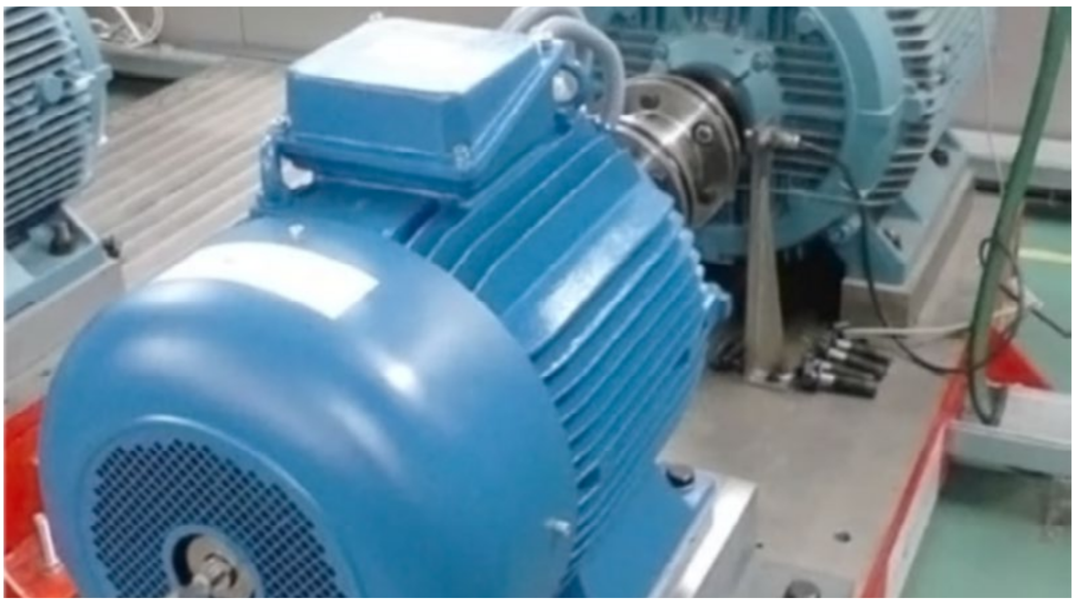
# MAGNETO-THERMAL PMSM PERFORMANCE SIMULATION WITH VALIDATION

In order to reduce energy consumption, efficiency is a key criterion that designers seek to optimize their electric motors. Complementary to the electromagnetic analysis, a thermal characterization is essential to study from the first design phase how temperature influences the performance of the machine. To obtain results close to the real working conditions, the motor control and the current harmonics produced by the electrical converter and control algorithms cannot be ignored.

This article summarizes a study of a Permanent Magnet Synchronous Machine (PMSM) which is designed and produced by Ikerlan in Spain[1,2]. It considers two different scenarios: fed with sinusoidal currents and fed by a converter and controlled using a Pulse Width Modulation (PWM). Multiphysics transient analysis are computed in Altair Flux™ and the results compared with experimental tests.



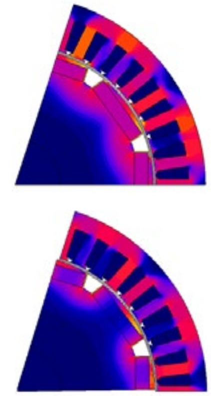
### The Machine

PMSM are widely used in industry because they offer high power density, a high level of efficiency while needing only limited maintenance. However, they require complex control systems, and the use of magnets and windings make them sensitive to temperature. While magnet temperatures should remain under their Curie temperature to avoid demagnetization, stator coil temperatures must be controlled to avoid insulation damage and reduced operating life. In this study, the PMSM is known as IkerMAQ.

| Type | | Surface PMSM | |
|---|---|---|---|
| Power | 75 kW | Torque | 700 Nm |
| Speed | 1080 rpm | Frequency | 90 Hz |
| V (phase) | 293 $V_{rms}$ | I (phase) | 87 $A_{rms}$ |
| Length (core) | 0,310 m | Diameter (core) | 0,188 m |

### The Finite Element Multiphysics Simulation

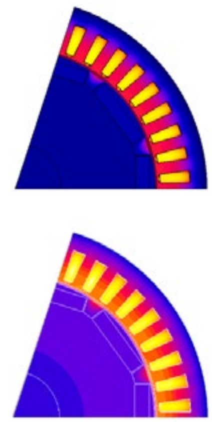
Altair Flux offers interesting capabilities to easily couple its electromagnetic solver with the thermal one, within the same working environment. Once the model is set up, a transient electromagnetic simulation calculates the losses which then serve as inputs to the transient thermal model. The thermal simulation estimates the temperature evolution within the PMSM, considering the different project time constants. Average losses in magnets, iron and copper are provided to the thermal simulation for each time instant.



Flux density for t=0s, without and with converter configuration

**Electromagnetic Analysis** - In both cases, constant speed of 1080 rpm is imposed. IkerMAQ has 5 pole pairs which implies an electric frequency of 90 Hz. Two complete electrical periods are simulated with a constant time step of 0.309ms, i.e. the sample frequency is equal to 3.2 kHz, far beyond the Nyquist limit for the PWM frequency of 1.2 kHz. This simulation scenario assures accurate results in both configurations in reasonable computation time.

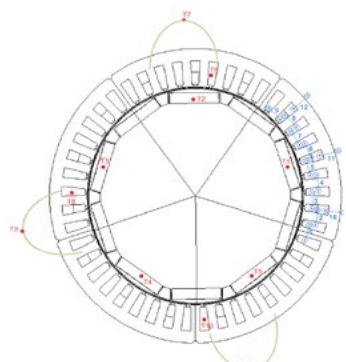
**Thermal Analysis** - Thermal characterization is carried out through a transient simulation which predicts temperature evolution during the first 3 hours of operation. This is the time necessary for all the motor parts to reach a thermal steady state. The main input for thermal simulation is the average losses previously calculated. Expected output is the temperature distributions all over the machine section. Material properties (e.g. heating capacity and thermal conductivity) are taken from material datasheets, while other critical thermal parameters, especially the convection coefficient between the machine and the surrounding air, along with the thermal resistance between the slots and the stator are obtained through experimental testing.



Temperature distribution without and with converter configuration

### The Testing Equipment and Procedure

A medium voltage laboratory set-up was used to perform the experimental tests. The facilities comprised a traction motor, a DC current source, a voltage converter and passive electric loads. The PMSM is mechanically coupled through its shaft to a traction machine.



IkerMAQ internal test points. Red: K-thermocouples; Blue: Magnetic test coils

Thermal sensors (thermocouples) and electric sensors (testing coils) were added to the motor during manufacturing to measure temperature at critical points. In the first case, the current is completely sinusoidal and the machine working point was established by an electric passive load, while the traction machine will impose its speed, i.e. IkerMAQ behaves like a generator. In the second configuration, torque is established by the voltage provided by the converter, while the traction machine still imposes the speed. With this set of measurements, four parameters can fully characterize the temperature evolution in the coils: mean and max temperatures in the embedded coils; mean and max temperatures in the end-winding region.

### Results Comparison

A complete set of measurements regarding both electromagnetic and thermal domains was performed with real sensors in the prototype to verify simulation results.

| Variable | Simulated | Measured | Error (%) |
|---|---|---|---|
| Mechanical power | 51.10 kW | 51.11 kW | 0.02 |
| Electrical power | 49.09 kW | 48.17 kW | 1.91 |
| Phase Voltage | 255.65 $V_{rms}$ | 255.00 $V_{rms}$ | 0.25 |
| Phase Current | 84.72 $A_{rms}$ | 87.97 $A_{rms}$ | 3.69 |
| Iron losses | 1.40 kW | 1.59 kW | 8.81 |
| Copper losses | 1.17 kW | 1.36 kW | 13.97 |

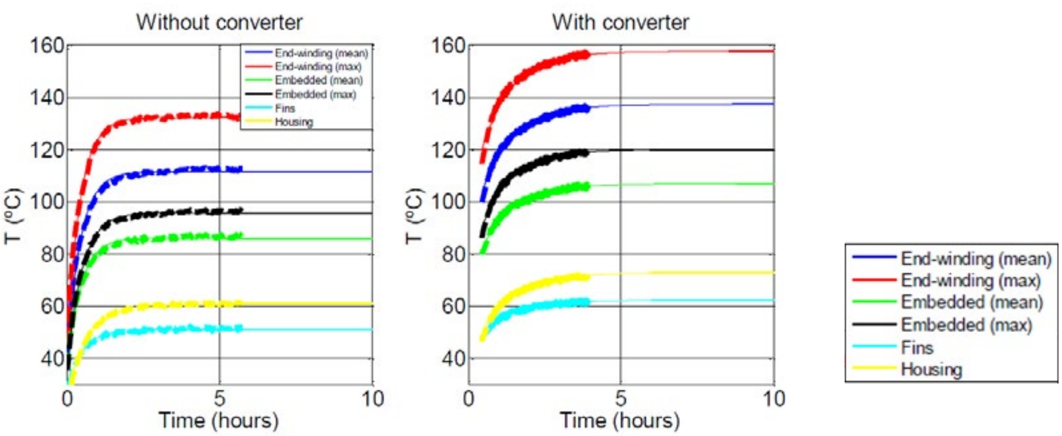
Electromagnetic comparison without converter configuration

| Variable | Simulated | Measured | Error (%) |
|---|---|---|---|
| Mechanical power | 40.73 kW | 40.46 kW | 0.67 |
| Electrical power | 45.62 kW | 45.57 kW | 0.11 |
| Phase Voltage | 242.8 $V_{rms}$ | 237.6 $V_{rms}$ | 2.19 |
| Phase Current | 89.0 $A_{rms}$ | 89.0 $A_{rms}$ | – |
| Iron losses | 2.22 kW | 2.32 kW | 4.31 |
| Copper losses | 1.52 kW | 1.66 kW | 8.43 |

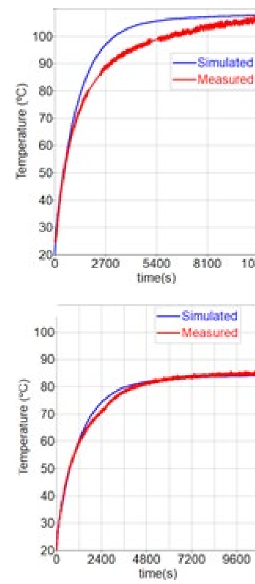
Electromagnetic comparison with converter configuration

**Electromagnetic Comparison** – Both global mechanical and electric quantities have been compared. It illustrates the high level of accuracy of Flux, but also the importance of considering the impact of the converter in the modelling to stay close to real life performance. Estimation of losses shows an error under 9%, which is an interesting result considering the approach (2D modelling only, iron losses measurement accuracy being limited).

**Thermal Comparison** – The steady-state temperature and the temperature transient evolution were measured and compared with the computed temperature at critical points in the machine, such as in the coils and the magnets. The temperature error under steady-state conditions remains under 2.5°C in both test configurations.




Temperature measured without and with converter




Mean coil temperature evolution without and with converter

### The Accuracy of the FEM Multiphysics Simulation

Magneto-thermal simulations computed within the Flux single environment, and experimental testing shows excellent correlation in both electromagnetic and thermal domains. The study also confirmed that the impact of current harmonics generated by the converter on the motor temperature has to be considered early in the design process, in order to keep its high level efficiency and optimize its working life.

The study also fully illustrates the potential of Altair Simulation-Driven Design approach to support and accelerate the multiphysics development of electrical machines, while reducing long and costly prototyping phases in the future.

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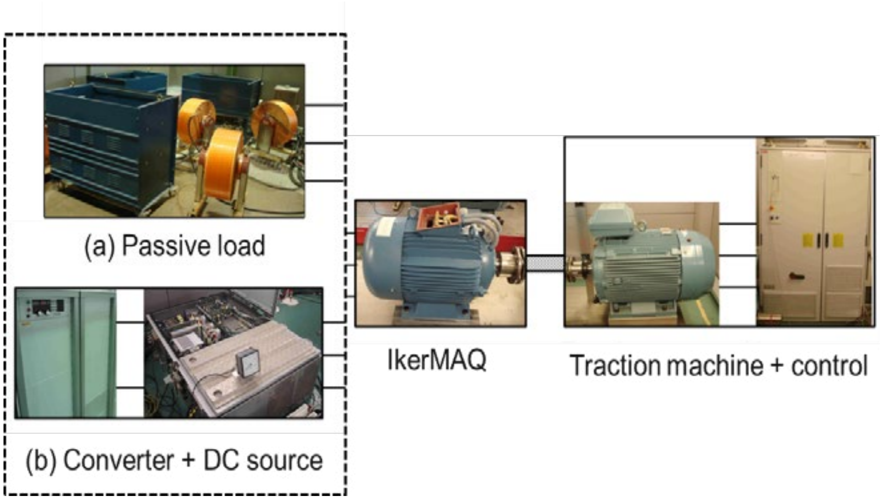


### Working with Altair

Whether starting from a concept or an existing design, Flux enables engineers to simulate, improve, and optimize electrical machines. The software provides detailed analysis with high-fidelity models. Powered by best-in-class numerical techniques, Flux delivers accurate analysis of motor behavior. Flux, coupled to Altair HyperWorks™ has a workflow to guide motor designers through an efficient process of Simulation-Driven Design. This analysis and optimization solution support multi-disciplinary teamwork to reduce design times and costly prototypes.

Altair is a global technology company that provides software and cloud solutions in the areas of product development, high-performance computing (HPC) and data analytics. Altair enables organizations across broad industry segments to compete more effectively in a connected world while creating a more sustainable future.

To learn more, please visit altair.com

**References:**

(1) Ikerlan, Spain https://www.ikerlan.es/en/

Original paper: “Thermal modelling of a Permanent Magnet Synchronous Machine through FEM simulation with experimental validation”, Alejandro L. Rodríguez, Philippe Wendling, Patrick Lombard – Altair Engineering, Irma Villar – Ikerlan Technology Research Centre