전기자동차의 다중레벨 모델링과 시뮬레이션

Multi-level Modeling and Simulation of Electrical Vehicles

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요 약

전기자동차들을 수학적으로 모델링하고 시뮬레이션 하는 많은 방법들이 있다. 전기 자동차의 각 요소들은 다른 물리적인 배경과 모델들을 갖고 있으나, 하나의 수학적 모델로 구성하기란 어려우므로 다양한 물리적 모델이 요구된다. 시뮬레이션이 목적에 따라 수행할 시뮬레이션에 관한 디양한 레벨들이 있다. 즉, 개념 체계 레벨, 회로 레벨, 더 상세한 요소레벨로 구성된다.

본 연구에서는 전기 자동차에서 여러 가지 요소들에 대한 다양한 물리적 모델들과, 다중레벨 시뮬레이션에 관하여 연구하고자 한다. 또한, 본 시뮬레이션 방법은 공학교육에 학습효과를 향상 시킬 수 있다.

Key Words : Modeling; Simulation; Multiphysics; Multilevel; IPM; Battery; Engineering Education

ABSTRACT

There are many ways in which electric vehicles are mathematically modeled and simulated. The components have different physical background and models, but have to fit into one mathematical model. A multiphysics model structure is required. Depending on the goal of the simulation, there are various levels on which the simulation can be performed. This is called multilevel, consisting of a conceptual system level, a circuit level and a more detailed component level. This paper discusses which multiphysics models and multilevel simulations are required for the various components in an electric vehicle. Also, this simulation approach could improve the effectiveness of learning in engineering education.

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I. INTRODUCTION

The market for hybrid electric and electric vehicles is growing, and presents numerous new challenges when it comes to technology, environment and acceptance. Concerning technology, these challenges not only require new ideas, but also engineering effort to realize these new technologies. Reduction of cost and improving system efficiency are the two main engineering challenges. In an electric vehicles various technologies come together, being mechanical, electromagnetic, power electronics, battery chemistry and cooling of these components, to name a few.

To understand the interactions of all these technologies, simulation is used to study the total system and to take decisions on the design. This requires that a single model can be build that incorporates all these technologies. And this is exactly where the gray area starts. How detailed should a model be and what is the impact of the accuracy of each single component model in the total model? The different levels of modeling for the common components in an electric vehicle are able to list. Here for each component the three models are explained required for a conceptual system simulation, a circuit simulation, or for detailed component simulation. The multiphysics models for each component from each level should interface in a single multilevel model. This introduces extra constraints on the model. Setting up a simulation model is one thing, but here are engineering challenges that have to be faced. Among these are cost reduction, reliability and improvement of the overall efficiency. Depending on the task of the simulation, a typical test is carried out with the simulation. Here a conceptual system model would have shorter simulation times than a circuit model, however, the fidelity of the semiconductor and thermal models will be very low. Therefore mostly a circuit model is required. The simulations using a conceptual system model can be carried out and the diminishing State of Health[SoH] can be estimated after carrying several drive cycle conceptual system simulations. To understand the need for the detailed component level, consider the saturation in interior permanent magnet synchronous machines [IPM]. Here a detailed Finite Element model is required to correctly build a circuit model for the IPM.

After analyzing, a circuit model can be build that can be used for detailed design of the control of such a machine.

Such simulation methods are improved the learning effects of education in engineering.

II. Levels of Modeling

Instead of setting up models just based on existing models available in a standard simulation package, it is better to have a better understand in the levels of modeling. Depending on the required details in the simulation results and the availability of model parameters, various models are possible. In general there is a division among three levels of modeling. There is a conceptual system level model, a more detailed circuit level model and finally a very detailed component level. Each level can contain linear and non-linear model-equations and the complexity might vary between the levels, the overall issue is that the fidelity of the model gets higher at a higher modeling level. For example, the detailed component model requires more parameters that an overall system model and also the simulation results will include small details that belong to the solution of the detailed equations inside the detailed component model.

A system level model might be very complex and yield a highly non-linear equation.

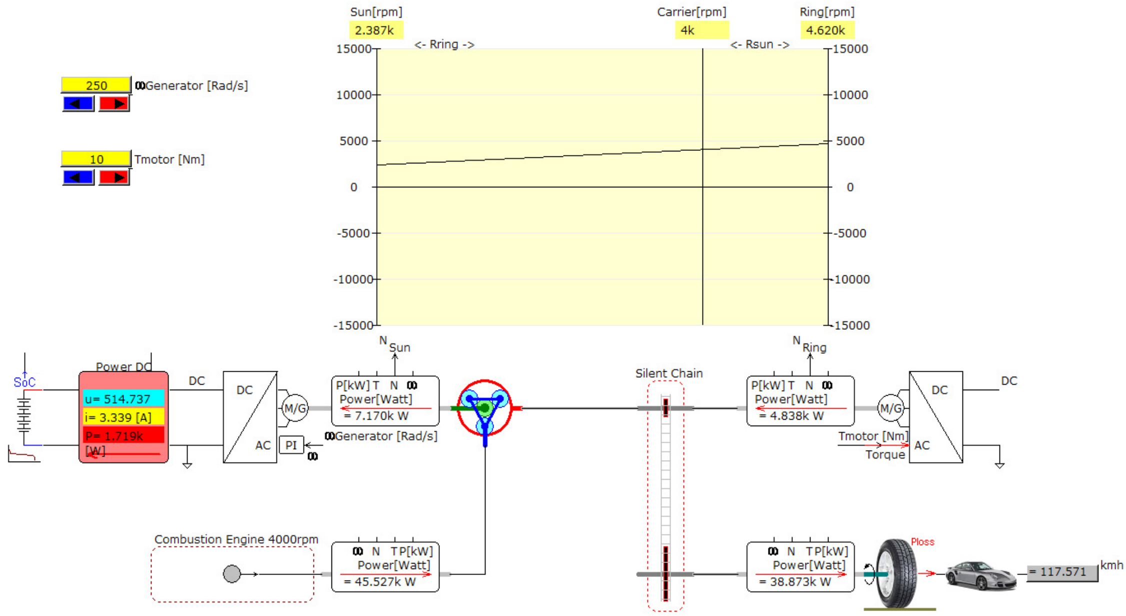

Figure 1: Conceptual system simulation of a hybrid electric vehicle

But as long as the inside details compared to the component model are negligible, the simulation results will be much more simple compared to the component model are negligible, the simulation results will be much more simple compared to those from a more detailed component level simulation.

The first step is to get an overall picture of the power distribution in the system and to look at the load of every single system component. Typically idealized system components are used. On this conceptual system level an early concept of the control system can be designed and tested in simulation. For example, the performance of an electric vehicle can be simulated for a given drive cycle. Another example is to study the power flow in hybrid electric vehicles [Figure 1].

The second step is to look at each component more in detail on the second, the circuit level. One method is to replace the idealized system models with more detailed models. This increases overall simulation time, but gives more detailed simulation results. For example, a model including the semiconductor switches (IGBT, Mosfet and diodes) could replace the ideal continuous model of an inverter [1],[2],[3]. The simulation results would now also include harmonics as well as typical modulation influences.

The third step would be to look at each component more in detail on the third, the component level. Instead of using more detailed lumped circuit models with limited parameter sets from the second step, the models could be based on more detailed engineering software. For example, a non-linear model based on look-up tables replaces the three-phase AC motor model, where the input-output relations are pre those from a more detailed component level simulation.calculated in Finite/Boundary Element Method (FEM/BEM) software.

The advantage of modeling on various levels is the gain in simulation speed when using system models and the matter of details in component simulations. On the circuit level, the interaction between the various components can be studied more in detail as with a system simulation, but still requires less simulation time compared to the simulation on the component level.

The different levels of modeling for the common components in an electric vehicle are listed in table 1.

Table I: Modeling levels for typical electric vehicle components

Component	Conceptual system model	Circuit model	Detailed component model
Battery	SoC(I) V(SoC)	Power loss(SoC) Time delay(SoC)	Thermal
Electric machines PMSM & IPM	Maximum torque and maximum power	dq model Saturation Harmonics Temperature	FEM
Power Electronics	Power Balance	Modulation Harmonics Losses	Gate drivers Blanking time
Control	Drive cycle Virtual driver	PI control Sampling Fixed point	Embedded system implement -ation

After further increase of model detail, the fidelity increases again, and keeps on increasing for every additional model extension. The system level can be viewed as the most left part of this characteristic, while the middle part covers the circuit level and the most right part the component level.

Ⅲ. Goal of the Simulation

There are various engineering questions that have to be answered using simulation. It is not only setting up a model and see if it is working. The real goals of today's simulations are trying to understand if the design is good, if it can be improved and of high importance, what is the expected lifetime of the design.

These are complex questions that depend on many factors in the design. However a number of well-understood problems can be investigated that will contribute to an overall better design. The most important in electric vehicles are:

- State of Health determination of the battery
- Lifetime expectation of the semiconductors in the power electronics
- Overall efficiency in the total drive train, including the electric machine, the power electronics as well the mechanical components

1. State of Health

A State of Health estimation of a battery can be carried out using simulation under the following two assumption. First a detailed and experimentally verified battery model is required. Second an experimentally verified SoH estimation for the battery is required. In [4],[5] a detailed model with parameter fitting was set up for a LiFePo4 battery. Here a dynamic circuit model is made that is depending on the SoC and charge/discharge current as well as cell temperature. Important in this circuit level model is the dependency of the internal loss and delay times of the battery on the temperature and SoC of the cells. In [5] the State of Health estimation is based on the battery model from [4],[5]. Using conceptual system simulations, the state of health is determined if the battery is used in many drive cycles[Figure. 2]. Capacity fading is used here to give a quantitative value for the State of Health.

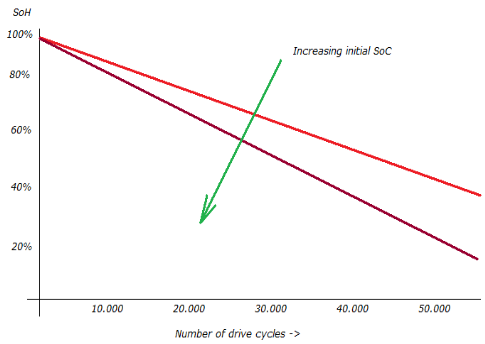

Figure 2: Battery State of Health after 50.000 drive for an initial value of SoC=90% and Soc=40%

2. Semiconductor lifetime expectation

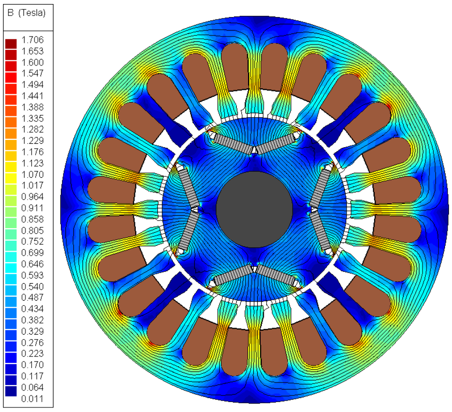

Figure 3: Field distribution in an IPM

In [6], [7] and [8] thermal cycling of power electronics semiconductors is simulated. Here a detailed circuit model is required that can estimate the losses in the semiconductor and is also temperature dependent. A coupled electric-thermal simulation is required here. Lifetime of the semiconductors can be estimated if thermal cycling is simulated.

3. Efficiency of the total system

To simulate the efficiency of the total drive train, the efficiency of every component should be take into consideration. This requires detailed models for various components. As example, consider an induction machine.

Here the losses inside a rotor bar depend on he deep bar effect. In a transient FEM simulation, these losses can be determined. Another example of using FEM to set up a detailed component model is an interior permanent magnet synchronous machine[Figure. 3].

The detailed geometric model in FEM is used to calculate inductance, back-emf and torque depending on rotor position, stator current and temperature. From the FEM analysis, look-up tables for the circuit model are created. The created look-up tables include detailed information about saturation is included. The torque is included in the look-up tables for every rotor position and stator current position. From this Maximum Torque per Ampere trajectories of the control can be tested in a simulation.

Figure 4 shows a principal circuit model for a hybrid electric vehicle. The models for the interior permanent magnet synchronous machines are based on the lookup tables that were calculated in

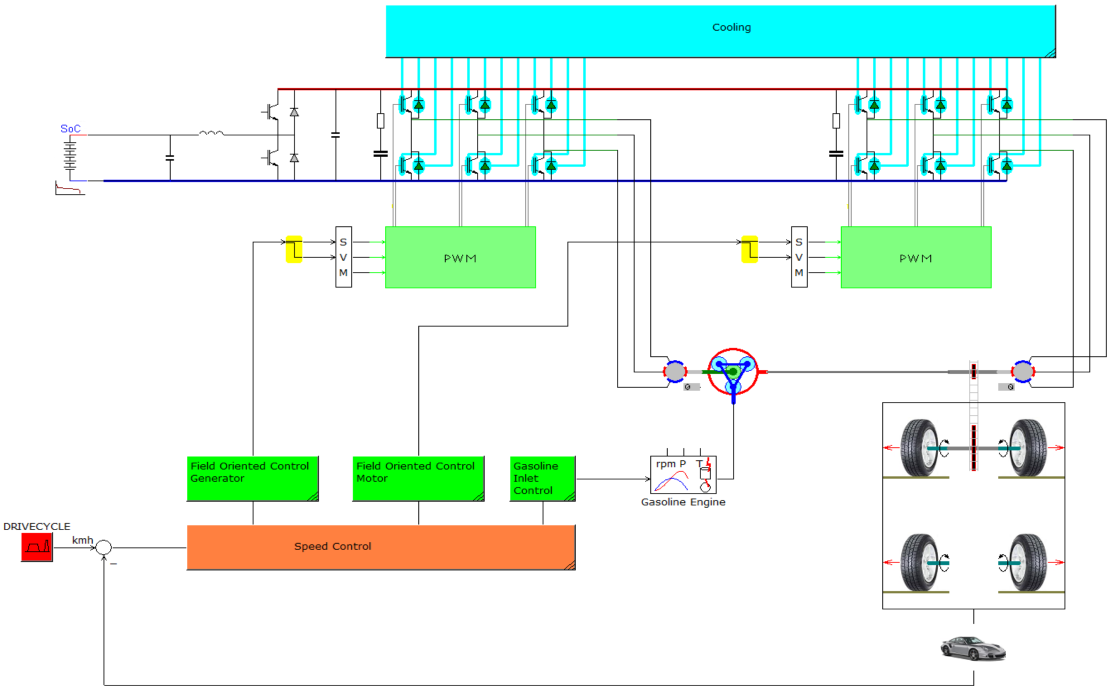

Figure 4: Circuit model of a hybrid electric vehicle including the detailed model of the IPM from FEM

FEM. The switching and conduction losses of the IGBT's are data sheet-based and are temperature dependent and coupled to a thermal model.

The influence of the modulation principle and control strategies such as Maximum Torque per Ampere can be studied using this multi level model.

Ⅳ. Conclusions

Multilevel modeling allows the combination of various levels of multiphysics models to be interconnected. Depending on the required goal for the simulation, conceptual system models can be employed for overall system behavior and can be interconnected with detailed component models. Concentrating on the minimum required levels in a model reduces overall simulation time and does not overcomplicate the total model.

A complete drive train including power electronics and electric machines with control can be simulated. Here a drive cycle can be applied, as well as the thermal model for the power electronics. In a conceptual system model, the power balance and overall behavior can be studied. In a circuit model, the influences of each component on the performance can be simulated. Detailed component models can be added, for example, the interior permanent magnet synchronous machines that are analyzed in detail in FEM. Efficiency studies using the circuit model are more detailed compared to the conceptual model. State of Health estimation of batteries is possible if a) an experimentally verified model of the battery exist and b) an experimentally verified estimation exist for the capacity fading on which the State of Health can be based.

References

[1] Bauer, P & Duijsen, PJ van, "Challenges and advances in simulation", *Proceedings of the 36th power electronics specialists conference* pp.1030-1036, 2005

[2] Bauer, P & Duijsen, PJ van, "Power electronics simulations", *International review on computers and software* IRECOS, 3(3), pp. 307-314, 2008.

[3] Bauer, P & Duijsen, PJ van, "Simulating losses and semiconductor junction temperature in power electronics", *Bodo's power systems*, 9, pp.36-38, 2009.

[4] Lam, L. Bauer, P. Kelder, E. "A Practical Circuit-based Model for Li-ion Battery Cells in Electric Vehicle Applications", *IEEE 33rd International Telecommunications Energy Conference INTELEC*, 2011.

[5] Lam, L. "A Practical Circuit-based Model for State of Health Estimation of Li-ion Battery Cells in Electric Vehicles", *Master of ScienceThesis, Delft university of Technology,* 2011.

[6] van Duijsen. P, Leuchter. J, Bauer. P, "Lifetime estimation with thermal models of semiconductors", *Energy Conversion Congress and Exposition (ECCE)* IEEE, pp. 978 - 985, 2010.

[7] Duijsen. PJ van, Bauer. P & Leuchter. J, "Thermal models for semiconductors", *14th International Power Electronics and Motion Control Conference,* Ohrid, Macedonia: IEEE. , pp.23-28, 2010.

[8] Bauer. P, Duijsen. PJ van, "Sensorless control for electrical and hybrid electric vehicles", *Bodo's power systems, 11,* pp. 50-52, 2009.

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