e-models

E-Machine Models—Approach, Usage and Validation

____ The increasing demands of the modern vehicle development process cannot be satisfied without employing sophisticated simulation tools. This is particularly true for electrified vehicles: the dynamic drive is able to provide short boosts of high power for a certain time, but quickly reaches its load limit. In order to be able to make precise predictions about output and consumption, for example, during every development phase, detailed simulations of the electrified powertrain are absolutely necessary.

By Dr. Malte Jaensch

Essential for accurate simulations of the performance of electrified vehicles are accurate electric machine models. The core of the E-drive seems to be very simply constructed at first glance: housing, rotor, stator and two bearings. On close inspection, however, it becomes apparent that it is indeed a very complex thermoelectromechanical device, the modeling and validation of which poses considerable challenges.

The complete vehicle model and its main components

An electric vehicle model suitable for the calculation of power and consumption comprises a large number of independent model blocks. The most important model blocks and how they interact are shown in Figure 1 in more detail.

The **driver model** takes on the role of a controller, comparing a vehicle speed set point, taken from a given **speed profile,** with the actual speed of the vehicle (as reported by the **vehicle dynamic model**) and using throttle and brake pedals to try and align both. A **control unit** translates the pedal position into a positive or negative torque demand, which is sent to the inverter. The **inverter model** then applies a matching AC current to the **electric machine model,** which sends back to the inverter information on the level of AC voltage occurring at the machine's power terminals. The **battery model** governs—inter alia—the relationship between DC current and DC voltage, where—as with the E-machine model, the current is taken to be the input and the voltage is the output of the model.

Within the electric machine, a power conversion from electrical to mechanical power is taking place. In motoring mode, the **electric machine model** accepts current and outputs torque, which is then used as an input to the drivetrain model. The **drivetrain model** block represents driveline components such as gearbox, differential and clutch. Having thus been manipulated by the drivetrain model, torque enters the **vehicle dynamics model** that computes the reaction of the vehicle in terms of vehicle and tire speed, weight balance, tire slip and so forth.

Many of the components that constitute the electrified powertrain require liquid cooling in the real vehicle. The corresponding component models therefore have thermal sub-models that use the coolant temperature as their input parameter. The change in temperature is calculated based on this and depending on the model block-specific losses in each case.

Electric machine modeling

A typical electric machine model is made up of four building blocks: the electromagnetic model, the power loss model, the thermal model and the mechanical model (see figure 2 on page 18).

The **electromagnetic model** serves two main functions: first, it calculates the AC voltage as a function of AC current, torque angle, angular frequency, winding (copper) temperature and magnet temperature. Second, it computes the internal torque as a function of current, torque angle, power loss and magnet temperature.

The **power loss model** computes the losses occurring inside the electric machine based on parameters such as current, torque angle, angular frequency and temperature. In order to cover a variety of different loss types, the power loss model is also made up of individual sub-models.

The **thermal model** calculates the temperature of the model components such as winding, stator, rotor and housing, as well as the initial coolant temperature. The flow rate and input temperature of the cooling medium are taken into account.

The **mechanical model** can be very basic, only considering the role of the E-machine's inertia in computing the output torque available.

Considering this simplified description of the inner workings of the electric machine model, it becomes apparent that there is a high level of interdependency between the individual modeling blocks, which is further increased by the regulating actions of the inverter. Modeling this complex behavior accurately is one of the greatest challenges for the simulation.

The quality of a simulation is determined by how close to reality its results are. Before the model of the electric machine can be used as part of a complete vehicle model, the model created needs to be checked for accuracy. This is done by comparing computed results with data gathered from the electric machine test stand.

Electric machine measurement for model validation

The simplified example of a test plan, as might be used by an OEM as part of the series development of the electric machine, consists of six major types of testing (see figure 3 on page 19).

Starting with tests to determine the fundamental machine parameters, a range of test programs are executed: mechanical testing, which subjects the machine to mechanical loads on housing and shaft; environmental testing that exposes the machine to adverse environmental conditions such as salt, water and heat; three sets of endurance testing, performed under varying climatic conditions and, most important from the viewpoint of the simulation engineer, performance testing. ›

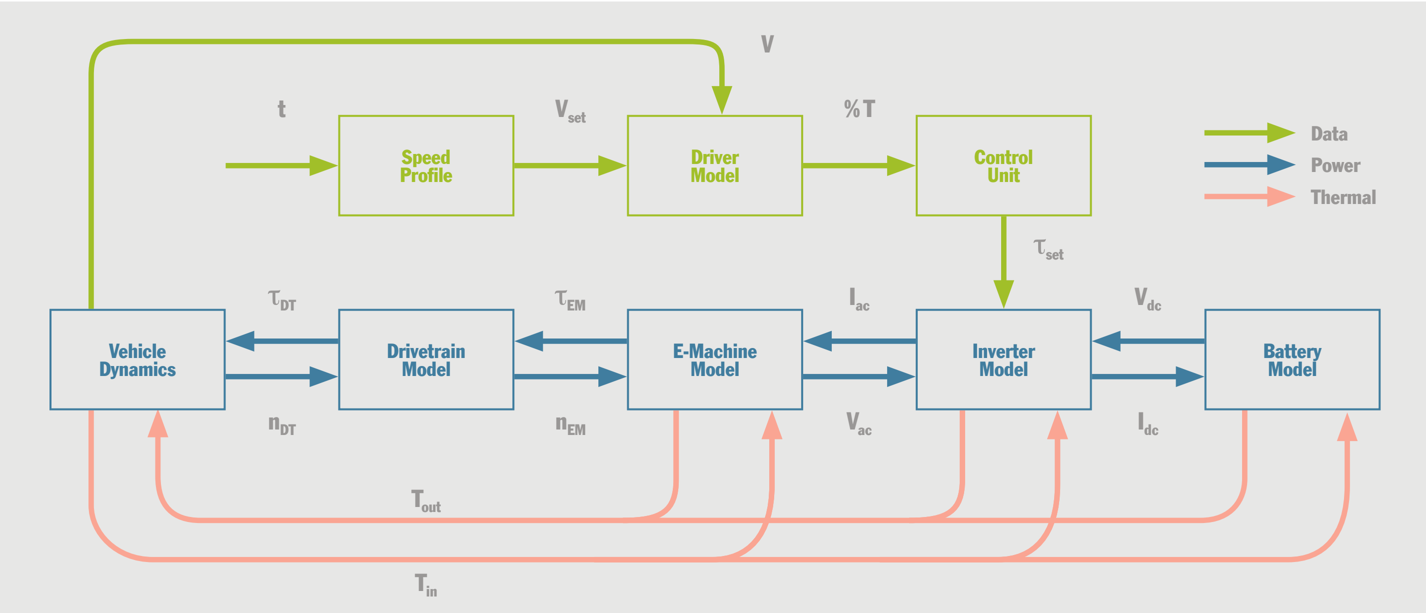


Figure 1: Outline of a simplified simulation model of a battery-electric vehicle

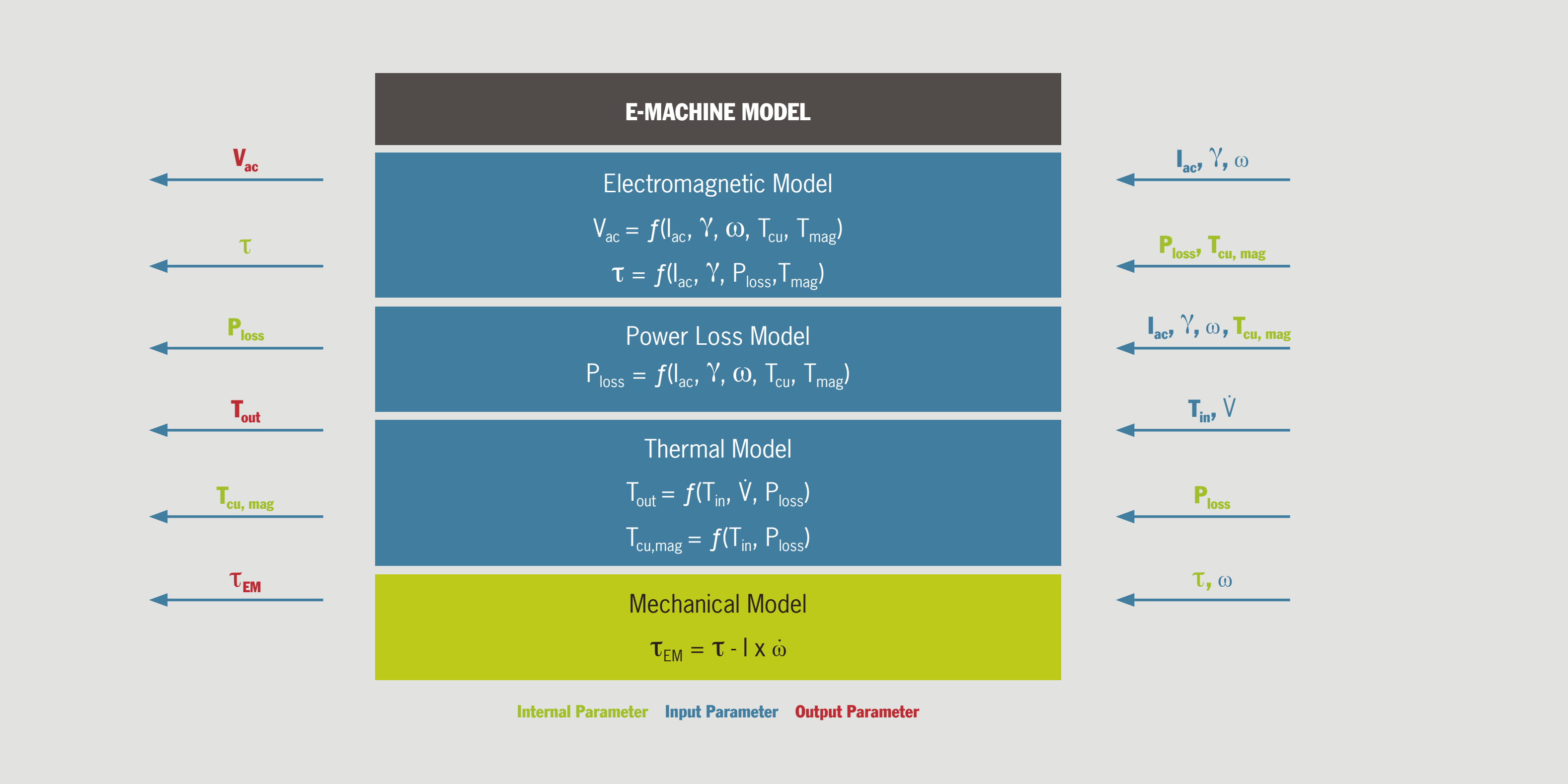


Figure 2: Building blocks of an electric machine model

For the validation of the E-machine models, the results of the performance testing and the inspection of the machine parameters are extremely important, even if they alone are often not sufficient for a complete validation. The measured data do, however, provide the basis for model validation. If the comparison of the measured and calculated results shows too great a deviation, the geometry, material properties and/or model coefficients are adjusted. What the model tells us is thus moved closer and closer to the real measured data successively by means of repeating the steps (simulation—measurement—comparison—change).

Validating the electromagnetic model

In order to validate a complex sub-model, additional special tests are often required, as shown by the following five examples:

Comparison of calculated and measured open circuit voltage

A very simple and useful test for validation of the electromagnetic model is the comparison of the calculated and measured open circuit voltage. The open circuit voltage can be measured during passive rotation of a (synchronous) machine at the electrical connections (see figure 4 on page 20). Basic modeling errors, such as wrong geometry or faulty winding patterns, become obvious immediately.

Apart from the engineers' skills and knowledge, the accuracy of the models is determined by the modeling approach chosen: the finite element method (FEM) provides extremely accurate results, while analytical approaches, such as the waveform of the AC voltage, can only provide an approximate picture.

Comparison of torque and current

An additional test used for the validation of the electromagnetic model is based on the interdependency of torque and current (see figure 5 on page 20). At low speed, the AC current is increased incrementally and the resulting torque is measured in each case. At high currents, saturation effects in the iron lead to a diminishing marginal utility of the current. As to whether—and how—this effect has been or should be taken into account during model formation, can only be determined by means of a comparison of calculation and measurement.

FUNDAMENTAL PARAMETER TESTING (START OF TEST PROGRAM)

Mechanical Testing	Environmental Testing	High Temperature Endurance	Heat Cycle Endurance	Humid Heat Endurance	Performance Testing
Axial Loads	Temperature Shock	High Temperature Endurance	Heat Cycle Endurance	Humid Heat Cycle Endurance	Passive Testing
Radial Loads	Salt Spray				Power Curves
Torsional Loads	IP Testing	Mech Shock & Vibration	Mech Shock & Vibration	Mech Shock & Vibration	Efficiency Mapping

FUNDAMENTAL PARAMETER TESTING (END OF TEST PROGRAM)

Figure 3: Overview of standard electric machine test schedule

Measuring drag losses

The power loss model comprises several different individual loss models that, taken together, determine the behavior of the E-machine. Power losses are the fundamental link between the electromagnetic and the thermal model and the subject of many optimization approaches.

Drag losses comprise mechanical and electromagnetic iron losses caused by the rotor's rotating magnetic field interacting with the stator (see figure 6 on page 20). These losses can be separated into mechanical and electromagnetic iron losses by repeating the test with a machine where magnets have been removed or replaced with passive material. This enables them to be measured by passively spinning the machine across a range of speeds and recording the torque required.

Calculation of copper and iron losses

In addition to the mechanical and iron losses, ohmic losses in the copper winding also play an important role. The calculation of these copper losses is quite simple in most cases, as long as resistance and temperature are known. Furthermore, this also allows iron losses to be derived from a measured overall loss during a test (see figure 7 on page 21). Iron losses themselves can be further subdivided into eddy current and hysteresis losses, identifiable by their respective frequency dependency and thus be used as the basis for validating the sub-models in question.

Validating the thermal model

The last example shows how a simple test can be used to adjust the capacities and resistances of the thermal model: at a set speed, the machine is subjected to maximum torque. Consequently, temperatures rise until a certain threshold is reached, where power is reduced by the inverter to prevent the machine from overheating (this is known as "Derating"). The machine reaches its stabilized state after approximately 30 minutes (see figure 8 on page 21).

In the first few seconds of the peak power phase (S6) losses accumulate predominantly in the thermal masses of the E-machine during the first few seconds. Measured temperature gradients can therefore be used to validate the respective heat capacities. Once the machine has stabilized and delivers nominal power (S1), there is no net ›

Figure 4: Comparison of calculated and measured open circuit voltage

Input:
Speed

Output:
Voltage

Properties/models to be validated:
> Geometry of stator and rotor
> Winding diagram
> Material properties

Test procedure:
> Spin passively at set speed
> Measure voltage wave
> Comparison with calculation

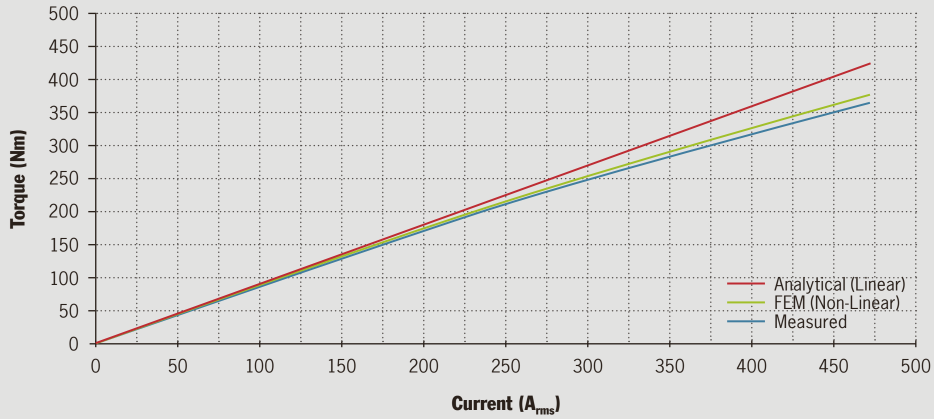


Figure 5: Interdependency of torque and current

Input:
Current

Output:
Torque

Properties/models to be validated:
> Torque generation
> Flux distribution
> Material properties

Test procedure:
> Drive machine against load
> At constant speed increase current
> Measure torque
> Compare with calculations

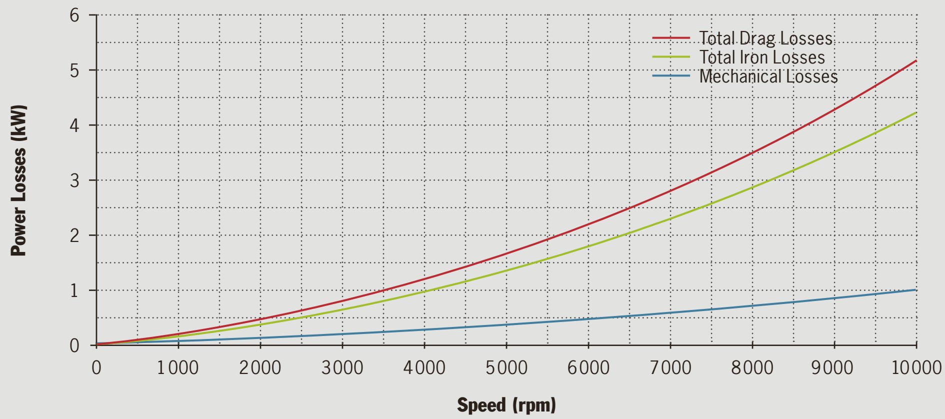


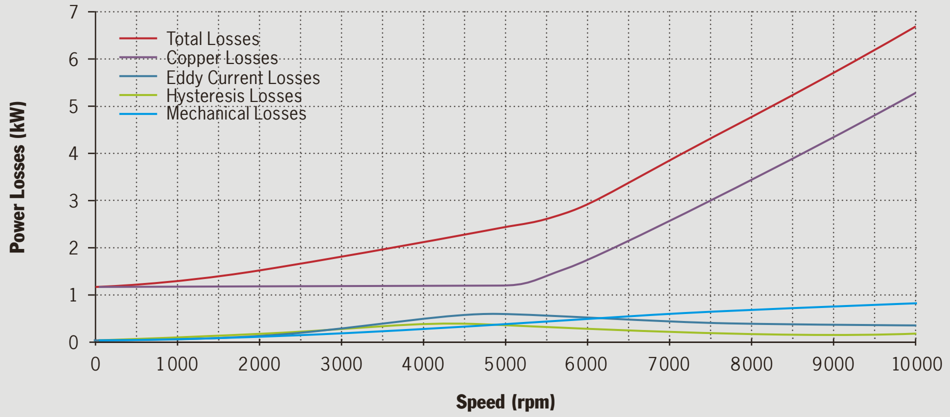
Figure 6: Drag losses across the rotary speed range

Input:
Speed

Output:
Power loss

Properties/models to be validated:
> Mechanical loss model
> Iron loss model

Test procedure:
> Drag machine at varying speed
> Measure power required
> Compare with calculations
> Test with & without magnets



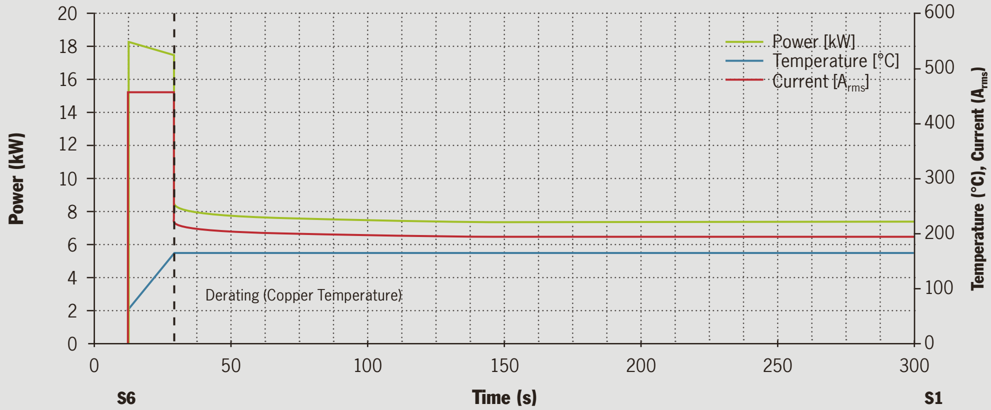
Input:
Current

Output:
Power loss

Properties/models to be validated:
> Individual components of power loss

Test procedure:
> Measure power loss
> Calculate copper and mechanical losses
> Split iron loss by frequency
> Compare with calculations

Figure 7: Power loss at constant torque



Input:
Current

Output:
Temperatures

Properties/models to be validated:
> Thermal capacities
> Thermal resistance

Test procedure:
> Measure maximum torque
> Derating at max. temp.
> Measure stabilized state
> Compare with calculations

Figure 8: Development of power, current and temperature

power flowing in or out of the thermal masses. Thermal capacities and thermal resistances can therefore be measured separately. The values thus determined can now be used as coefficients for the thermal model.

Summary

E-machines are highly complex electrothermomechanical systems. Every model must take this into account if it wants to enable exact simulation results.

The validation of the E-machine model and its diverse sub-models, which is absolutely necessary for a precise and viable calculation, requires comprehensive testing on the test stand. The basic data set is supplied by the OEM tests that are carried out as part of standard testing. The validation of complex models, however, requires additional measurements.

The integration of modeling and measuring of the E-machine is essential for a precise simulation of the behavior of an electrified powertrain. As it is at the heart of the electrical powertrain, the E-machine affects the behavior of the entire vehicle. ■