Multi-physics Analysis of a High Torque Density Motor for Electric Racing Cars

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Abstract—This paper presents a newly developed high torque density motor design for electric racing cars. An interior permanent magnet motor with a flux-concentration configuration is proposed. The 18slots/16poles motor has pre-formed tooth wound coils, rare-earth magnets type material, whilst employing a highly efficient cooling system with forced oil convection through the slot and forced air convection in the airgap. Losses are minimized either by using special materials, i.e. non-oriented thin gage, laminated steel or special construction, i.e. magnet segmentation or twisted wires. The thermal behavior of the motor is modelled and tested using Le Mans racing typical driving cycle. Several prototypes have been built and tested to validate the proposed configuration.

I. INTRODUCTION

Within the hybrid and electric power traction field, the electric racing cars represent a novel and demanding application for electrical machines. FIA Formula E Championship started in 2014 using identical cars, generically named [1]: Spark-Renault SRT\textunderscore 01E – Fig. 1. The elements of the cars are provided by various specialized manufacturers: (2) Powertrain and electronics: McLaren Electronics; (3) Gearbox: Hewland; (4) Battery 200kW: Williams Advanced Engineering; (6) Tyres: Michelin. From the season 2015-2016, various electrical machines will be accepted, allowing teams to pick their own power traction system. In car racing, the motors are subjected to a highly transient drive cycle that allows the delivery of peak performance for short intervals. Therefore, not only is it critical for the design of the electrical motor to have reduced weight, but also a very efficient cooling system.

High torque density translates into a high torque ratio per weight (TRW) and in Table I, a comparison between various existing power traction motor in electric and hybrid vehicles is given [11-18]. All motors are liquid cooled and we should notice the higher values for permanent magnets (PM) motors over induction motor topology. This comparison does not include the cost/weight and other technological issues as protection against demagnetization or the battery capacity.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Motor brand & Motor Type & Peak torque (Nm) & Total weight (kg) & TRW (Nm/kg) \\
\hline
YASA 400 & Axial PM & 360 & 24 & 15 \\
Tesla & Induction & 430 & 90 & 4.77 \\
Nissan Leaf & Interior PM & 300 & 46 & 6.52 \\
Toyota Prius & Interior PM & 400 & 51 & 7.84 \\
\hline
\end{tabular}
\caption{TORQUE DENSITY COMPARISON IN POWER TRACTION MOTORS FOR HYBRID/ELECTRIC VEHICLES}
\end{table}

In a racing car application, a direct drive solution is preferable and in addition it is required that the electrical machine operates as a motor and regenerative brake, for speed values up to 12,000rpm. This in turn imposes the selection of fractional-slot concentrated winding with high winding factor for the fundamental MMF. Consequently, the number of rotor magnetic poles has be minimum 10 [2], which translates into a minimum fundamental electric drive frequency of 1kHz. The high fundamental value of the frequency and its higher order harmonics will induce AC losses in the winding, extra losses in the iron core and losses in the magnets.

The following comments complete the performance requirements:
The motor has to operate for maximum 1 hour in racing driving cycle conditions
The ambient temperature not to exceed 40°C
Inlet fluid temperatures within 40-50°C
Sinusoidal drive with 3rd harmonic injection
Motor should have the possibility to be scaled for a wider power range by extending the axial length

II. HIGH TORQUE DENSITY MOTOR CONFIGURATION

A. Electromagnetic topology

A fractional slots/pole motor configuration is chosen with tooth wound coils. Considering different slots/pole combinations, an 18 slots/ 16 poles topology is selected for this motor. Such a combination ensures a high fundamental winding factor, \( k_{w1} = 0.945 \), while the higher order space harmonics are minimized. Another advantage of 18 slots / 16 pole is that it guarantees a torque ripple, including the cogging torque component, while keeping to a minimum the unbalanced magnetic pull [7].

The torque is maximized through a concentrated magnetic flux topology [2, 5] that also provides a good mechanical retention of the magnet blocks within the rotor assembly.

In a high torque density motor, special techniques are required to minimise the magnetic losses. The following technical solutions are used:

1. Magnet losses: magnets are segmented both in tangential direction, with 5 segments/magnet pole and in axial direction with 3 blocks per pole. This design can be built with either NdFeB or SmCo magnet types. For thermal management reasons, the existing prototypes are equipped with SmCo magnet type.

2. Core losses: A laminated structure is used for the stator core, with a preferred material of non-oriented silicon-iron steel, with 0.1mm strip thickness. The rotor magnetic poles are built using the same laminated material as the stator, but a solution with solid magnetic steel is currently investigated.

3. Rotor assembly: The rotor is constructed from multiple layers of magnets (see point (1) above) and laminated core segments; the laminated core segments are retained by bolts, while the segments retain the magnets. At each end of each segment, the bolts are restrained radially and tangentially by a plate: at the ends of the rotor these plates are relatively stiff and fixed axially to the hub. Between segments, the plates float axially and transmit torque to the central hub via splines. Magnets are placed on a rotor hub manufactured from aluminium and titanium alloy components.

4. Encapsulated stator tube: The heat generated by the winding copper losses is extracted using forced liquid cooling through the slot. The fluid is retained by a tube. In order to minimize the losses created by the possible induced eddy-currents, the tube material is selected to carbon fiber.

With all the electromagnetic loss components minimised, an extremely efficient cooling system is still required for the heat extraction from the motor without compromising the overall system performance.

Figure 2 - Prototype of high torque density motor

Figure 3 - Prototype high torque density motor on the stand test

Figure 4 Axial view of the high torque density motor

The stator winding is cooled with forced liquid – Paratherm LR [8] – through the slot. The fluid is retained in the stator slots region with the above mentioned carbon fibre tube,
whilst the end-windings are potted. The volume flow rate is variable between 5 and 15 l/min allowing a winding temperature below 120°C in all cases.

In the airgap, a constant air volume flow rate of 1000 l/min helps with maintaining the rotor surface and magnets temperature less than 160°C. Inlet temperatures are between 40°C and 50°C. Various elements of the developed motor are illustrated in Figs. 2-7. Table II summarizes the motor specifications.

The high torque density motor is designed and modelled using a combined analytic and numerical 2D transient finite-element approach. The same geometry is further used for a thermal behaviour analysis. In Figs. 8 and 9, are presented the motor’s radial and axial view respectively, whilst Figs. 10 and 11 illustrate the winding distribution pattern, a star connection with six coils per phase and two parallel paths.

### TABLE II: HIGH TORQUE DENSITY MOTOR SPECIFICATIONS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque ratio per weight (Nm/kg)</td>
<td>9.27</td>
</tr>
<tr>
<td>DC bus voltage (V)</td>
<td>650</td>
</tr>
<tr>
<td>Rated speed (rpm)</td>
<td>6,000</td>
</tr>
<tr>
<td>Rated output power (kW)</td>
<td>60</td>
</tr>
<tr>
<td>Rated current (Arms)</td>
<td>200</td>
</tr>
<tr>
<td>Maximum speed (rpm)</td>
<td>12,000</td>
</tr>
<tr>
<td>Peak output power (kW)</td>
<td>95</td>
</tr>
<tr>
<td>Peak current (Arms)</td>
<td>325</td>
</tr>
<tr>
<td>Rated efficiency (%)</td>
<td>93</td>
</tr>
<tr>
<td>Stator OD (mm)</td>
<td>160</td>
</tr>
<tr>
<td>Stator bore (mm)</td>
<td>112</td>
</tr>
<tr>
<td>Airgap (mm)</td>
<td>1</td>
</tr>
<tr>
<td>Axial active length (mm)</td>
<td>72</td>
</tr>
<tr>
<td>Rotor poles</td>
<td>16</td>
</tr>
<tr>
<td>Stator slots</td>
<td>18</td>
</tr>
<tr>
<td>Total weight (kg)</td>
<td>11kg</td>
</tr>
<tr>
<td>Coolant</td>
<td>Paratherm/Air</td>
</tr>
<tr>
<td>Maximum flow rate (l/min)</td>
<td>15 (oil)/1000 (air)</td>
</tr>
</tbody>
</table>

Figure 5 - Partial radial view of the rotor assembly

Figure 6 - Exploded view of the stator assembly

Figure 7 Rotor structure – main elements

Figure 8 Radial view of the high torque density motor

Figure 9 Axial view of the high torque density motor
The winding connection shown in Fig. 11 allows the motor to be operated also in a 6-phase configuration with 2 parallel power converters.

By comparing the magnetic flux patterns at open-circuit and under load (Figs. 12 and 13), we notice that the stator tooth width and the magnet width have been determined based on the demagnetization study of the magnets and the MMF drop in the stator iron when the motor is under load.

Also, it is important to observe from the flux pattern in Fig. 13 that the bolts used to give mechanical strength to the rotor assembly can be made of either magnetic or non-magnetic material without a significant effect on the motor output performance.

Special attention was given to various electromagnetic losses. Critically, the magnet losses are mitigated via a tangential segmentation in the x-y plane. Such segmentation solution is along the flux lines in the magnets and ensures a limited amount of magnet losses.

Fig. 14 shows that most of the losses will be localized in the top magnet segments toward the airgap. Consequently,
this magnet block will be prone to demagnetization by thermal effect. In this region a high flow rate of air is used to extract the heat. Also, it is demonstrated in the demagnetization analysis section that SmCo magnets are to be preferred due to their properties stability at higher temperature.

At high frequency, i.e. 12,000rpm translates into a fundamental drive frequency equal to 1.6 kHz and the AC losses are concentrated in the coil turn located at the slot opening region in the rotor rotational direction (Fig. 15). Considering slot openings comprise 20% of the slot area, it is estimated that for frequencies above 1 kHz, 70% of the winding copper loss within the active length of the motor (i.e. end-winding not included) will be located in slot opening region (Fig. 16).

Notice that a higher number of strands in hand and a smaller wire cross-section have no effect in minimizing the AC losses for this motor. Most of the winding AC losses are of bundle effect nature [5]. Consequently, rather than using twisted conductors of Litz type to mitigate the AC losses, a high thermal conductivity fluid with a high volume flow rate was used to cool the winding.

For reference, the measured and estimated ratio of the total AC/DC copper losses is 2 at 200Arms and 6000rpm.

For completeness, the back EMF and electromagnetic torque waveforms are given in Figs. 17 and 18. Notice the total harmonic distortion for the induced EMF, THD EMF = 6% while the motor torque ripple considering ideal sinusoidal current is estimated as 7.5% [10].

B. Efficiency map with maximum torque per amp

The motor is controlled using the maximum torque per amp (MTPA) strategy. Essentially this requires the maximization of the electromagnetic torque given by:

\[ T = \frac{m}{2} p (\Psi_d I_q - \Psi_q I_d) \]  

(1)

while the voltage limit equation is respected:

\[ V_{lim} \geq \omega_s \sqrt{\Psi^2_d + \Psi^2_q} \]  

(2)

and the power inverter operates within the current limit:

\[ I_{max} \geq \sqrt{I^2_d + I^2_q} \]  

(3)

Where \( T \) is the torque, \( m \) the number of phases, \( p \) the number of pole pairs, \( I_{d,q} \) the direct and quadrature components of the peak phase current, \( V \) is the peak phase voltage, \( \omega_s \) is the electrical rotational speed, \( V_{lim} \) is the maximum voltage available from the inverter and \( \Psi_{d,q} \) are the direct and quadrature axis flux linkages.

In Figs. 19 and 20, there are given the estimated torque versus speed curves and power versus speed curves, respectively. The motor is capable of delivering a constant torque of 102Nm with 325Arms input current. The base speed beyond which the motor goes into field weakening region is 6,200rpm. The corresponding peak power is 75kW.
Figure 20 Power – speed characteristics, magnets at 120°C

Figure 21 Torque-speed (a) and power-speed (b) efficiency loci

Figs. 21 (a) and (b) show the efficiency loci considering the torque and power variation with speed. It is estimated that the high torque density motor can achieve an efficiency above 90% for a minimum torque level of 55Nm and speed operating range between 6,000rpm and 12,000rpm.

C. Demagnetization

A sudden 3-phase short-circuit fault that occurs at 6,000rpm, 200Arms is estimated to have the current profile variation given in Fig. 22. In approximately 20ms the steady-state short-circuit current is reached. The peak value of the short-circuit current is calculated as 280A.

Considering that in transient mode this current is applied when the magnetic

Figure 22 Transient 3-phase short circuit current variation

Figure 23 Flux-density plot in short-circuit conditions, minimum flux-density in the magnet 0.18T: (a) all magnetic regions; (b) magnets only

rotor field and the stator field are opposed, i.e. negative D-axis current, the magnets will be subjected to a strong demagnetization stress. Fig. 23 shows that it is possible for large parts of the magnets to reach 0.18T. This necessitates the selection of a permanent magnet material that has the irreversible demagnetization knee point above the minimum flux-density within the magnet blocks. A typical demagnetization curve for NdFeB and SmCo magnets is given in Fig. 24 [9]. This justifies the preference for SmCo magnet material in this high torque density motor.
D. Thermal model with real driving cycle

The cooling system has two main components: (a) One path oil forced convection through the slot and returning through the housing water-jacket. The fluid is Paratherm LR with the following properties: thermal conductivity 0.15W/m/K, density: 745 kg/m$^3$ and dynamic viscosity: 0.00113 kg/m/s. A flow volume rate between 10-20 l/min is available. The liquid is retained in the slots by using a carbon fibre tube with 0.5mm thickness. (b) One path air
forced convection, through the airgap. The volume flow rate is minimum 1000l/min.

The inlet temperatures for both cooling paths are between 40°C and 50°C. By using a lumped thermal network and considering 20 driving cycles that are typical for a racing car, the thermal response of the motor can be predicted. Figs. 25-27 illustrate the variation of speed and required torque for Le Mans circuit driving cycle. In Fig. 28, the transient thermal response of the motor is presented. Notice that the magnets are estimated to reach the highest temperature, i.e. 160°C, while the winding will experience hot spots of 120°C.

III. EXPERIMENTAL DATA

The prototype motor from Figs. 2-3, have been tested at magnet temperature of 40°C and the measured torque at 1,000rpm vs RMS line current is reported in Fig. 29. The line back EMF variation with speed is given in Fig. 30. We note a good agreement with calculated data. It is interesting to analyze the variation of the total losses at the same magnet temperature, with load current and speed (Fig. 31).

The total loss increase with current is almost quadratic and this demonstrates that the main loss component is created by Joule effect in the stator winding. The increase in the fundamental frequency from 266.6Hz (2,000rpm) to 1333.3Hz (10,000rpm) determines also the total loss increase, mainly due to the core loss dependence on the supply frequency, but also by the presence of the AC copper loss component in the winding. Notice that at 10,000rpm, the total loss variation with current shows some inconsistencies. These are considered to be of mechanical origin, i.e. bearings losses. Ongoing tests with drive cycle from Fig. 25 are currently performed and will be reported in a future work.

IV. CONCLUSIONS

A new high torque density motor for electric racing cars has been developed. The 18slots/16 pole synchronous permanent magnet motor has a spoke rotor – concentrated flux – configuration, with individual rotor core poles and axial segmentation. The motor has to withstand thermally highly transient driving cycles as specific for racing cars. The constructive motor details are given in this paper together with experimental validation data.

REFERENCES

3. Carraro, E. and Bianchi, N. "Design and comparison of interior permanent magnet synchronous motors with non-uniform airgap and conventional rotor for electric vehicle applications" IET Electric Power Applications, 8(6), 240-249.