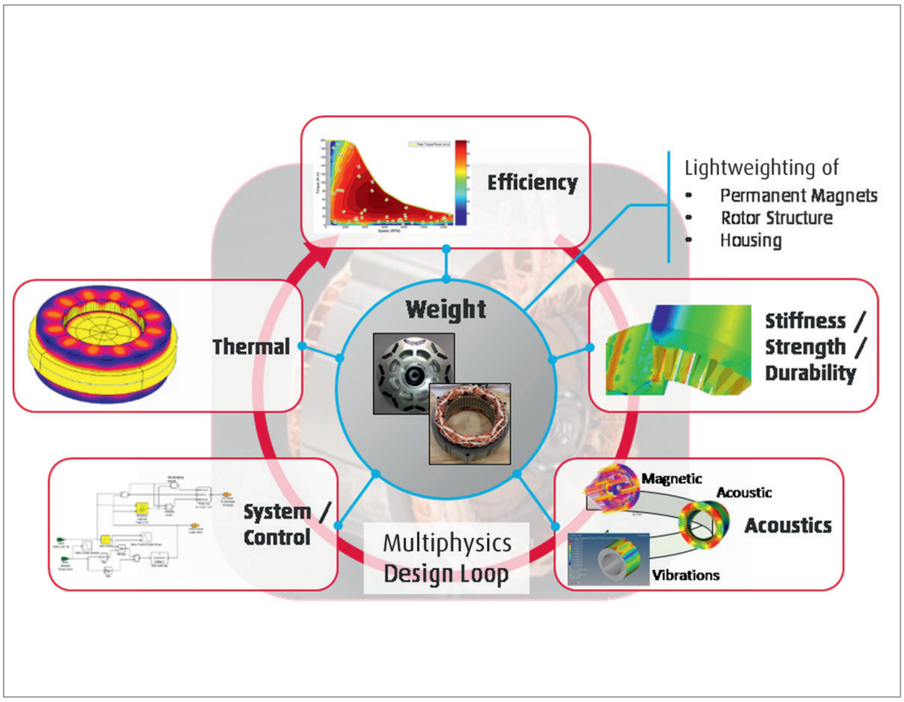
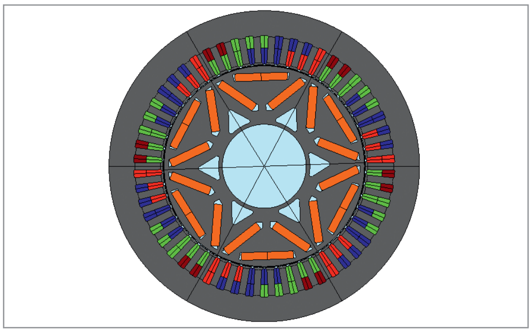
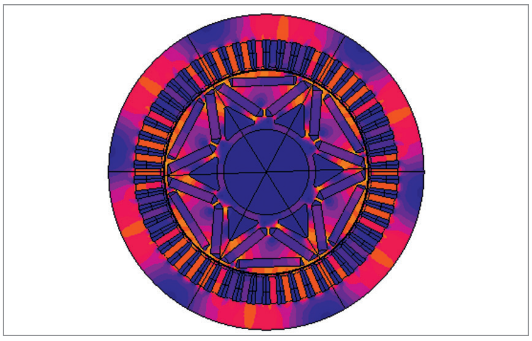
Porsche

E-motor Design using Multiphysics Optimization







1. Introduction

The rate of which electric hybrid and full-electric vehicles are reaching the market and being developed has increased significantly over the last years and the requirements on the e-motors been designed for new cars are increasing rapidly as well. The goal is to develop better motors within tighter time and cost schedules. Simultaneously, the technical requirements on the motors being developed are increasing rapidly, both in terms of level and bandwidth of requirements. Today, an e-motor cannot just be developed looking at the motor as an isolated unit; it must be assured that tight requirements concerning the integration into both the complete electric or hybrid drivetrain system and tight requirements concerning perceived quality are fulfilled. Thus, it is necessity to develop the e-motor not in isolation but as a system to fit work optimally with other components and systems. Noise and power consumption are two of such integration challenges.

2. Simulation-Driven Design

FE and other simulation methodologies have traditionally been used very successfully to verify designs and design directions. Today, FE and especially numerical optimization is increasingly used to support drive the design process, i.e. optimization is used to help the design team finding best alternatives, executing sensitivity studies, performing trade-offs between different design alternatives, etc. This design strategy is often denoted “Simulation-Driven Design”. Simulation-driven design is especially beneficial, where the design is less intuitive because of high design complexity and/or complexity of loads and targets for the design. Products and designs which experience requirements from several different types of physics and attribute disciplines are especially suited for using simulation-driven design since it quickly becomes impossible to comprehend the relationships between design change and change in behavior using traditional design methods.

Industry
Automotive

Challenge
Improving the total balance in e-motor development

Altair Solution
Altair Flux, Altair FluxMotor, Altair OptiStruct, Altair Activate

Benefits
Initial design can be improved significantly when run through the design optimization process

3. Multiphysics Optimization / Multi-Disciplinary Optimization

Multi-disciplinary and multiphysics optimization methodologies make it possible to design an e-motor for multiple, completely different design requirements simultaneously, thus avoiding a serial development strategy, where a larger number of design iterations are necessary to fulfill all requirements and unfavorable design compromises need to be accepted. Multiphysics and multi-disciplinary optimization however, need efficient processes to be executed within the narrow constraints and time limitations of a live product development. The processes need to be integrated with all departments in the e-motor development. Simulation models for different physics need to be made available and need to be up to date.

Design input and restrictions from design, packaging, production etc. need to be considered when setting up the design optimization problem. Otherwise, the results will not be feasible or relevant. Finally, all input and restrictions need to be brought into one single optimization loop as shown in Figure 1.

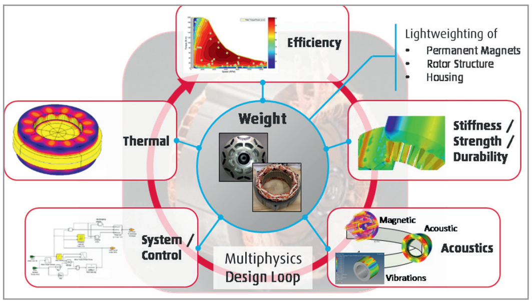


Figure 1: Generic E-motor Multiphysics Optimization Environment

4. The Porsche / Altair Optimization Environment

A simplified view of the Porsche / Altair multiphysics design optimization environment is depicted in Figure 2. Altair HyperStudy constitutes the optimization engine and is used to drive all other subprocesses and tools necessary to execute a complete optimization study.

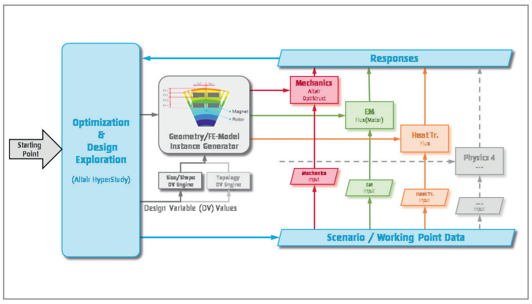


Figure 2: Altair Multiphysics / Multi-Disciplinary Design Optimization Environment

The execution of a typical study in time is depicted in Figure 3. A baseline design is used as starting point for the optimization. A design space is then created by defining variables (design variables, DVs) that influence the design. In this study shape variables, which influences the size and position of the magnets are used to create the design space. Then, the essential responses are selected. Depending on the choice of responses, one or more solvers must be used to perform one or more simulations to yield the necessary responses. In certain cases, co-simulation of solvers is necessary to resolve responses depending on each other, i.e. multiphysics situations, i.e. situations where time dependent output from one solver is needed to solve responses in another solver and vice versa.

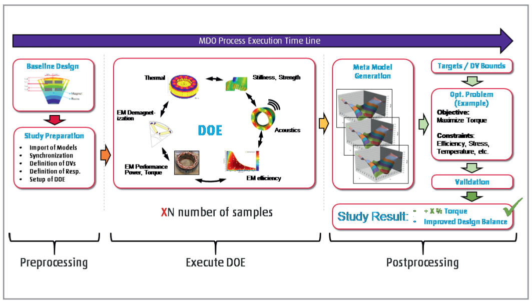


Figure 3: Execution of a Multi-Disciplinary Study in Time

Before launching the study, general study parameters must be defined and how the optimization should be executed.

If metamodel-based optimization is chosen, response surfaces of all responses are created based on the samples from the DoE (Design of Experiments). Optimization and design exploration can then be carried out using these response surfaces.

A strength of DoE based optimization is clearly the ability to use the data to answer a large number of different questions and to play through numerous design scenarios. Hereby it is possible to use single or multi objective optimization and response constraints can be turned on and off as desired. Such studies can be carried out without executing new simulations but are based on the response surfaces which are created from the DoE.

Design Problem

Objectives
- Maximum power (base point)
- Minimize torque ripples

Constraints
- Demagnetization at base point
- Mechanical strength
- Temperature of winding lower than 200°C

Requirements
- Iron fill factor: 0,92
- Magnet: Br 1,15
- Tmax winding: 200°C
- Tmax rotor: 180°C
- Minimum power: 170kW
- Max phase voltage: 241V
- Max phase current: 300A
- DC-link voltage: 650V, 800V

The stator is imposed. The rotor design is open in any direction, meeting the requirements

Figure 4: Porsche Design Requirements

5. The Design Problem – Overview

Porsche is aiming at developing high performance e-motors with high requirements on key performance data such as power, torque and speed. A list of the essential requirements are depicted in Figure 4 .

Porsche and Altair agreed on applying a three-step optimization-driven design process aligned with the discussion in previous sections to develop a concept matching above requirements. An overview of the process is depicted in Figure 5.

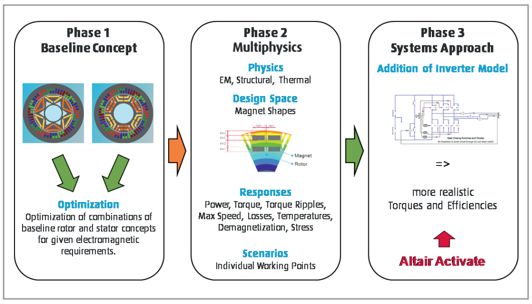


Figure 5: Phases in the E-motor Design Project

Phase 1: Baseline Concept Phase
The first phase supports the development of a baseline combination of stator and rotor concepts focusing on magnet configuration. For each magnet configuration, design optimization is executed to derive an optimal set of design parameters.

Phase 2: Multiphysics Development Phase
In the second phase, the design scope is extended to include other important physics to be considered during the e-motor design process. In addition to phase 1, heat transfer, structural strength and demagnetization responses are added to the design problem.

Phase 3: Systems Approach Phase
The third phase is focused on looking at the e-motor in its environment and thus including other parts of the drivetrain. As a first step, the inverter is added to generate more realistic currents into the e-motor design process. Later, the systems approach will be used to calculate efficiencies and temperature development for complete drive cycles

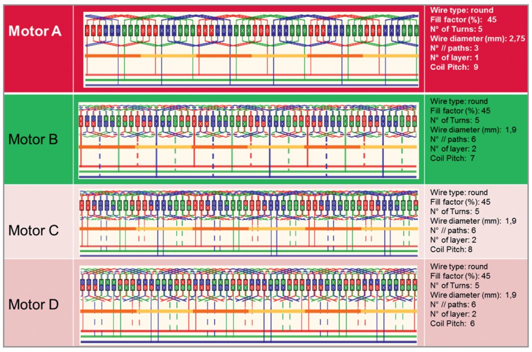


Figure 6: Comparison of Different Winding Configurations

6. Phase 1 – The Baseline Concept Finding Process

The first phase concerns the task of finding the right starting point for the multiphysics design process. Altair FluxMotor was chosen for this task. Based on a classical rotor topology, different winding configurations were investigated with respect to maximum torque and power for one working point close to the base point. Figure 6 summarizes the different configurations.

When the preferred winding configuration has been found, the next task is to find the best matching rotor configuration based on the design requirements stated for the e-motor to be developed. In this project, four competing rotor designs were investigated and compared. In FluxMotor different test scenarios are available to analyze a motor concept and for the requirements in this project, the "efficiency map test" was chosen to compare the four different topologies. From this test, both the base point and the max point data could be extracted and used for the comparison of the designs. Four different topologies were tested as depicted in Figure 7.

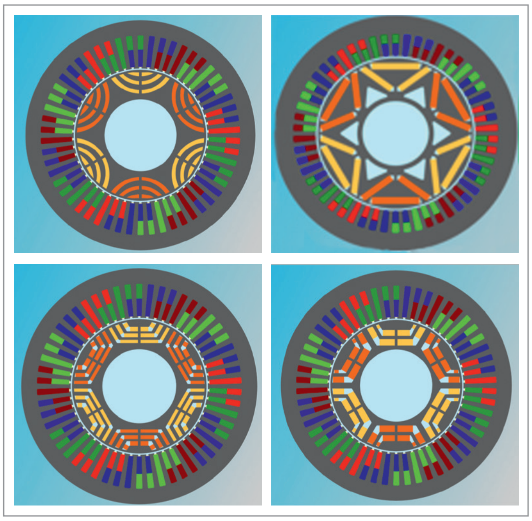


Figure 7: Four selected Baseline Rotor Topologies were Compared

Based on the performance results achieved for the four different baseline configurations, it was decided to keep on working with Configuration 2. Configuration 1, which had better EM performance than the others was dismissed due to production feasibility and cost reasons.

7. Phase 2 – The Multiphysics Design Process

To satisfy different requirements coming from different physics, a strategy was chosen to use a multi-disciplinary optimization process, in which several computations using different tools were used, see Figure 8. The different tools and simulations where necessary to calculate all requested responses for the multiphysics design optimization problem. The simulation types and the working points were chosen such that all responses could be extracted using a minimum of calculation effort.

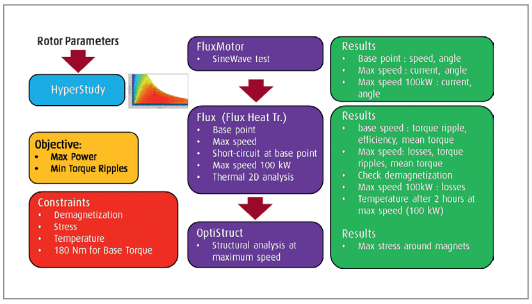


Figure 8: The Multiphysics Design Optimization Environment

7.1 FluxMotor Simulation to Extract Main Characteristics

In order to study the mentioned working points, FluxMotor was first used to extract the main characteristics of the motor, such as speed, current rms and control angle values. These values being known, FE based tools could be used to accurately calculate all motor characteristics including iron losses, efficiency, etc. The following simulations where included in the study:

#	Description	Solver
1	General Characterization of the E-motor	Altair FluxMotor
2	Base Point Simulation	Altair Flux
3	Maximum Torque Point at Max Speed	Altair Flux
4	100 kW Point at Max Speed	Altair Flux
5	2-D Thermal Analysis Test	Altair Flux (Heat Transfer)
6	Short-Circuit Test for Demagnetization Check	Altair Flux
7	Static Stress Analysis	Altair OptiStruct

7.2 Flux Simulations for the Base Point, for the Max Speed, and for 100 kW at Max Speed

Flux 2D is the FE tool used to completely derive the e-motor behavior at three different working points as described above. The input data for all these simulations includes material properties, (B(H) curves and iron losses for rotor and stator), the electric properties (resistance, and current supply) and the speed of the motor.

After having reached steady-state for these simulations, the following output data could be extracted:
• torque
• torque ripples
• losses and efficiency

For the last simulation, the 100 kW at max speed test, a dedicated analysis is done for extracting losses in each region (iron losses in rotor and stator, eddy current losses in magnet, Joule losses in coil). These are later used to feed the thermal simulation, see Section 7.3 below.

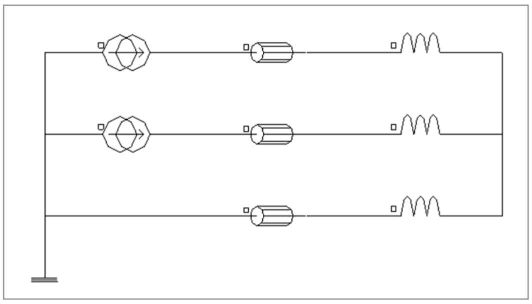


Figure 9: Electric Circuit for Working Point Simulations

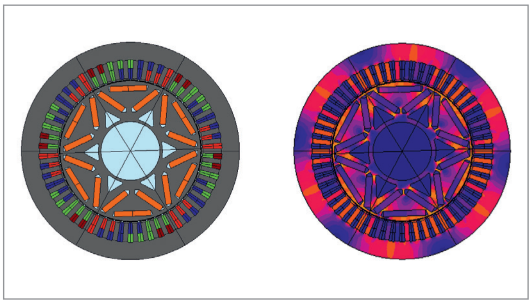


Figure 10: Favorized Concept and Magnetic Flux at Max Speed (Right)

7.3 Simulation to Extract Thermal Responses

Flux 2D is used for a thermal test load case. The cooling is done through a water jacket on the outside of the stator. Convection and radiation are accounted for through boundary conditions. The test case prescribes to stay at maximum speed for 2 hours, the motor being able to deliver 100 kW as output. The goal is to check that there is no risk of overheating the coils. The losses determined from the previous test are used as input for this test. Finally, the temperature is determined as a function of time, in order to test the coil winding temperature at the last time step.

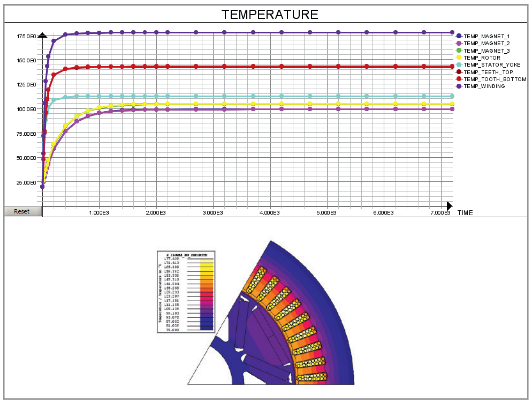


Figure 11: Top - Temperature vs Time, Bottom – Temperature Profile After 2 Hours

7.4 Flux Simulation to Determine Risk of Demagnetization

When designing e-motors, it must be assured that the risk of magnet demagnetization is minimized. Porsche uses a short-circuit test at the base point to address this issue. Based on such simulation, a specific feature and procedure in Flux is applied to compute the remnant flux density at the end of the computation, see Figure 12. We can then extract a percentage of magnet which is demagnetized. The challenge is to get the highest value of current after short-circuiting. A parametric analysis has shown when to start the short-circuit, see Figure 13.

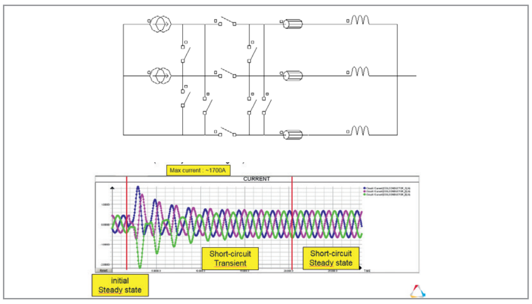


Figure 12: Top - Electric Circuit for Short-Circuit, Bottom – Short Circuit Current

7.5 OptiStruct Analysis to Extract Mechanical Responses

Mechanical stresses must be constrained to be kept below a specific level to assure mechanical integrity. The stress occurs mainly due to rotational forces at high speed. The starting point is a STEP file generated as a result of the Flux 2D load cases. Based on the geometry information in the STEP file, an FE mesh is created, and all mechanical properties are automatically set in a batch process within Altair HyperMesh. The simulation to evaluate stresses is executed in Altair OptiStruct. The maximum stress values are finally extracted from OptiStruct, see Figure 14. At this point the focus lies on tensile stresses since they are considered more critical in comparison to compression stresses.

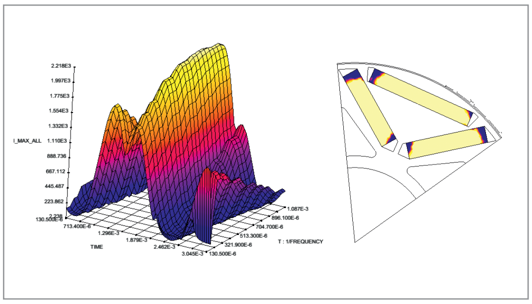


Figure 13: Max Value of Current versus Time (Left), Remnant Flux Density After Test (Right)

7.6 DoE and Optimization of the Multiphysics Problem

The complete study with all simulations was setup in Altair HyperStudy as depicted in Figure 15. Total run time to extract all responses for one single design was 29 minutes. A DoE with 358 runs was executed in order to cover the design space. The total run time was 17.45 hours running 15 jobs in parallel.

Following the DoE, optimization and design exploration could be performed. Such optimizations and design explorations can be executed on a subspace of simulation types and responses and on the complete problem. The optimization problem can be formulated as a single or multi-objective optimization problem. Figure 16 shows an example of global optimization that was formulated and executed on the basis of the DoE. The optimization efficiently supports the search for an improved solution and all constraints could be significantly improved and pushed into the target range within accepted tolerances. Using the DoE data, studies can be executed on a subset of variables or on the complete problem. Studies can be performed concerning driving design variables, sensitivities and trade-offs between different design objectives and constraint settings. The overall goal of such studies is to provide efficient and in-time support for the design engineers developing the e-machine. Figure 17 shows a study where different optimization objectives were used to study general sensitivities to the choice of objective function. The designs in Figure 17 were found by looking at the individual response surfaces and selecting the DoE design with the best performance for the selected response.

8. Phase 3 – Improving Optimal Design by Adding Power Inverter

In the third phase, it is considered how to improve the design of the motor by adding the power electrics and control methods which improve the accuracy of the electrical inputs driving the machine.

The design process up to this point has assumed the inputs to the e-motor are idealized (i.e., purely first harmonic) sinusoidal inputs to the three phases. However, the actual system supplies input voltages based on modern power electronics and pulse width modulation (PWM) techniques to approximate the desired driving voltage from the control algorithms in the system. This particular system includes a two-level inverter along with a current and speed controller cascaded to drive the logic of the transistors with space vector pulse width modulation. PWM methods create higher order harmonic content of the electrical inputs which can degrade certain aspects of the performance off the e-motor, like losses and torque ripple in the machine. The losses effect efficiency and the thermal behavior, and the torque ripple cause speed pulsations and NVH problems, and thus simulating the inverter and dependent systems in an important aspect to getting toward an optimal design. Electromagnetic losses also contribute to the thermal behavior which is very important for design: consideration for critical components like the coils and magnets are important to capture accurately and this helps to improve the accuracy for the cooling system design as well. In this way we can get a more accurate result that leads to more confidence that the e-motor has been designed optimally compared to using the prior design process up to this point.

Altair Flux does have electric circuit building capabilities, which is useful for simple circuits; however, in order to achieve more accuracy for our control system, we will use a different simulation tool that is better suited for this task and integrate this into our design process. Building this system will be accomplished in Altair Activate, a multidomain system simulation environment that will allow us to model the complex inputs not only for the power electronics, but also the detailed controls algorithms, in this case using space vector pulse width modulation (SVPWM). Our end goal is to generate more accurate inputs to Altair Flux by modeling a power inverter + space vector PMW method to apply input to our three-phase motor. Our approach is as follows using Altair Activate and Altair Flux:

In Phase 1, the inverter can be modeled in different ways, either with the traditional "signal-based" blocks to mimic the effective behavior of the transistor switches, or using Activate's Modelica libraries, where this provides advantages in giving a range of fidelity of transistor models, from ideal switches to more detail in IGBT or MOSFET.

Phase	Description
1.	Build a two-level inverter with a constant DC bus voltage using Altair Activate
2.	Supply the inverter transistor switches with inputs from our current controller, based on the space vector PWM method (Activate)
3.	Drive our current controller with a speed controller based on optimal Field Oriented Control currents (e.g., optimal direct and quadrature currents) (Activate)
4.	Use a motor model based on the earlier phase design – this may be based on FE model with co-simulation or a reduced fidelity model based on data extracted from the Flux model.
5.	Drive the motor model with inverter voltage and extract the steady state current waveforms
6.	Use the steady state current waveforms from Step 5 as input to the optimization process established in the earlier phases and re-run process to produce optimal design

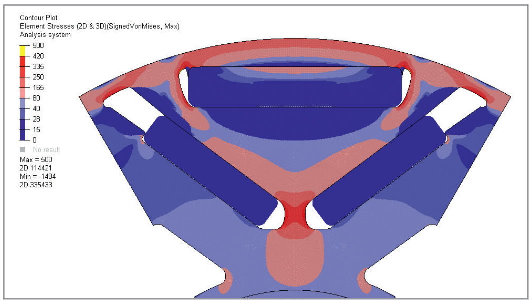


Figure 14: Stress Distribution on Rotor Segment (Compression Stresses Ignored)

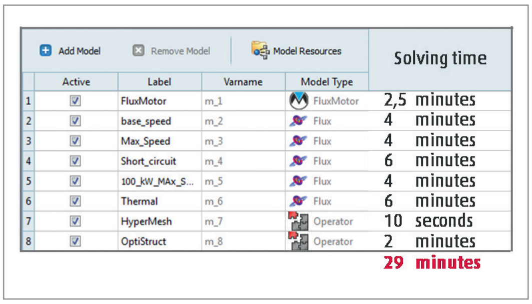


Figure 15: Complete Multiphysics Problem in Altair HyperStudy

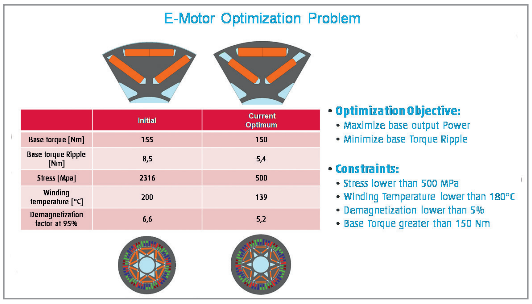


Figure 16: Complete E-motor Optimization Problem – All Constraints Fulfilled Within Acceptable Tolerances

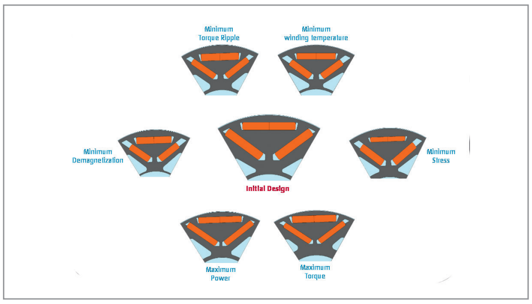


Figure 17: Design Directions with Different Optimization Objectives

Additional support for SPICE models also allows for more user choice in modeling these systems. In our system, the inverter is modeled as idealized switches.

In Phase 2, space vector PWM is used in our system as it has many advantages in three phase systems to efficiently drive the motor; however, it is a relatively complex algorithm and building this is more easily done in block diagram environment like Altair Activate to help model this part of the system. The control algorithms in Phase 3 are also based on Field Oriented Control and most easily simulated in Activate for similar reasons. Depending on the application, our speed controller can be modeled as the well-known PI controller or we can also consider using the analytic and optimization capabilities with Flux to find the optimal direct and quadrature currents for a given speed/torque input which also leads to a more efficient system.

In Phase 4, we need to connect the inverter to a motor model. This can be different levels of fidelity depending on the simulation needs and time available. With co-simulation between Flux and Activate, both applications solve and synchronize each time step and provides the most accuracy; however, this approach is also the costliest for the time required of the methods. In our case, since we have only three design points of interest for optimization, we choose to complete using this highest level of fidelity model. Alternatively, Flux may also be used to create reduced order models (ROM's) of the e-motor that are based on lumped parameters for coil inductance, resistance, etc. which can be constant parameters or look-up tables for the values. The latter method is a nice compromise for simulation speed for the model implemented in Altair Activate compared to co-simulation; however, it also requires the simulation runs to generate this data. Lumped parameter models coupled with inverter models can be sufficiently accurate, and you can find other work like in [1] which shows results of a similar approach to test results which show good correlation.

This ROM approach may be advantageous for scenarios where a full range of speed and torque is desired so that a user may consider an entire drive cycle like WLTP or otherwise to simulate the motor behavior where co-simulation is prohibitively expensive. This may allow the user to get a better understanding of the performance and thermal behavior of the motor within a full vehicle system for realistic driver behavior.

Upon selection of the e-motor model, we drive this with input voltage from the inverter in Phase 5. The transient behavior of the system necessitates a simulation time long enough to generate steady state current waveforms. Flux is simulated most efficiently with current profiles, and we can use this steady state current to drive the optimization process we established earlier. Now that we are driving the motor process with the current waveforms in Phase 6 with higher harmonic content from our PWM methods, we can get more accurate results for motor losses and torque ripple as we optimize the design.

Understanding how other systems interact and affect the performance of the motor helps to achieve the right design that is "right-sized" – neither undersized leading to failure or oversized leading to cost and/or weight gains and leading to best overall system performance.

9. Summary and Conclusions

The project described in this paper is focused on multiphysics design of an e-motor for Porsche AG. A simulation-driven approach has been introduced which supports the development of e-motors using a series of optimization intensive phases building on each other. The first phase is concerned with the early concept design and the choice of baseline conceptual layout. In this phase, an optimal combination of stator and rotor layout is found based of electromagnetic design criteria. In the second phase, a multiphysics approach is used to design the motor against criteria coming from different physical domains, in this case electromagnetics, heat transfer and structural mechanics. The presented approach is generic and other physics and types of responses can be added to the design problem if desired. The third phase is concentrating on adding other essential components and systems into the design process with the aim to further improve accuracy and results and to find a design which also fulfills constraints coming from integration the e-motor into a complete e-powertrain system.

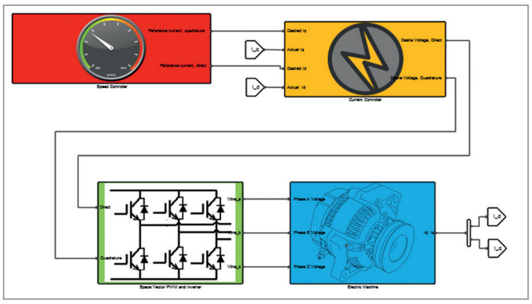


Figure 18: Altair Activate Model of Speed and Current Controller, Power Inverter and E-motor

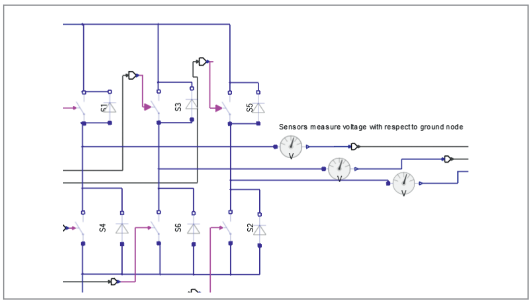


Figure 19: Example Inverter Model using Modelica

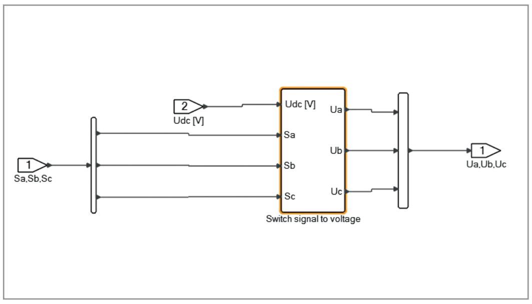


Figure 20: Example Inverter Model using Signal-Based Blocks

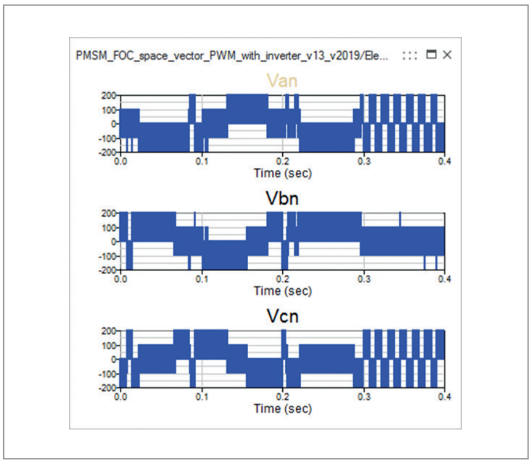


Figure 21: Example of Applied Phase Voltages using SVPWM

In the project, new methodology and new processes have been developed in order to successfully execute all tasks and phases. Since the execution in the optimization engine (HyperStudy) requires that all steps can be executed automatically, effort has been spent on designing batch scripts which support the automatic execution of the process. The developed processes have been developed on the basis of the Altair HyperWorks suite of tools which have open APIs and can be executed in batch.

The project shows the potential of using simulation-driven design, i.e. multiphysics design optimization as design tool for e-motor development. As soon as the design optimization process has been successfully setup, it can deliver significant information of design directions, sensitivities and of the consequences of design choices made during the development. The studies performed so far in Phase 2 shows that an initial design can be improved significantly when run through the design optimization process.

The process described in this paper has not yet reached the final state. Porsche and Altair are working on improving the process and adding new aspects into the design optimization process.

Sven Luthardt, Dr. Ing. h.c. F. Porsche AG, Weissach; Dr.-Ing. **Lars Fredriksson,** Altair Engineering GmbH, Böblingen;
Vincent Leconte, Altair Engineering, Grenoble; **Andrew Dyer,** Altair Engineering Inc, Troy;
Patrick Lombard, Altair Engineering, Grenoble

References:
[1] Matlab/Simulink Coupling to Finite Element Software for Design and Analysis of Electric Machines",
Gaizka Almandoz Gaizka Ugaide, Javier Poza, Faculty of Engineering, University of Mondragon – Spain,
Ana Julia Escalada, Orona EIC Elevator Innovation Centre, Hernani, Spain

Altair Engineering Inc., World Headquarters: 1820 E. Big Beaver Rd., Troy, MI 48083-2031 USA
Phone: +1.248.614.2400 • Fax: +1.248.614.2411 • altair.com • info@altair.com