A Novel Topology of High-Speed SRM for High-Performance Traction Applications

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***Abstract* — A novel topology of high-speed Switched Reluctance Machine (SRM) for high-performance traction applications is presented in this article. The target application, a Hybrid Electric Vehicle (HEV) in the sport segment poses very demanding specifications on the power and torque density of the electric traction machine. After evaluating multiple alternatives, the topology proposed is a 2-phase axial flux machine featuring both segmented twin rotors and a segmented stator core. Electromagnetic, thermal and mechanical models of the proposed topology are developed and subsequently integrated in an overall optimisation algorithm in order to find the optimal geometry for the application. Special focus is laid on the thermal management of the machine, due to the tough thermal conditions resulting from the high frequency, high current and highly saturated operation. Some experimental results are also included in order to validate the modelling and simulation results.**

Keywords—Switched Reluctance Machines; electrical traction machine; Hybrid Electric Vehicles; optimisation; thermal management

I. Introduction

The following paper presents a summary of the work carried out by the authors within the project M2SRM at the Energy and Power Group, Department of Engineering Science, University of Oxford, UK, and McLaren Automotive Ltd, Woking, UK. The original publications as well as numerous supporting references can be found in [1 – 7].

Electric and Hybrid-Electric powertrains are becoming more and more common in the market and nowadays virtually all OEMs (Original Equipment Manufacturers or vehicle manufacturers) offer one or several of such models. The motivations for electrification differ across the different vehicle segments. While for small passenger cars the main motivation is the reduction in fuel consumption and emissions, in the higher performance vehicle class electric traction machines are used for their superior dynamic response and higher power density. High performance turbocharged combustion engines can suffer “turbo-lag” that drastically slows the response of the engine to step increases in torque demand, which can amount to whole seconds of delay at low rpm. In contrast, an electric drive provides comparatively instantaneous changes in torque. Combining both in a hybrid powertrain results in a vehicle with increased performance and driveability that is ultimately much more fun to drive.

While the majority of the commercial EV and HEV solutions sport some form of PMSM (Permanent Magnet Synchronous Machine) mostly due to their higher power and torque density, PMSMs also bring in a number of disadvantages. Currently, over 80% of the rare earth material needed for the fabrication of the permanent magnets used in traction machines (neodymium and dysprosium mostly) is concentrated only in China. Therefore, the market price of these materials is somewhat volatile and a change in trade policy by the Chinese government could have a large impact in the supply chain of the EV and HEV industry. Moreover, in a PMSM the magnetising field cannot be switched off, hence so called field weakening currents need to be applied whenever the machine is operating above its base speed, even if no torque is being produced. This field weakening currents will originate losses in the windings, reducing the overall energy efficiency of the PMSM in such conditions.

SRMs (Switched Reluctance Machines) do not feature permanent magnets, which can be seen as an advantage for the aforementioned reasons, while retaining comparatively high torque and power density. The higher levels of noise and vibrations associated with SRM operation could be problematic, especially in a pure EV, but they are not considered a hinder in a hybrid sport application as the one in this study since the ICE (Internal Combustion Engine) will create much stronger noise and vibrations than the SRM.

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In order to reduce cost and increase performance levels there is a large drive to increase the torque and power density of traction motors. By increasing the rotational speed the power density can be increased, although care must be taken to preserve the mechanical integrity of the rotating parts. In addition, the high speed needed for high power density together with the high pole count needed to keep the magnetic paths as short as possible while boosting the torque density result in high frequency operation, which leads to magnetic losses both in the iron core of the machine (iron losses) and in the copper windings (proximity losses). Besides, the lack of permanent magnets leads to higher current levels in order to produce the desired torque. For all these reasons, the thermal management of this kind of machines is not trivial, and it will determine to a large extent the success of any particular machine design.

II. Topology Selection and Description

A. *Topology selection process*

In order to find the optimal topology for the application, an extensive design space was explored. All machine concepts considered in this process were permanent magnet free, and the aim was to maximise power and torque density. As a starting point for the project, the machine should preferably be multi-rotor, since this was considered a good feature increasing both torque density and reliability.

Fig. 1 shows some of the geometries analysed.

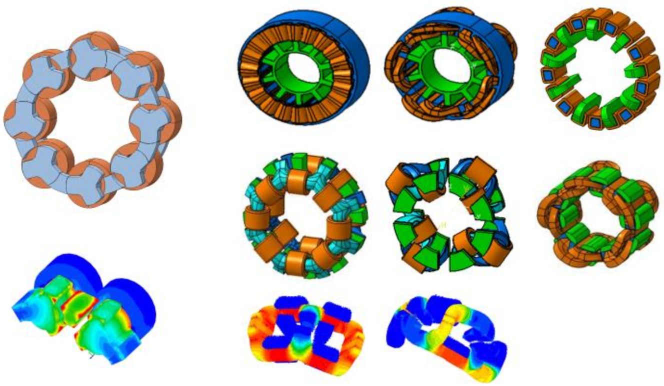

Fig. 1: Some of the machine concepts analysed

All the machines were simulated in 3D FE (Finite Elements) to obtain the basic electromagnetic characteristics, and those that seemed interesting were investigated further. The outcome of this selection process is the machine topology presented in the next section.

B. *Description of the SRM topology*

The selection process described in the previous section resulted in the following electrical machine topology: 2-phase, axial flux, segmented twin rotors, segmented stator SRM. The stator is formed of individual poles made of SMC (Soft Magnetic Composite) to achieve the complex geometric shapes and reduce magnetic losses. These poles are wound separately and then assembled together as shown in **Fig. 2** for the first prototype. [4,5,7]

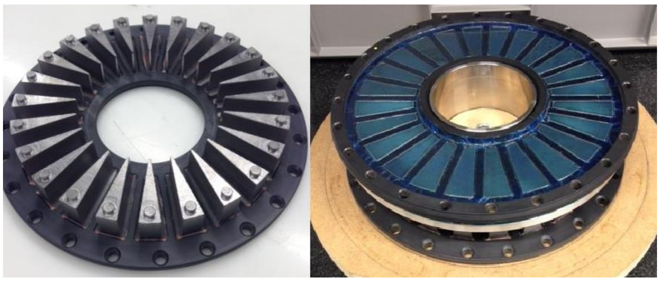

Fig. 2: Stator of the first prototype machine [5]

The stator coils are pre-wounded and impregnated in high thermal conductivity epoxy prior to assembly. Due to the specific requirements of the cooling concept - presented in a later section - the coils must be structurally solid and self-supported when mounted on the stator poles. In addition, the high electrical frequency during operation requires the use of litz wire for the coils. Accounting for all of these, the manufacturing of the coils have proved to be significantly more challenging than initially expected. **Fig. 3** shows a coil under manufacturing and a terminated coil. [5]

Fig. 3: Manufacturing of a winding coil (left) and fully finished coil (right) [5]

The twin-rotors are also segmented, consisting of triangular SMC poles mounted together in a structure that guarantees mechanical integrity at maximum rotational speed.

A CAD (Computer Aided Design) model of the described SRM topology can be seen in **Fig. 4**, where only the active parts of the machine are shown. A list of the most relevant target specifications for the design of the SRM traction machine is presented in Table I.

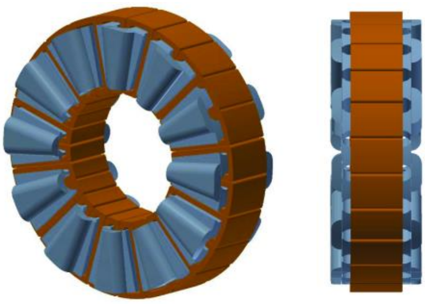

Fig. 4: CAD model of the proposed SRM topology [4]

TABLE I. MAIN DESIGN PARAMETERS FOR THE SRM

Parameter	Value
Rated power	60 – 80 kW
Maximum rotational speed	20 000 rpm
Base rotational speed	10 000 rpm
Maximum fundamental electrical frequency	4 kHz
Maximum outer diameter	254 mm
Maximum axial length	170 mm
Decoupled deceleration	> 10 000 rpm/s
Rotor pole outer pressure limit	< 125/353 MPa
Maximum winding temperature	180 C
Maximum SMC temperature	250 C
Maximum coolant outlet temperature	125 C

C. Cooling concept

Due to the high current levels in the winding, high frequency and magnetic saturation during operation, the losses in the proposed SRM topology are very much distributed in both the coil and the stator and rotor poles [6]. For this reason, a cooling concept in which the temperatures of the winding coils and iron poles is decoupled is highly desirable.

In order to do that, a liquid coolant, preferably water based, is circulated through cooling channels formed between the winding and the stator poles as shown in **Fig. 5**. In this way, the cooling effect will be approximately the same for both parts, and the only thermal coupling besides the coolant temperature is due to the plastic spacers used to mount the winding coils onto the iron cores. [3]

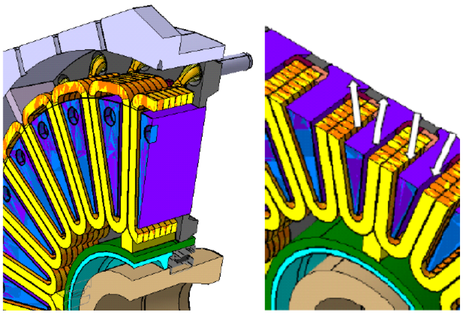

Fig. 5: Cooling ducts between the winding coils and the stator poles [3]

III. TOPOLOGY OPTIMISATION

A. Optimisation process description

In this section, a brief description of the optimisation of the selected SRM topology is presented. In this optimisation, FE electromagnetic analysis is coupled with a lumped parameter thermal model in order to evaluate the impact of the different design parameters in the performance of the machine. [2]

For each machine geometry considered, after the initialisation of the main parameters the algorithm proceeds with the peak speed iteration, i.e. it finds the optimal number of turns for the stator coils such that at peak speed and full voltage the winding current is maximised without exceeding the maximum temperature threshold. In this iteration a transient thermal model considering only the thermal mass and excluding all cooling actions is used, ensuring that the peak power can be sustained for at least 10 seconds.

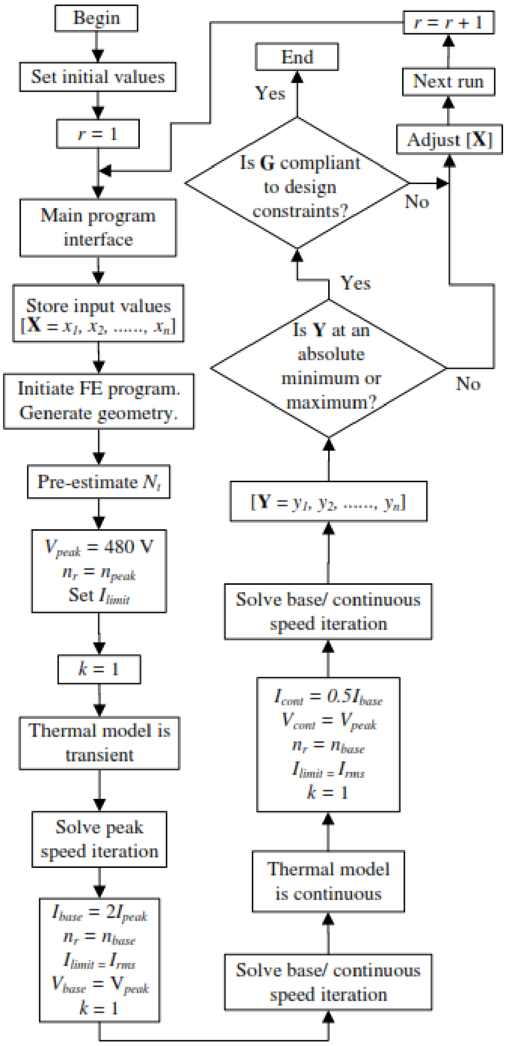

Fig. 6: Optimisation process flow diagram [2]

Then, the current is reduced to half of the current obtained in the peak speed iteration, the speed is set to base speed and the algorithm checks whether the current can be controlled to the specified value or a fixed pulse voltage excitation should be used. From this point, the algorithm iterates again in order to find the current level that can be sustained indefinitely without exceeding the thermal limits. In this case a steady state thermal model is used, taking into account the direct cooling of both winding coils and stator poles.

Finally, the optimiser evaluates the objective function for the analysed geometry and checks if it corresponds to a minimum point, in which case the optimisation is finished. Otherwise, a new parameter set is proposed and the whole process described is repeated for the corresponding geometry.

B. Electromagnetic modelling

Both a 3D FE model and a 2D FE linearised model have been developed to evaluate the performance of the machine. During the optimisation process, the 2D model is used due to its lower computational cost. Once a good machine candidate is identified, a more exhaustive FE simulation is conducted using the 3D model. [2,4]

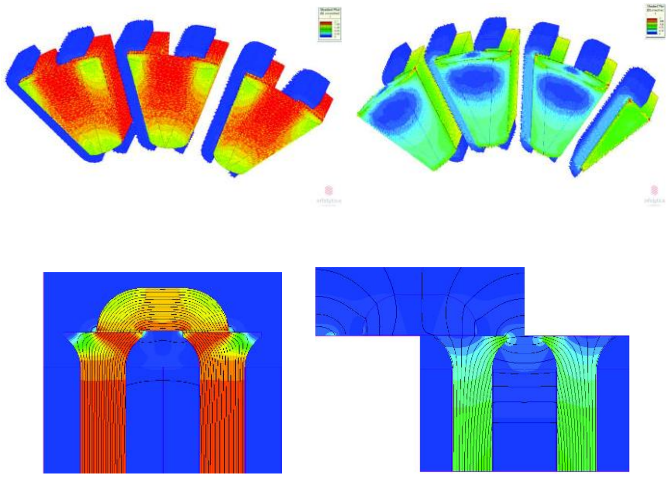

Fig. 7: 3D and 2D linearised FE models of the proposed SRM in the aligned (left) and unaligned (right) position [4]

C. Coolant flow and thermal modelling

In order to evaluate the temperature distribution inside the machine for the different loading cases, two models are created: a coolant flow model in order to estimate the coolant flow distribution, heat transfer coefficients and pressure drop in the cooling channels, and a thermal model to evaluate the temperature in different parts of the machine. Both models are lumped parameter models because of the need for fast execution. [3]

The coolant flow model estimates the flow distribution in the different cooling paths by calculating the pressure drop based on the Darcy-Weisbach equation and experimental correlations for the different bends and fittings.

The thermal model uses the convection coefficients calculated from the flow model, together with the losses obtained from the FE analysis in order to evaluate the temperature of the coils and the stator poles. The thermal model of the coil (shown in Fig. 8) models each turn individually with four nodes, and takes into account not only heat conduction along the wire, but also axial heat conduction between consecutive turns. [7]

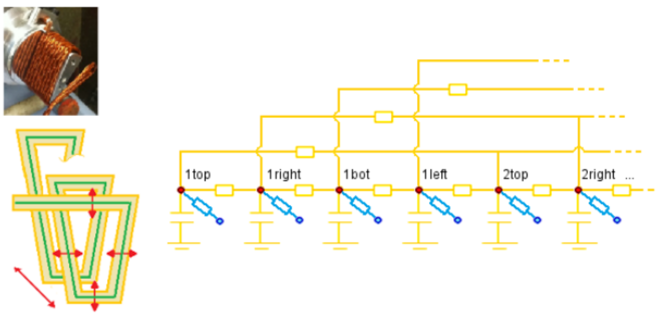

Fig. 8: Lumped parameter thermal model of a coil [7]

IV. Experimental Results

The degree of novelty in the proposed topology resulted in a number of unexpected delays during manufacturing – particularly of the winding coils – and also during the testing phase that could not be addressed completely within the project time scope. For these reasons, only two types of tests were successfully carried out: thermal tests of purposely designed motorettes and static tests of the first version of the machine prototype. Some relevant experimental results are presented in this section.

A. Thermal experiments

In order to validate the performance of the proposed cooling approach and to calibrate the thermal models described before, a motorette comprising one stator tooth and one coil has been manufactured (see Fig. 9). [5,7]

Five miniaturised thermistors installed in different locations over the winding allow to characterise the temperature distribution in the coil. This motorette is placed in the test bench shown in Fig. 10, supplied by 5 kW DC power supply capable of delivering 25 V and 200 A. An electric pump circulates the coolant fluid (distilled water) through the circuit. The coolant flow as well as the inlet and outlet coolant temperatures are also recorded.

Several experiments have been conducted in this setup. As an example Fig. 11 shows the logged results for a loading current of 180 A (equivalent to 30.5 A/mm2 current density in the winding). The temperatures measured by Thermistors 1 and 5 do not follow the same trend as the others, remaining just above the coolant temperature. This implies that these two thermistors are actually glued to the coil surface in direct touch with the coolant.

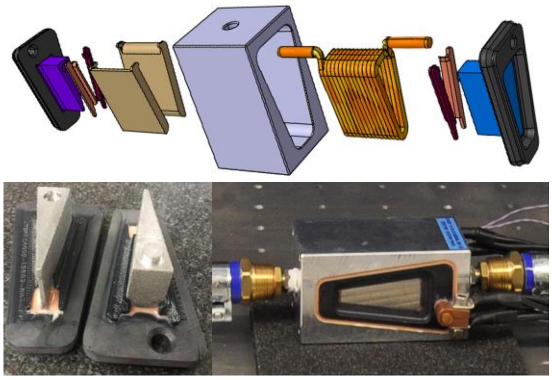

Fig. 9: Single core test motorette [5]

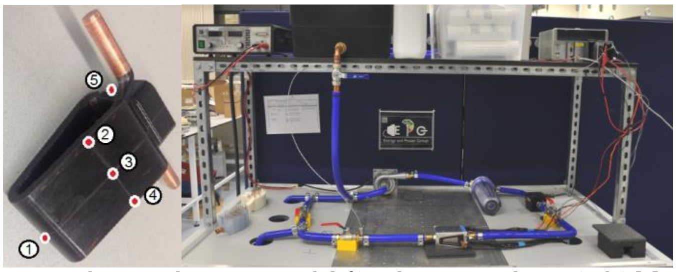

Fig. 10: Thermistor location in a coil (left) and experimental setup (right) [5]

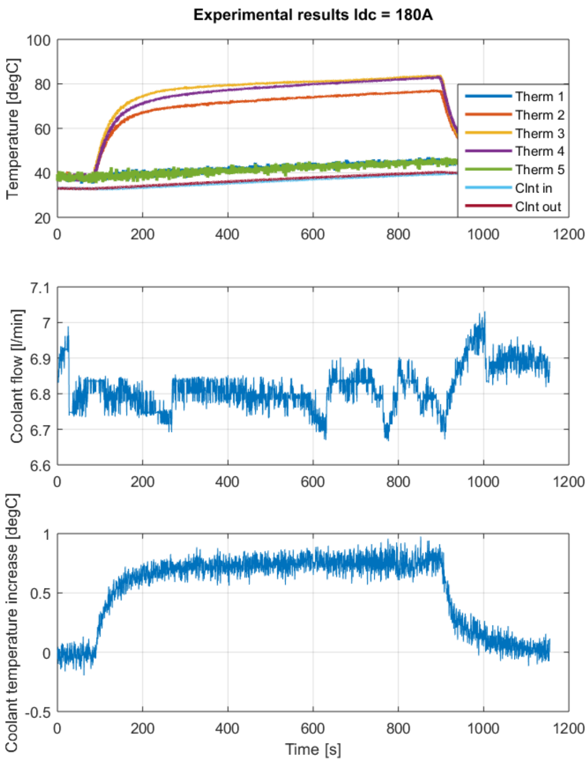

Fig. 11: Logged temperatures (top), coolant flow rate (middle) and coolant temperature increase (bottom) for 180 A [7]

It can be seen that the coolant inlet temperature increases slowly during the experiments, superimposing a temperature offset to the winding temperatures logged. However, this variation is small and the coolant properties can be assumed constant in the temperature range measured. Steady state is reached when the temperature difference between the coil surface and the coolant remains stationary. The thermal experimental tests were also compared to the proposed thermal model, and the obtained results and discussion can be found in [5,7].

B. *Static mechanical tests*

The built prototype was installed in a test-bench in the lab and static torque measurements are performed locking the rotor at certain predefined positions.

The figures in this section show some of the measurement results obtained from these tests and their comparison to FE results when relevant. [4]

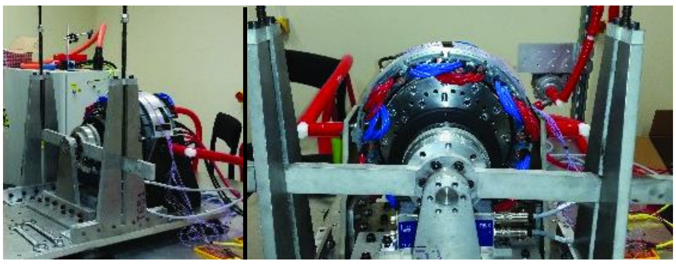

Fig. 12: Experimental SRM on the test bench interfaced with a static adjustment mechanism [4]

Fig. 13 to 15 show the FEA results obtained for the prototype SRM. Fig 13 shows the voltage and current of the machine when in operation. Fig. 14 shows the torque vs. electrical angle obtained if the machine is supplied with the voltage and current in Fig. 13. Fig. 15 shows the predicted torque and power as a function of motor speed. Peak speed is defined as 20 000 r/min and base speed as 10 000 r/min.

Fig. 16 shows the static measured and FE-predicted torque versus position at a constant current of 30 A per inverter leg. Fig. 17 shows the measured static torque versus electrical angle for three different current values. Fig. 18 shows the measured average torque per electrical cycle versus the FE predicted torque. It should be noted that the results shown are not conclusive and more testing is required to provide a more indicative view on the performance of the new concept SRM.

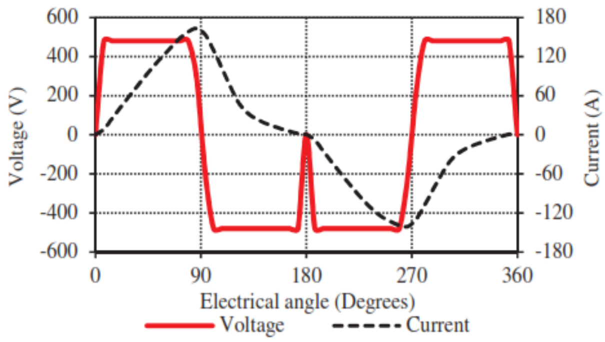

Fig. 13: Voltage and current vs. electrical angle for the SRM prototype (from FE simulations) [4]

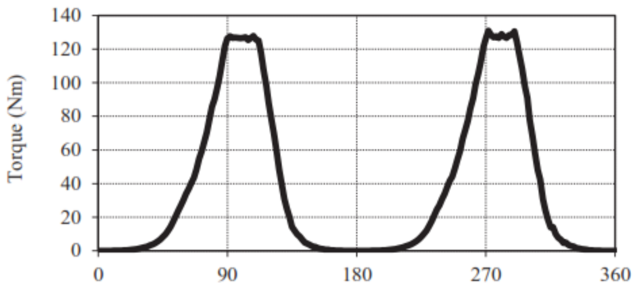

Fig. 14: Torque vs. electrical angle for one electrical period for the SRM prototype (from FE simulations) [4]

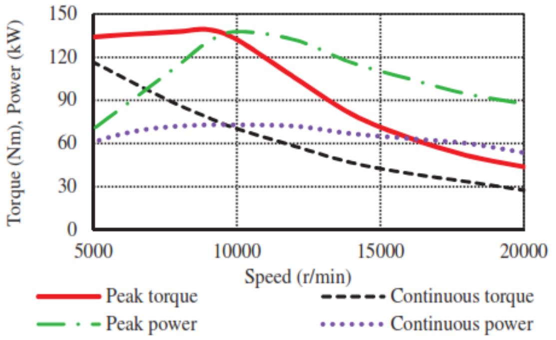

Fig. 15: Peak and continuous torque and power vs. speed for the SRM prototype (from FE simulations) [4]

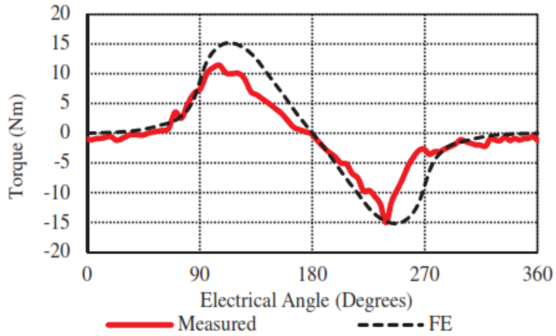

Fig. 16: Measured and predicted static torque waveforms at a fixed current of 30 A [4]

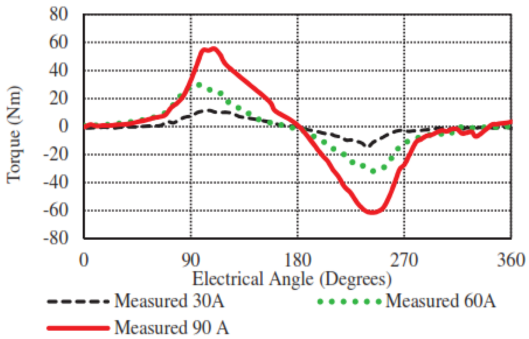

Fig. 17: Measured static torque waveforms at three different current values [4]

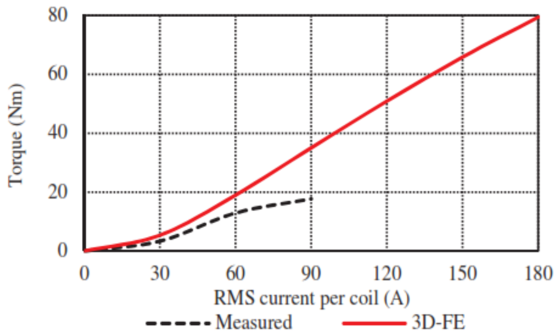

Fig. 18: Measured and FE predicted average torque vs. current per coil of the experimental SRM [4]

V. Conclusions

This contribution to the Workshop on "SRM drives as an alternative for e-Traction" summarises the work done on a novel SRM concept, featuring a 2-phase axial flux topology, with a segmented stator and twin segmented rotors. The proposed topology is designed for high-speed operation, aiming for power density values in the range of 7 kW/kg. This extreme operation conditions motivate the development of a novel cooling concept, decoupling the temperatures of the winding and the stator poles.

Mechanical and thermal models of the machine have been developed and integrated in an optimisation scheme. A prototype has also been built and tested.

The design methodology has proven to be useful, and the optimiser with integrated mechanical and thermal models has provided meaningful results.

The results from the experimental tests on the single-core motorettes show great potential for the cooling solution. However, a number of manufacturing problems in the full machine prototype impossible to solve in the available time for the project limited the number of tests significantly. The static tests conducted show good agreement at low current values, however, further testing would be required to understand the deviations as the current level increases.

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Johannes H. J. Potgieter received the B.Eng. degree in electrical and electronic engineering in 2008 and the M.Sc. (Eng.) and the Ph.D. (Eng.) degrees in electrical engineering from the University of Stellenbosch, Stellenbosch, South

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