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Innovative Design and Performance Prediction of Traction E-Machine for Motorsport Application

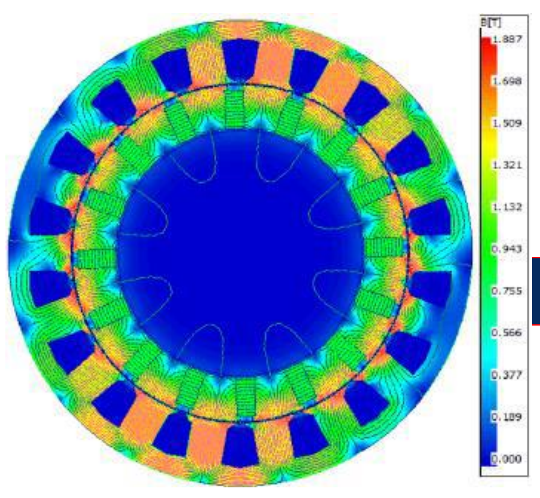
Introduction

Alongside the road electric vehicles increasing in popularity, several fully electric motorsport competitions, such as the Formula E Championship are being born. Within the development of powertrains, the electric motor has a central role. It needs to deliver high performance (high torque and low weight), be efficient and operate over dynamic drive. An innovative high-performance brushless permanent magnet (BPM) machine has been designed. Maximum motor speed is 12000rpm and maximum torque is 480Nm, achieving a torque per weight ratio greater then 15.5 Nm/kg. In order to design the machine, several models and equations have been introduced with the aim of including 3D effects in 2D simulations and high frequency losses in the winding. These new models have assisted with the machine performance prediction over single operating points and real racing cycles. It has been possible, therefore, to consider the machine behavior during a race and with these models will be possible to analyze different racing circuits.

High Permormance Electric Motor for Motorsport: Design, Manufacturing and Test

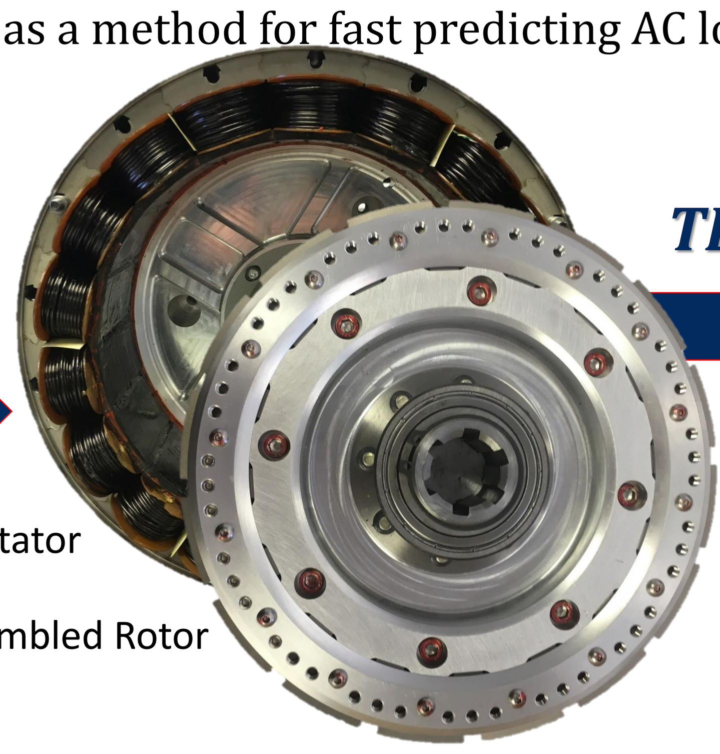
An high torque density interior permanent magnet motor, for the application, has been designed. The 18slots/16poles motor has pre-formed tooth wound coils, rare-earth magnets, with a highly efficient cooling system of forced oil convection through the slot and the rotor. To accurately predict the machine behaviour, 2D and 3D machine models are created and a new formulation is proposed, at the same time as a method for fast predicting AC losses during the design process.

DESIGN



4000RPM 380Arms On Load

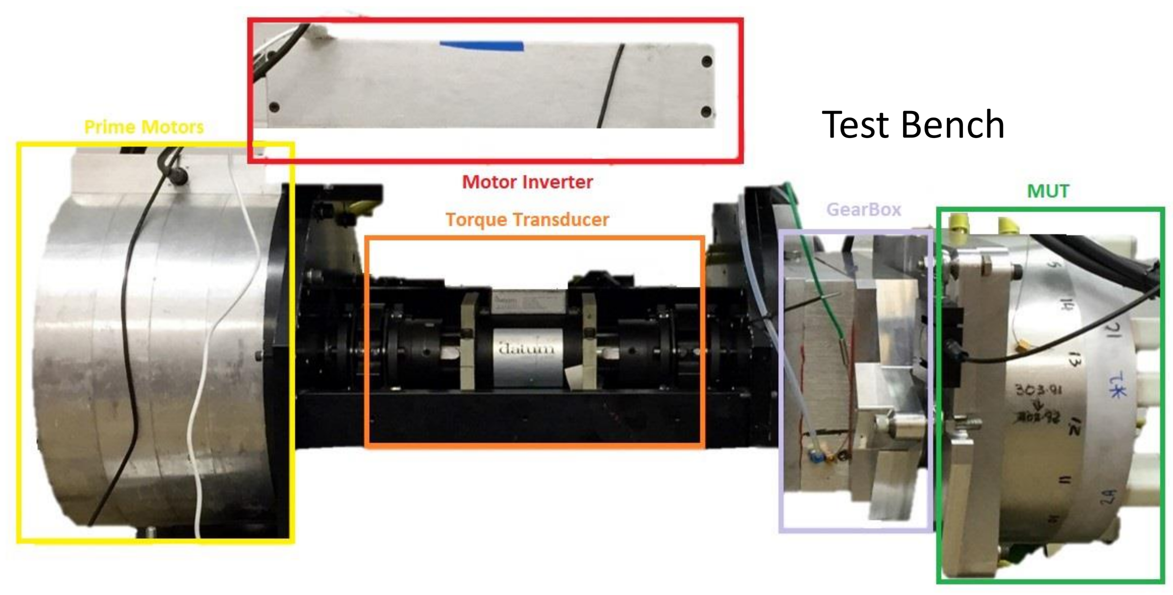
PROTOTYPE



Assembled Stator

Assembled Rotor

TEST



Test Bench

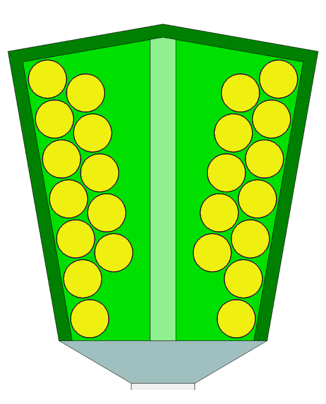
Maximum predicted Torque is 480Nm with 380Arms and the measured one is 476.5Nm (Err<1%)
Maximum Power 220kW Maximum Speed 10000RPM Overall Weight 30Kg Torque/Weight Ratio 15.8 Nm/kg

AC Losses

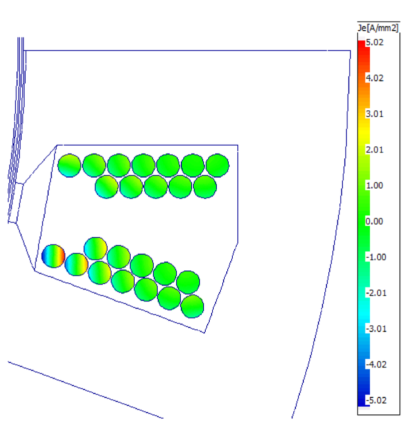
Conduction losses in the winding are one of the major sources of loss and they require special attention. Most often skin and proximity effects in windings are ignored to avoid computationally heavy and time-consuming analysis. However, in the application in hand, the behavior of the device is significantly altered by these effects.

The AC Losses can be estimated, on one hand, with a fast method: the Analytical one. It is easy to use and easy to set-up without special memory requirements. However, it suffers of low accuracy and it is not suitable for the study of complex geometries. On the other hand there is an accurate method: the finite elements analysis one with conductors in place. It can be very accurate, also for the study of complex geometries. At the same time the model can be very difficult and time consuming to set-up. Hence the idea of looking for a method able to satisfy accuracy and speed requirements.

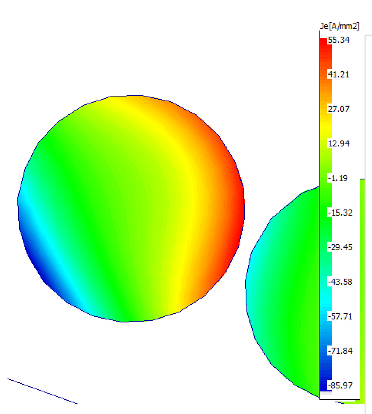
The proposed Hybrid method uses advantages of the analytical and of the FEA methods, being fast and accurate. This has been made possible using in the analytical formulations the flux density measurements in few key points using the "conventional" FEA and not the "detailed" one .
The Hybrid Method is 40 Times quicker than the FEA and gives a maximum error of 10%.



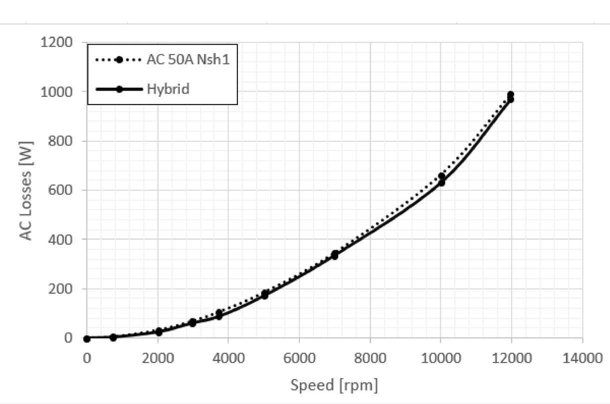
Single Strand Slot



Slot View FEA



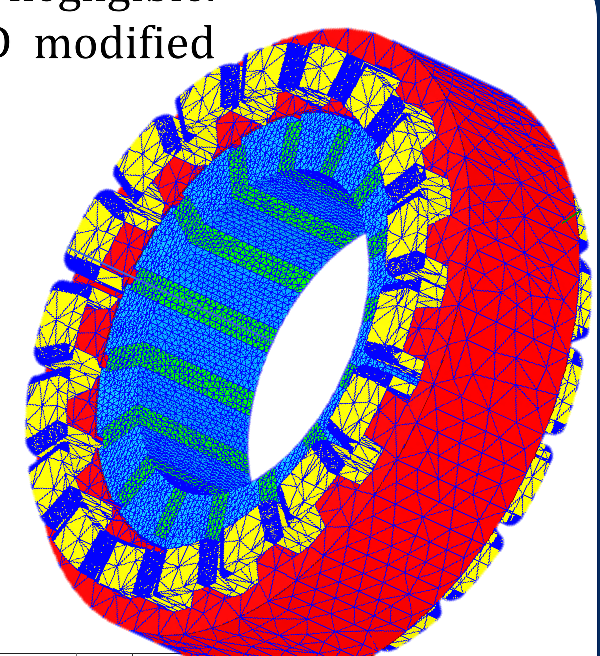
Conductor View



Comparison FEA and Hybrid

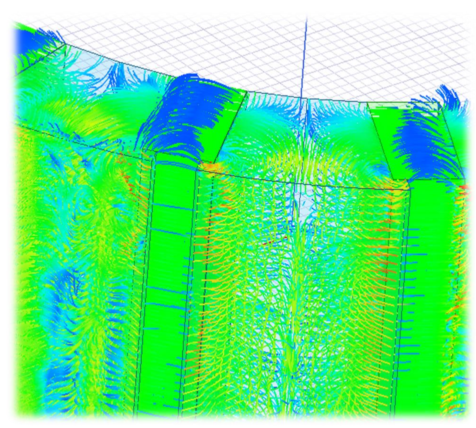
3D Effects

For this machine structure, 3D leakage effects are not negligible. Therefore, analyses have been carried out using a 2D modified model able to take into account the 3D leakage effects. These 3D effects have been estimated and formulated through an easy and accessible computation that has been validated against 3D simulations.

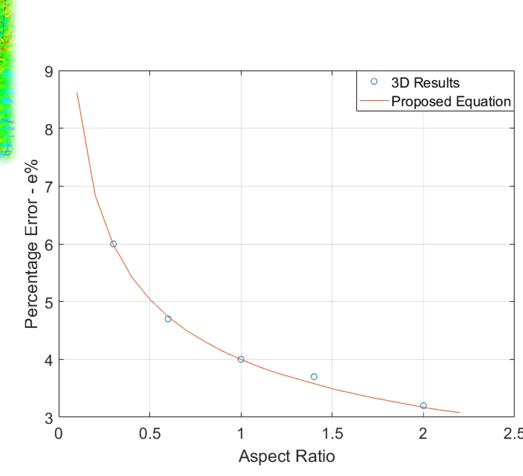


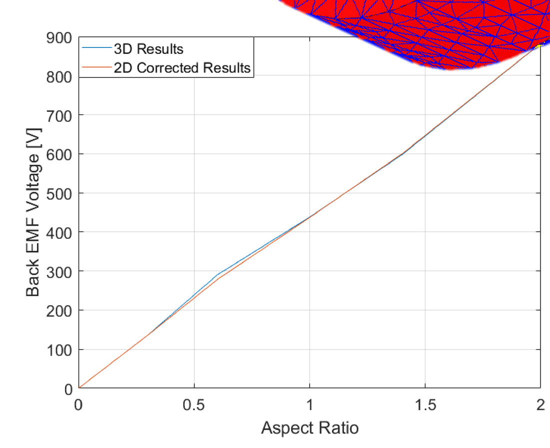
$$e_{\%} = a * \frac{w_m}{w_{rl}} * \left(\frac{L}{D}\right)^{-b}$$

Proposed equation for taking into account 3D effects in 2D models



End leakage effect

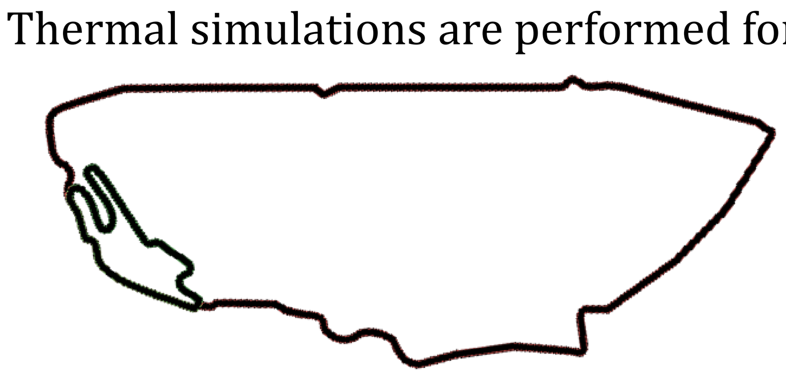




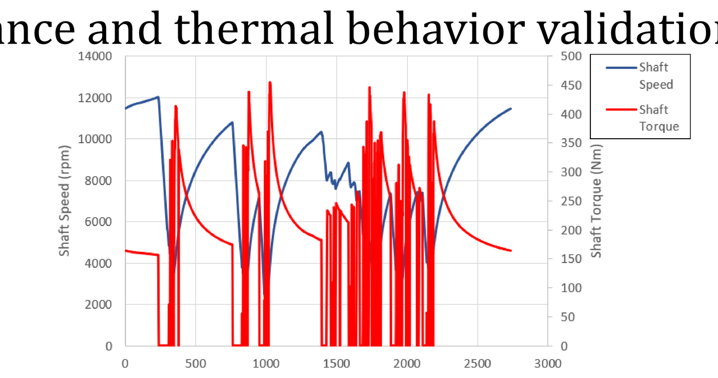
Proposed equation validation

Race Tests on Le Mans Circuit

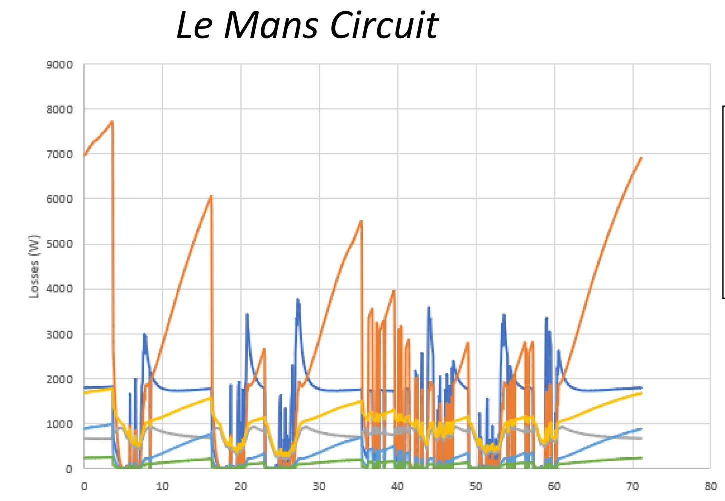
A real racing circuit cycle, Le Mans circuit, has been simulated using 2D modified FEA. 3D effects and AC losses have been taken into account using the proposed formulation. During a lap performed in 1'11.190" by a real racing car, 900 torque/time and speed/time points have been measured. Electromagnetic and Thermal simulations are performed for performance and thermal behavior validation.



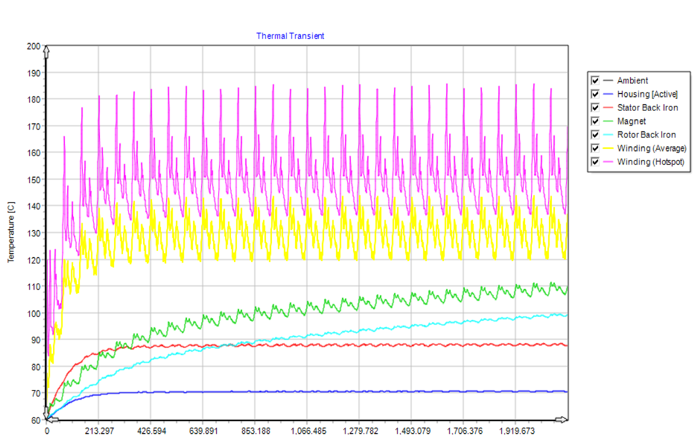
Le Mans Circuit



Torque-Speed requirements over the race



Machine Losses over the race



Thermal behaviour of the machine over the race

Publications

[1] G. Volpe, F. Marignetti, J. Goss, M. Popescu, D. Staton and I. Foley, "High-Performance Electric Motor for MotorSport Application", IEEE Vehicle Power and Propulsion Conference (VPPC), Belfort, France,2017
[2] G. Volpe, Accounting for AC Winding Losses in the Electric Machine Design Process, White Paper, https://www.motor-design.com/ac-winding-losses-news/, 2018
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[4] G. Volpe, M. Popescu, F. Marignetti, J. Goss, "Modelling AC Winding Losses in a PMSM with High Frequency and Torque Density", IEEE Energy Conversion Congress and Expo (ECCE), Portland, 2018
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[8] G. Volpe, F. Marignetti, C.Cecati, S. Mirimani "Electromagnetic Design and Modeling of a Two Phase Axial Flux Printed Circuit Board Motor," in IEEE Transactions on Industrial Electronics.