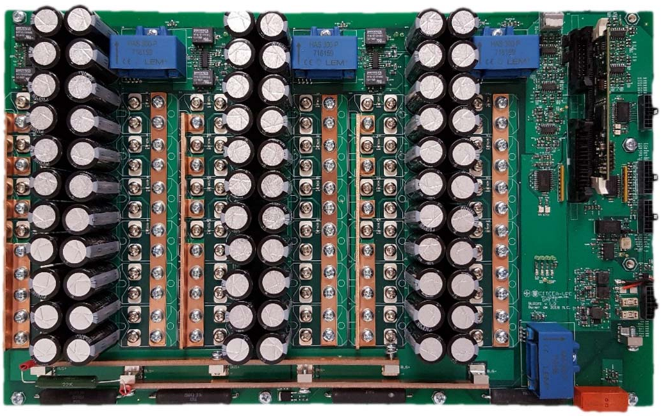


Fig. 8 Plant view of the converter

Fig.9 Picture of the designed converter

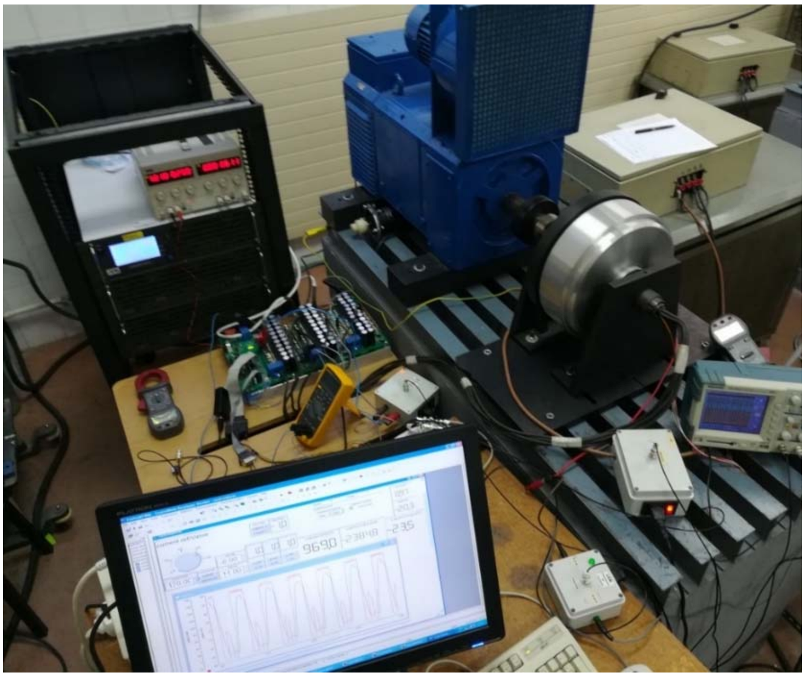


Fig. 10 Test rig

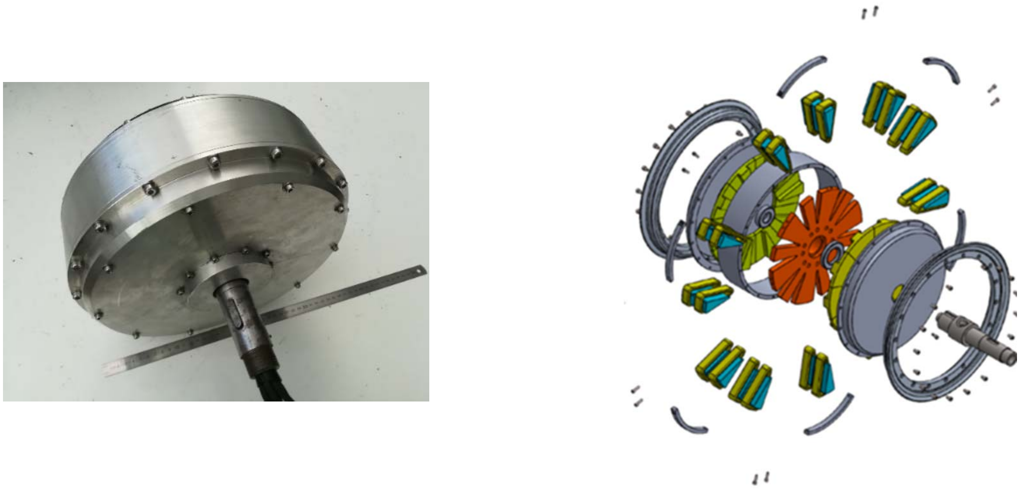


Fig 11. Photograph of the in-wheel AFSRM and exploded view

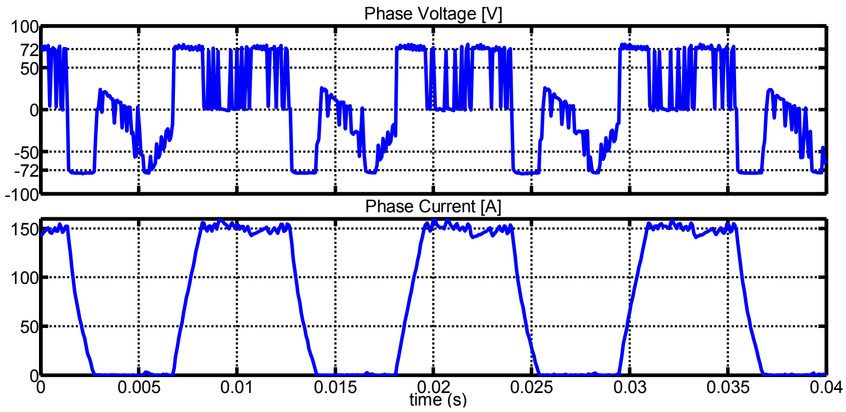


Fig. 12 Experimental waveforms, hysteresis control

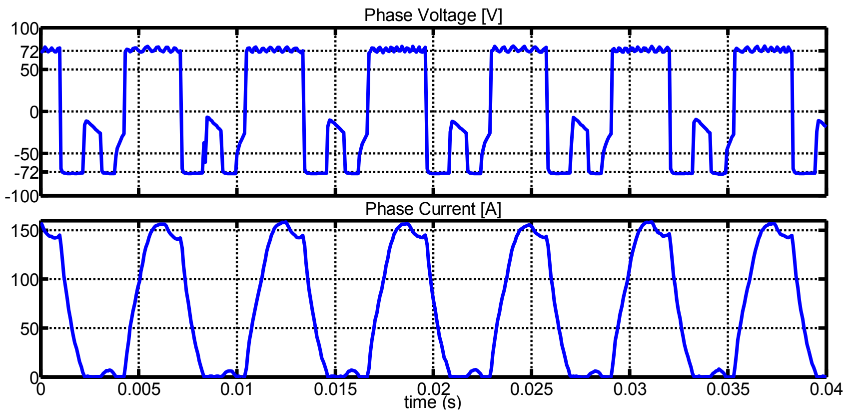


Fig.13 Experimental waveforms single pulse control

Experimental results

A prototype version of the SRM controller, without the IP66 enclosure, was tested in a test rig, consisting of a SRM powered from a DC adjustable source, instead of a battery, and loaded by means of a separately DC machine Fig 10. The SRM was an in-wheel 12/10 axial flux switched reluctance motor, in-wheel AFSRM, of 72 V, especially intended for light electric vehicles, Fig. 11. The SRM controller was controlled through a HIL using a dSPACE platform. Different types of control were considered so in Fig. 12; waveforms of phase voltage and phase current for hysteresis control are shown with a turn on angle of - 6º and a turn off angle of 10º, for a speed 528 rpm and a torque of of43.5 Nm. In Fig.13 waveforms of single pulse control are depicted with a turn on angle of – 6º and a turn off angle of 11º for a speed of 969 rpm and a torque of 23.4 Nm.

Conclusion

SRMs are one of the most promising alternatives for the elimination of permanent magnets in the electric traction systems. Nowadays, unlike PMSM and IM drives there is not any commercial controller in the market intended for SRM for E-traction applications. This paper proposes a new controller intended for any type of SRM. The controller has been specially designed for use in light electric vehicles. The controller is suitable for input voltages, from a pack of batteries, between 24 V up to 100 V and should be able to work with a peak current of 400 A for 2 minutes and 150 A RMS for 60 minutes. The controller has to manage the signals of the SRM sensors (speed/position, current, temperature) and the control inputs/outputs. The controller should allow to load external software for the control of the SRM or even to connect it to a HIL platform. The paper explains with detail the sizing choices that have been made (power switches, diodes, capacitors and PCB). Preliminary experimental results carried out on an AFSRM drive have demonstrated the adequacy of the controller for its applications in light traction vehicles. However, the SRM converter before its total approval must still undergo a greater number of trials and should be tested with different types of SRM.

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