Vaasan yliopisto
UNIVERSITY OF VAASA

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Development of an EV powertrain on system level by utilizing simulation-based design platforms

School of Technology and Innovations
Master's Thesis
Electrical Engineering

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Foreword

This Master's thesis is done at the University of Vaasa school of technology and innovation as a part of the degree of Master of Science in technology. The thesis is a part of EDR & Medeso oy's Digital Electrification Laboratory (DEL) research project, that aims to explore system simulation solutions of Ansys software environment. I am thankful for the opportunity to participate in the research project of EDR & Medeso oy.

My greatest thanks go to the instructor of my thesis Mika Masti for the continuous support and guidance. I have enjoyed the cooperation with Mika. I also want to thank the DEL project manager Pasi Tamminen for the cooperation, my supervisor Juha Ojanen for his support and Matti Uusimäki for the contribution to the DEL concept. I appreciate the support and guidance that Timo Vekara at the University of Vaasa has provided me throughout the writing process of the thesis.

The thesis topic was new and interesting for myself, and I gained more knowledge about the utilization of simulations in the electric powertrain design process. Hopefully, this thesis will be useful for EDR & Medeso oy.

Tampere, 25.9.2020

Heidi Lind

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Symbols and Abbreviations

Greek symbols

η	efficiency
θ_e	electrical angle
θ_m	mechanical angle
Ψ_pm	permanent magnet flux linkage
ω_e	electrical angular speed
ω_m	mechanical angular speed

Other symbols

C_1	cell short-time capacitor
C_2	cell long-time capacitor
i_d	d-axis stator current
i_q	q-axis stator current
I_DC	DC cell current
J	motor rotational inertia
L_d	stator d-axis inductance
L_q	stator q-axis inductance
m	vehicle mass
p	number of poles in rotor
P_heat	cell heat power
r	wheel radius
R_int	internal cell resistor
R_1	cell short-time resistor
R_2	cell long-time resistor
R_s	cell series resistor
R_st	stator resistance

t	time
T_e	electrical torque
T_m	mechanical torque
v_d	d-axis stator voltage
v_q	q-axis stator voltage
V_oc	open circuit voltage.

Abbreviations

AC	alternating current
ACT	Ansys Customization Toolkit
BMS	battery management system
CAD	computer-aided design
CFD	computational fluid dynamics
DEL	Digital Electrification Laboratory
DC	direct current
ECE	equivalent circuit extraction
ECM	equivalent circuit model
HPPC	hybrid pulse power characterization
EV	electric vehicle
FMI	functional mock-up interface
FMU	functional mock-up unit
GPS	global positioning system
GUI	graphical user interface
HEV	hybrid electric vehicle
ICE	internal combustion engine
IM	induction motor
IPM	interior permanent magnet motor
IPMSM	interior permanent magnet synchronous motor
MTPA	maximum torque per ampere

NRMM	non-road mobile machinery
PI	proportional integral
PMBLDC	permanent magnet brushless DC motor
PMSM	permanent magnet synchronous motor
ROM	reduced order model
LTI	linear and time invariant
LTO	lithium titanium oxide
LUT	Lappeenranta University of Technology
NTGK	Newman, Tiedemann, Gu and Kim, a battery model
SML	Simplorer Modeling Language
SOC	state of charge
SOH	state of health
SCiB	superior characteristics industrial battery
TUAS	Turku University of Applied Sciences
2D	two-dimensional
3D	three-dimensional.

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Abstract

The challenges within electric powertrain design are managing multiple physics, time scales and spatial scales. There are existing methods available in different industries for modeling individual functional blocks of the electric powertrain. In this thesis a system level model of an electric vehicle (EV) powertrain is developed by examining different modeling and simulation methods. The final applications of an electrified powertrain can be for instance tractors, dumpers, harvesters and passenger cars. The target of the study is to provide modeling methods for evaluating energy efficiency and the performance of an electric powertrain. We focus on modeling a system including the battery, electric machine and a load.

This Master's thesis is done for EDR & Medeso oy's Digital Electrification Laboratory (DEL) co-innovation project, which is a part of the e3Power project funded by Business Finland, that investigates the electrification of vehicles. The modeling and simulation are done in a digital platform using Ansys simulation software. Turku University of Applied Sciences eRallycross car project is used as a public reference for the modeling and simulation of the electric powertrain.

The thesis aims to divide the electric powertrain into functional blocks, analyze functional block models and to define generic functional block parameters for the implementation of a system representation. Developed models utilize actual physical measurements performed on the eRallycross car components. Electrical, thermal and mechanical performance of the electric powertrain is analyzed.

The study shows that it is possible to model and simulate a complex system that includes multiple physics and fidelities. The fidelity of each component model is adjustable and highly dependent of the input values available. Parameter ranges can be defined for individual component models. A main challenge of the study was the lack of component information from the manufacturers side.

The study represents the first trial of a development platform for modeling an electric powertrain on system level. During the DEL project the system model shall be further improved, so that the system model can enable reliability and efficiency improvements of existing electric powertrains, and structural or operational changes for future electric powertrain designs.

Keywords: EV powertrain, system modeling and simulation, eRallycross, Ansys

VAASAN YLIOPISTO	
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Tiivistelmä

Sähköisten voimansiirtoketjujen mallien haasteita ovat eri fysiikoiden, aika- ja tila-alueiden hallitseminen. Eri aloilla on vallitsevia menetelmiä yksittäisten sähköisten voimansiirtoketjujen komponenttien mallinnukseen. Tässä tutkimuksessa kehitetään järjestelmätason malli sähköisen ajoneuvon voimansiirtoketjusta tutkimalla eri mallinnus- ja simulointimenetelmiä. Sähköistetyn voimansiirtoketjun sovellusalue voi olla esimerkiksi traktorit, dumpperit, puimurit ja henkilöautot. Työn tavoite on tarjota mallinnusmenetelmiä sähköisen voimansiirtoketjun energiatehokkuuden ja suorituskyvyn arviointiin. Keskitymme mallintamaan järjestelmää, joka koostuu akustosta, sähkömoottorista ja kuormasta.

Tämä diplomityö tehdään EDR & Medeso oy:n Digital Electrification Laboratory (DEL) projektille, joka on osa Business Finlandin rahoittamaa ePower projektia, jossa tutkitaan ajoneuvojen sähköistymistä. Mallinnus ja simulointi suoritetaan digitaalisella alustalla käyttäen Ansys – simulointiohjelmistoa. Turun ammattikorkeakoulun eRallycross projektia käytetään julkisena viitteenä sähköisen voimansiirtoketjun mallinnuksissa ja simuloinneissa.

Tutkimus pyrkii jakamaan sähköisen voimansiirtoketjun komponenteiksi, analysoimaan komponenttien malleja ja määrittelemään geneerisiä komponenttien parametreja järjestelmän esityksen toteuttamiseen. Kehitetyt mallit hyödyntävät fyysisiä mittaustuloksia, jotka suoritetaan eRallycross auton komponenteille. Sähköisen voimansiirtoketjun sähköistä, termistä ja mekaanista suorituskykyä analysoidaan.

Tutkimus osoittaa, että on mahdollista mallintaa ja simuloida monimutkainen järjestelmä, joka sisältää useampaa fysiikkaa sekä tarkkuustasoa. Jokaisen komponenttimallin tarkkuustaso on säädettävissä ja riippuvainen saatavilla olevista sisäänmenoarvoista. Parametrien vaihteluvälit voidaan määritellä yksittäisille komponenttimalleille. Tutkimuksen eräs haaste oli komponenttitietojen puute valmistajien puolelta.

Tutkimus edustaa alustavaa suunnittelualustaa järjestelmätason sähköisen voimansiirtoketjun suunnitteluun. DEL projektin aikana järjestelmämallia parannetaan niin, että järjestelmämalli mahdollistaa parannuksia olemassa olevien sähköisten voimansiirtoketjujen luotettavuudessa ja tehokkuudessa, sekä rakenteellisia ja toiminnallisia muutoksia tulevilla sähköisillä voimansiirtoketjumalleilla.

Avainsanat: Sähköisen ajoneuvon voimansiirtoketju, järjestelmätason mallinnus ja simulointi, eRallycross, Ansys

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Abstrakt

Hantering av multifysik, olika tids- och rumsskalor tillhör utmaningarna av planeringen av elektriska drivlinor. Inom olika industrier finns det metoder för modelleringen av komponenter som tillhör elektriska drivlinor. I denna forskning utvecklas en system modell av en elektrisk fordons drivlina genom att utforska olika metoder kring modellering och simulering. Tillämpningsområden för elektriska drivlinor kan vara till exempel traktorer, dumprar, skördare och personbilar. Målet med detta diplomarbete är att presentera modelleringsmetoder för validering av energieffektivitet och prestation av en elektrisk drivlina. Vi fokuserar på modellering av ett system som består av ett batteri, en elektrisk motor och en belastning.

Detta diplomarbete görs för EDR & Medeso ab:s Digital Electrification Laboratory (DEL) projekt, som tillhör Business Finlands finansierade e3Power projekt där elektrifiering av fordon utforskas. Modellering och simulering utförs på en virtuell platform av Ansys. Åbo yrkeshögskolans eRallycross projekt används som en offentlig referens för modelleringen och simuleringen av den elektriska drivlinan.

Arbetet strävar till att dela upp den elektriska drivlinan i komponenter, analysera komponenterna och identifiera generella parametrar för komponenterna för skapandet av en representation av systemet. Utvecklade modellerna utnyttjar fysiska mätningar som gjorts på eRallycross bilen. Elektriska, värme och mekaniska effekter av den elektriska drivlinan analyseras.

Arbetet visar att det är möjligt att modellera och simulera ett komplext system, som inkluderar flera fysikområden och noggranhetsnivåer. Noggranhetsnivån för varje komponentmodell kan justeras och den är beroende av tillgängliga inputvärden. Räckvidden för parametrarna kan defineras för individuella komponentmodeller. En av arbetets utmaningar var bristen på komponent information från tillverkarens sida.

Forskningen representerar ett basis av en utvecklingsplattform för modellering av en elektrisk drivlina på systemnivå. Under DEL projektet förbättras system modellen på så vis, att system modellen möjlighetgör förbättring av pålitlighet och effektivitet av elektriska drivlinor, och strukturella och funktionella förändringar för framtida modeller av elektriska drivlinor.

Nyckelord: Elektrisk fordons drivlina, system modellering and simulering, eRallycross, Ansys

1 Introduction

Urbanization forces people to city areas that have initially limited resources of services. The urbanization trend results in an increasing need of energy in focused areas. Simultaneously, polluted emissions in those areas become a problem. The solutions that can be utilized for such environment are optimized designs and systems, that meet energy efficiency requirements.

Technology development in areas such as power electronics and electric machines contribute to more energy efficient solutions available. Cheaper products penetrate new components and materials into the markets. Additionally, the availability of high-speed internet connections enables more ways of product design, manufacturing and usage experience.

Electrification of powertrains is one of the best options in meeting environmental consciousness and indicating efficiency improvements in comparison to conventional powertrains. The utilization of energy storages in powertrains increases the flexibility of the powertrain performance. Energy storages used in electrified powertrains can utilize the diversity of energy production options provided by the electric grid.

This thesis aims to study the physics of the main components of an electric vehicle (EV) powertrain, model those on required multiple fidelity levels and demonstrate a system level simulation against an application using the modeled components. In this thesis the characteristics and challenges of electric powertrain design are presented. This thesis introduces the benefits of the utilization of digital platforms and simulations when a transition into redesign occurs.

In this thesis vehicle refers to transporting something and it covers planes, trains, working machines and passenger cars. This thesis focuses on system modeling and simulation of an electric car powertrain, but similar methods and tools can be applied to any other vehicle type.

System design can be done in the traditional way with physical prototypes and physical measurements. One purpose of the thesis is to introduce the digital test laboratory concept, where system design is done on digital platforms that allow model building and simulations based on computational methods that represent the physical performance of the system. The software used in this thesis is Ansys simulation software, that enable the integration of detailed physics simulations into system level models. The main physics modeled and simulated in this thesis are thermal, electronics and mechanical.

The thesis consists of seven chapters in total. The following sections of the first chapter introduce briefly electrified vehicles, EDRMedeso and Ansys, and the eRallycross project. In the second chapter the component and system level modeling are discussed. The topics include system simulation potential users, variations and the role of physical measurements. The third chapter presents physics of the main powertrain components, the battery chemistry and its characteristics. The physics of internal permanent magnet synchronous motor are presented in detail and the power converter behavior is explained. In Chapter 4 the modeling methods of main powertrain components are presented. Battery electrical and thermal performance is modeled and a parametrized model for an interior permanent magnet synchronous motor (IPMSM) with a simple control is presented. In Chapter 5 a coupling of the battery and electric machine model is explained, and a demonstration is shown against a drive cycle. Chapter 6 provides the conclusions of the study and it is followed by a short summary of the study that is discussed in Chapter 7.

1.1 Electrified vehicles

The global warming and weakening air quality issues set emission limitations to the traffic sector. There are various environmentally conscious options developed for meeting the emission limitation requirements. In addition to the natural gas and fuel cell vehicle, vehicles that use biofuels as an energy storage form are suitable vehicle options from an environmental aspect. The electrified vehicles have however managed to provide benefits in an energy efficient aspect as well as that of environment.

The motivation behind this study is the increasing demand of the electrification of vehicle powertrains. The regulations and standards of vehicle manufacturing and the transport sector are updated continually. Carbon Dioxide (CO_2) emission regulations push the passenger car sector to rethink and react. Similar changes are expected even in the working machinery industries with years of delay. Carbon dioxide is a side product of the combustion process in an ICE and besides CO_2 also toxic nitrogen oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbon (HC) are emitted. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

A conventional internal combustion engine (ICE) driven vehicle uses heat for the generation of mechanical energy, whereas an electric machine driven vehicle uses electrical energy for that purpose. Another significant difference between the fundamentals of ICE and electric machine driven vehicles are the energy storages that the machines require. The ICE requires a fuel tank whereas the electric machine a battery storage.

The electrification process of vehicle powertrains includes the fitting of a battery storage and an electric machine. In order to fulfill the vehicle performance requirements, the electrification of the powertrain can be implemented fully or partly. An electric vehicle is driven by one or more electric machines and it uses a battery storage as the power source. A hybrid electric vehicle (HEV) uses both an ICE and an electric machine for the power generation and it is equipped with both a fuel tank and a battery storage. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

For system integrators the transition from ICE driven vehicles to partly or fully electrified vehicles require changes in competence, technologies and tools. This thesis aims to demonstrate the key techniques used in electrified powertrains through modeling and simulation. The powertrain electrification generates new boundary conditions that depend of the application. New boundary conditions can be component dimensions and mass.

One of the challenges of the electrification of powertrains is the limited energy. In vehicles the used energy sources are battery storages. The charging stations of batteries among working machinery sites are also limited. Additionally, the battery storage produces heat and requires a heat management system. Overheating of battery storage correlates with a decrease in battery lifetime, which is one of the main concerns regarding the electrification process. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

In addition to environmental benefits, the electrification of vehicle powertrains provides other advantages. Compared to ICEs, the electric machines have higher efficiencies, their construction is more robust, and they can operate in the generator mode. The electric powertrain provides even new configuration variations. Alternatively, the powertrain can be designed with several smaller sized electric machines instead of one main ICE. The increasing number of EVs requires more power generation to the electrical grid. However, the EVs can be seen as moving battery storages from the electric grid point of view. With an increasing optimization demand on the electric grid side, the two-way flow between electric cars and the grid is a valuable opportunity. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

1.2 EDRMedeso

EDRMedeso is a consultancy company in the engineering field that provides Ansys simulation software products, training, support and simulation projects. EDRMedeso is working with digital twin concepts, which are real-time running digital versions of actual physical products. Digital twins use measured usage conditions to enable product monitoring, fault prediction and forecasting of product lifetime. (EDRMedeso, 2020)

This thesis is done as a part of EDR & Medeso oy’s Digital Electrification Laboratory (DEL) project, that aims to provide detailed knowledge, demonstrated tools and processes for electrified powertrain development through modeling and simulation methods. During the DEL project an electrified vehicle powertrain model is developed in Ansys software environment. The DEL project is a co-innovation project of the e3Power research project funded by Business Finland. The e3Power research project involves Finnish academic institutions Turku University of Applied Sciences (TUAS) and Lappeenranta University of Technology (LUT) and several companies to investigate the electrification of vehicles (E3Power, 2020).

1.3 Ansys Engineering Simulation Software

Ansys is an American software company that provides a wide portfolio of engineering simulation software including 2D and 3D design software. Ansys provides tools for all engineering industries including electronics, system simulations, mechanics and fluids. Ansys environment enables simulations of multiple physics together in one platform. (Ansys, 2020)

In this thesis the main electric powertrain components are modeled on a system level by using Ansys software platforms. With Ansys solutions detailed 2D and 3D simulations of multiple physics can be integrated to a system level as reduced order models (ROM). Ansys ecosystem enables detailed yet fast system analysis. Ansys software platforms enable modifications of model contents, accuracies and time requirements by scripting. As a part of this thesis different Ansys tools and methods are tested and verified in order to find the most suitable solutions for the electric powertrain model.

1.4 ERallycross project

The eRallycross cooperation project of TUAS and Valmet Automotive involves student resources together with several companies to develop an electric car for rallycross purpose. The eRallycross project of TUAS represents a physical test laboratory for the e3Power project. The target of eRallycross project is to transfer an A-class Mercedes into a fully electric rallycross race car. The car is built out of components of different manufacturers, which describes the situation of many system integrators. (ERallycross, 2020)

In this thesis the eRallycross car is used as a reference for the modeling of the powertrain components. Measurements of the eRallycross car components are carried out at TUAS and the results are utilized in the modeling and simulations of this thesis. That demonstrates the reliability of simulations and the idea of a digital test laboratory environment.

2 System level modeling and simulation

System level modeling and simulation can be implemented in various ways. Issues that affect the implementation are the system model target user and its initial information about the system components that are to be modeled.

2.1 User groups for system simulations

System simulation users can be divided in three categories, component manufacturers, system integrators and system end users. These groups use system simulation for different purposes and therefore, they have different requirements for the system modeling. Another factor that differs the user groups is the available information of powertrain components, which is used for system modeling. Additionally, the resources and required competence regarding simulations are specific for each company.

Component manufacturers have detailed information about their product, which enables detailed simulations of their product. However, component manufacturers need to be aware of any changes in the final applications of their product. There can be new requirements of duty cycles, operating temperatures, power limitations or an increase of vibration. For ensuring the product performance and safety in dynamic environments, system simulations can be profitable. Additionally, when designing a new product type, the simulations are beneficial to use at an early stage of the product development.

System integrators typically use system components originated from external manufacturers. The system integrators fit the commercial components together as a working system and integrate the necessary control for the system. System simulations are profitable for managing complex designs. The challenge of using commercial components is the lack of information about the details of the product. Typically, the only information of commercial products is the product datasheets. The only way to understand a commercial product characteristics and behavior better is via physical measurements or simulations.

System end users can have needs of using the purchased system energy efficiently and cost-effectively. The system end users may want to estimate system lifetime and required maintenance. For these purposes system simulations can be beneficial for system end users. As the digitalization proceeds, a virtual model of a purchased product can be provided together with the physical product for the end user for testing purpose. That kind of business requires all the parties to use compatible simulation platforms in order to run the virtual models.

In this thesis the eRallycross project of TUAS is used as a reference for the design of the powertrain component models. The initial conditions of the eRallycross project is comparable to system integrators since the powertrain components originate from external manufacturers and the target is to fit the components together in a way that the system requirements are met.

2.2 System modeling and simulation options

The purposes of system models differ depending on the system model user. A major difference between the system model users is the available information about system components. The available information of components to be modeled determines the possible accuracy of the model. Additionally, the required outputs of the system model determine, how accurate models are needed.

The simplest system model can be implemented by analytical functions and differential equations, that originate from publications. That is a suitable modeling method if the powertrain component information is narrow. The simplest system models often consist of ideal component models, which means that losses are neglected. (Cellier, 1991)

Another simple system simulation method is to integrate look-up tables into system level. The look-up table can be 2D or 3D and it can contain information about the machine efficiency at different ranges of torque and speed. Interpolation can be used to determine an operating point that falls between two determined values of the look-up table.

The content of look-up tables can originate from product datasheets, physical measurements or simulations. These simple models are quasi-static models, as the output of the model is determined as an operation point based on the model input. (Cellier, 1991)

In order to get a more accurate system model, dynamics need to be included in the system model. Dynamic models can be implemented by integrating dynamic response models, such as state space models, into system level. A state space model is equation based and it determines the output on the basis of the model input (Cellier, 1991). State space models are generated from detailed 2D or 3D physics simulations. An accurate dynamic response model captures all essential points from the detailed simulation. Response models are used at system level in order to maintain the high speed of simulation runs. Detailed physics simulations require information about materials and dimensions of the component. That information can originate from component manufacturers and physical measurements.

The most accurate system simulation method is implemented by co-simulation between multiple 2D and 3D physics solvers. That sort of system modeling reaches high fidelity, but as a drawback the simulation duration times are long. Additionally, that kind of system simulation requires many different physics simulation tools.

2.3 System simulation advantages

Introducing new technologies and optimization on an initially complex multi-physics system requires the right tools, competence and knowledge. In order to overcome the challenges of managing complex new designs a suitable addition of support can be a virtual environment.

From a system point of view the powertrain components have good efficiencies as individuals. There are narrow improvements that can be made to an individual component due to physical boundaries. When system providers want to do optimization of their product the final application needs to be considered. System optimization means fitting the components together and managing the dependencies between different parts of the system from a system perspective. Simulation tools are an option for system optimization that involves managing of complex designs and intelligent control. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

One benefit of system modeling and simulation is the possibility to test different configurations even in an early phase of the product development. Simulations can make the product development process more efficient. The traditional way of proceeding for component manufacturers is to test their product against different applications by performing physical measurements. With modeling tools that can be implemented more efficiently by simulating various application scenarios simultaneously. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

2.4 Physical measurements

A way to understand a commercial product characteristics and behavior better is via physical measurements. However, there are challenges with physical measurements, such as safety issues, high costs, test equipment variables mismatch with the needed ones and environmental disturbances (Cellier, 1991).

Modeling and simulation tools enable safe testing and isolation of the component from its natural environment (Cellier, 1991). Limitational factors are fewer in digital laboratories than in the physical ones. Typical obstacles or limitations of physical laboratories, such as test module availability or safety issues are not concerns of a digital laboratory.

TUAS is equipped with physical laboratory facilities, which enables the performance of physical measurements on the commercial components. This thesis aims to demonstrate powertrain modeling that is implemented with component information that is based on product datasheets, physical measurements and simulations.

Physical measurements are utilized in this study as an input data for battery simulations for the demonstration of the system level battery performance against different applications. Physical measurements of a real drive cycle are used as a reference to demonstrate the performance of the electric powertrain model against an actual load profile. Including physical measurements adds more value and increases the reliability of the simulations. The thesis aims to introduce that by using physical measurements together with simulations, the design process can be more efficient than by proceeding the traditional way, with physical measurements and building physical prototypes.

2.5 Limitations of this thesis

The target of this study is to provide valuable information about powertrain design challenges and analysis of the multi-physics performance on system level. In this paper the core of a powertrain is developed, and a simple load is applied to the electric powertrain in order to demonstrate the functionality. Throughout the development of the system platform the focus is on a final platform that includes tools for powertrain optimization.

The electric powertrain model is implemented by modeling each component separately. The key components of an electric vehicle powertrain are battery storage, power conversion and electric machine. In system simulations simplified models of components are used, since the detailed information is not necessarily essential. Rather, in system models the information of how the components work together as a system is profitable.

The powertrain model is developed initially as a less accurate system level model. The target is to integrate detailed models as response surfaces to the system platform in order to enable the optimization of the system. A response surface is created by running a detailed 2D or 3D physics simulation of a component with a 2D or 3D physics design software and extracting the essential information with an automated process to a simple ROM. The component data that is utilized in detailed 2D or 3D physics simulations originate either from product datasheets, physical measurements or simulations.

The outcome of this study is highly dependent of the available information of component details. Therefore, the final powertrain model of this study combines system level models of the battery pack and the electric machine. Additionally, a ROM of battery thermal behavior and a drive cycle is integrated to the system model. After the study or when more information of component details is available, the system model can be further improved.

An essential aspect of powertrain modeling is the understanding of demanded model outputs and the analysis focus. The final applications of an electrified powertrain can be tractors, dumpers, harvesters and passenger cars. The application determines the operating conditions, charging possibilities and required powers. The desired outputs of the system model can be efficiencies, performances, energy consumption or aging effects. This thesis uses the TUAS eRallycross car as a reference which means that the output requirements of the powertrain model originate from the race car sport such as high speed.

3 Modeling of electric powertrain

In this chapter the physics and chemistry behind the main electric powertrain components are presented. Mathematical equations and essential parameters for the modeling of the battery storage and electric machine are presented. The TUAS eRallycross car is used as a reference for the modeling and therefore a specific battery chemistry and electric machine type are considered in this chapter. The eRallycross car is equipped with an interior permanent magnet synchronous motor from BorgWarner and the battery modules are provided by Celltech.

3.1 Powertrain configuration

There is a variety of powertrain configurations for electrified vehicles. The fully electric vehicle is powered only by the battery source. The hybrid electric vehicle uses a combination of both the electric and the traditional traction types. The configuration variations of HEVs differ between which of the motors are connected mechanically to the axles of the wheels. The ICE can be set to either move the vehicle via the axle or to charge the battery storage. One optional feature of hybrid electric vehicles is the external plug-in charging and the regenerative braking. In some applications regenerative braking is not profitable and is therefore left out. In this thesis a powertrain model of a fully electric vehicle is developed, as the eRallycross project of TUAS works as an initial reference for the powertrain modeling. Electrified vehicle powertrain configuration options (Ehsani, Gao, Longo, & Ebrahimi, 2019) are the following:

- Series hybrid electric vehicle
- Parallel hybrid electric vehicle
- Series-parallel hybrid electric vehicle
- Complex hybrid electric vehicle
- Fully electric vehicle.

Figure 1 presents the different HEV powertrain configurations. In the series HEV the ICE generates power for the battery storage. The parallel HEV utilizes both motors for the

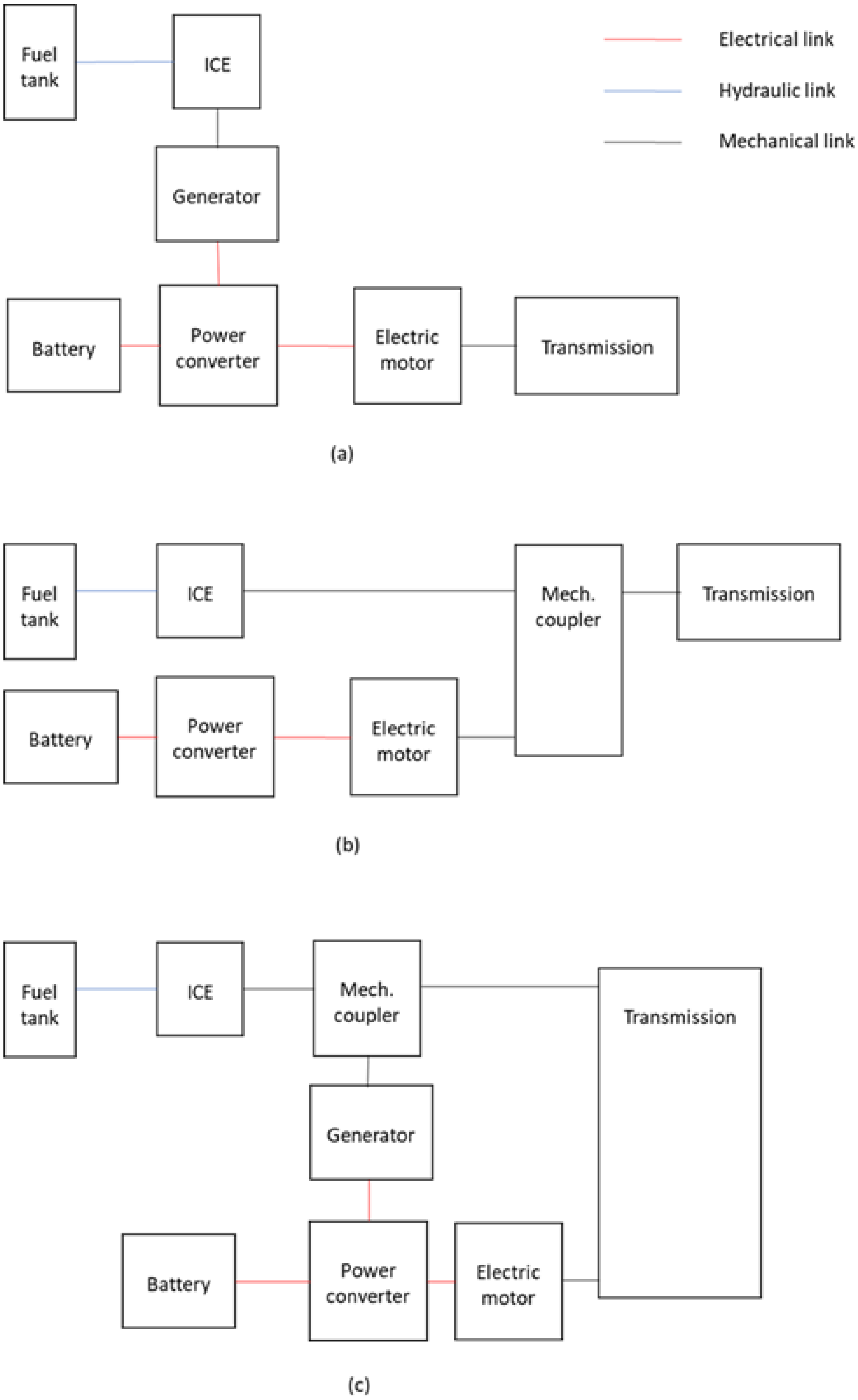


Figure 1. Hybrid electric vehicle powertrain configurations. Series (a), parallel (b), and series-parallel (c).

mechanical coupling between the motor and the wheel axles. Series-parallel HEV uses the ICE both for charging the battery and for the mechanical power. Fully electric vehicle uses only an electric machine for the propulsion. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

HEV powertrain configurations include more components than fully electric vehicles and are therefore more complex systems. The energy collection during braking can be executed optionally with a supercapacitor configuration. HEV solutions are commonly used for the electrification since they are not fully dependent of the plug-in charging accessibilities. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

An electric powertrain can be defined and explained in various ways and with different component combinations. Therefore, a clarification of the expression electric powertrain is necessary in this thesis, where the electric powertrain represents the electrical power transmission between an energy source and the mechanical energy transmission.

Figure 2 demonstrates the electric powertrain of this study, which includes a battery pack, an IPMSM and a load demand. The load represents a reference input for the mechanical power demand. The electrical power demand of the electric machine is sent to the battery storage and the battery storage delivers the possible current to the electric machine. The power of the electric machine is transferred to the load. The functional blocks to be modeled more detailed regarding this electric powertrain are the battery storage and the electric machine. The power conversion between the direct current (DC) battery storage and the alternating current (AC) electric machine is considered in the coupling between these two functional blocks.

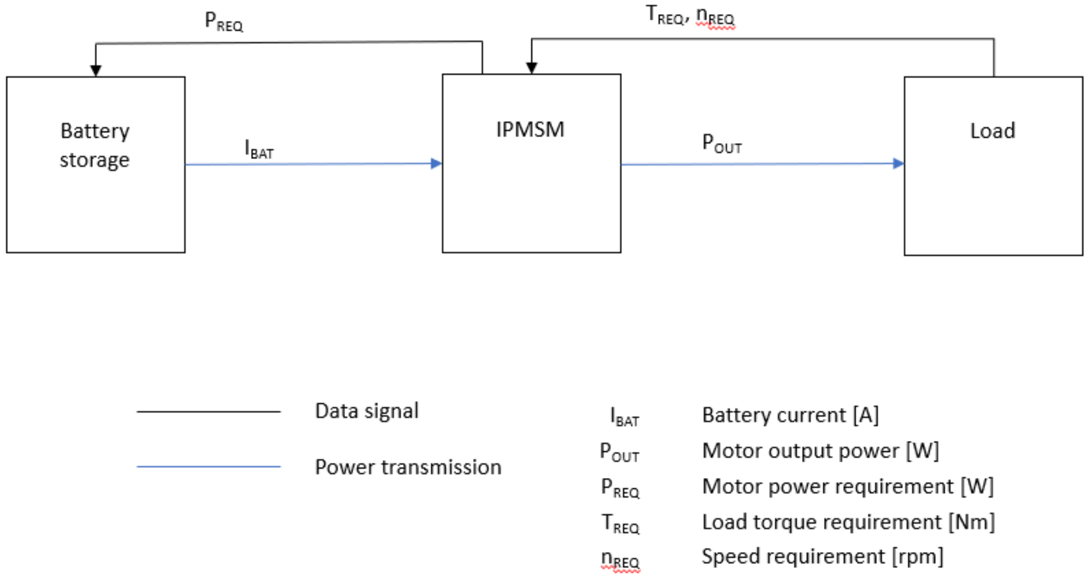


Figure 2. Electric powertrain functional blocks.

3.2 Battery storage chemistry

Energy storage technology in electric vehicles differ from traditional ICE driven vehicles. In battery cells the storage form of electrical energy is electrochemical. In comparison, the ICE stores the energy in chemical form inside a fuel tank. In some automotive applications where the hybrid powertrain is implemented, supercapacitors can be used. The supercapacitor stores the energy as a capacitor in electromagnetic form. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

3.2.1 General battery description

The battery storage of an electrified vehicle is structured. The battery cells used can be pouch, prismatic or cylinder shaped. The cells are covered with material, commonly aluminum. These shapes are used in the automotive applications since they are easily packaged which is viable when minimizing the volumes of battery storages in vehicles. Battery cells are connected in series or parallel to form a battery module. Coupling cells in series increases the voltage of the battery module and coupling cells in parallel increases the capacity of the battery module. Similar pattern applies in the battery pack level, which includes battery modules connected either in series or in parallel. Battery characteristics such as temperature and SOC are measured and monitored at either cell, module or pack level with a battery management system (BMS). The BMS is a tool for remaining a balance between the battery cells during operation.

There are different chemical compounds used in battery cells, such as lead-acid and nickel metal hydride (NiMH). In electric vehicles lithium-based battery cells are commonly used, especially lithium-ion batteries. The lithium-ion has suitable qualities for passenger cars such as high energy density, long lifetime estimations and light weight. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

In the Business Finland funded e3Power project there are companies, experts and researchers from the battery field that contribute to the project by examining a lithium-based battery chemistry and the heating and cooling of a battery pack. The lithium-based battery chemistry that is examined is lithium titanium oxide (LTO) Li_2TiO_3, also referred to as lithium titanate (Mei, Cheng, & Fong, 2016). LTO is chosen due to its high-power capabilities, high-energy characteristics and the good tolerance of colder operating temperatures (Mei, Cheng, & Fong, 2016). Other valuable features are fast charging, safety and long lifetime (Mei, Cheng, & Fong, 2016). Since the e3Power project aims to achieve a better understanding of the electrification of non-road mobile machinery (NRMM), the LTO battery chemistry is a suitable option to examine.

The eRallycross car is equipped with Celltech's battery modules that are using Toshiba's rechargeable 23 Ah Superior Characteristics Industrial Batteries (SCiB) LTO battery cells. The lithium titanium oxide is used in the anode of the lithium-ion battery cell (Toshiba 2019). The Toshiba SCIB cells are widely used in different applications such as automotive and backup power sources (Toshiba 2019). The battery module is structured with twelve cells connected in series. Primarily, the eRallycross car battery pack design is assumed to be built with 14 battery modules that are connected in series. Using this assumption, the modeling and simulations of the battery pack are implemented with a total of 168 cells connected in series. The nominal voltage of the Toshiba SCiB LTO cell is 2.3 Volts (Toshiba 2019). The battery pack total voltage is 386.4 Volts, when the cells are connected in series.

3.2.2 Operational effects

The discharge and charge process of the battery storage is performed by electrodes in the battery. The cathodes (positive electrodes) and anodes (negative electrodes) change their positions during a discharge and charge process. The battery cell consists of electrochemically active materials around cathodes and anodes that react during a discharge and charge process. Electrolyte is used in the cell to work as both an insulation and a gate for ions. A battery cell also includes a separator that disables a short circuit inside the battery. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

Battery cell performance can be described with various parameters such as voltage (see Figure 3), capacity and state of charge (SOC). Battery cell specifications contain an upper and lower voltage limit for the full charge and full discharge of the battery cell. Battery cell full discharge is determined when the lower limit of the cell voltage is reached and the current decreases towards zero. One important battery cell parameter is the open circuit voltage V_{oc}, which is measured from a fully charged battery cell that is disconnected from the circuit. It represents the free energy that is caused by the battery cell behavior. The open circuit voltage is SOC dependent. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

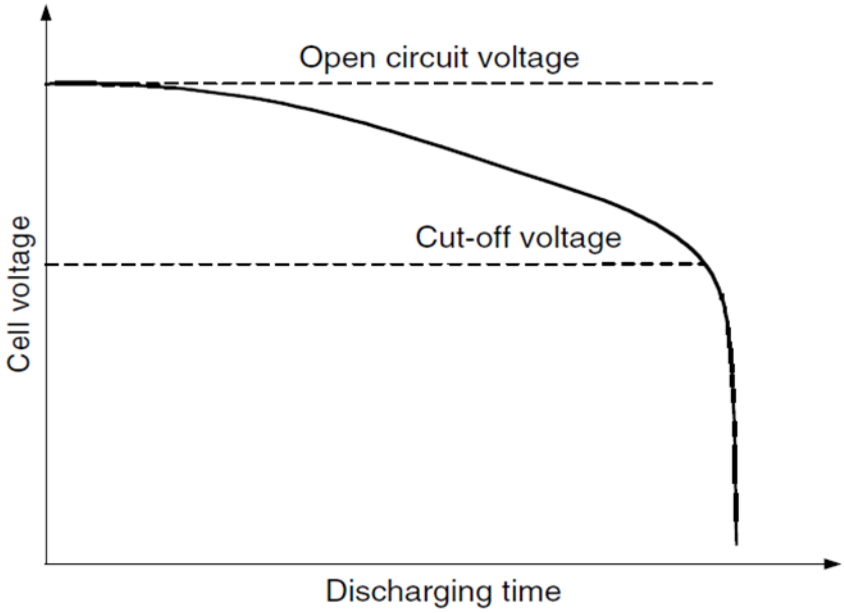


Figure 3. Battery cell voltage characteristics during discharge (Ehsani, Gao, Longo, & Ebrahimi, 2019).

The operational conditions of the battery cell are significantly dependent of the SOC, temperature and discharge or charging current rates. The battery storage is heat sensitive, which sets limitations for charging and discharging of the battery at different temperatures. (Stroe, Swierczynski, Stroe, & Teodorescu, 2015)

3.2.3 Aging effects

The parameter state of health (SOH) is used for the explanation of the aging effects of batteries. Besides calendar aging, battery lifetime is announced with the number of cycles. One cycle for a battery means a charge and discharge. Things that affect the battery aging are the operating conditions, such as temperature, SOC levels and charge and discharge currents. The battery aging can show as an increase of the internal resistance and a decrease in battery capacity. (Zhang, Sun, & Gu, 2015)

3.2.4 Hybrid pulse power characterization test

The hybrid pulse power characterization (HPPC) test is a characterization test for battery cells. The initial conditions of the test are determined by a sequence containing specified discharge, charge and rest periods. The actual test phase is implemented by applying quick higher DC discharge and charge current pulses into the cell, followed by typically a 1C-rate discharge until reaching a reduction of 10 % of the SOC level (see Figure 4). After that a relaxation period follows to avoid the overheating of the cell. The voltage of the cell is measured with high sampling rate during the higher C-rate discharge and charge (see Figure 5), and with lower sampling rate during the SOC reduction discharge. The process is repeated with the desired SOC levels, maintaining selected temperature. The whole process can be remade using multiple temperatures and load currents in order to include more dependencies. The essential test temperatures and load current can be originated from the battery final application, such as minimum, maximum or nominal operation values. (Christophersen, 2015)

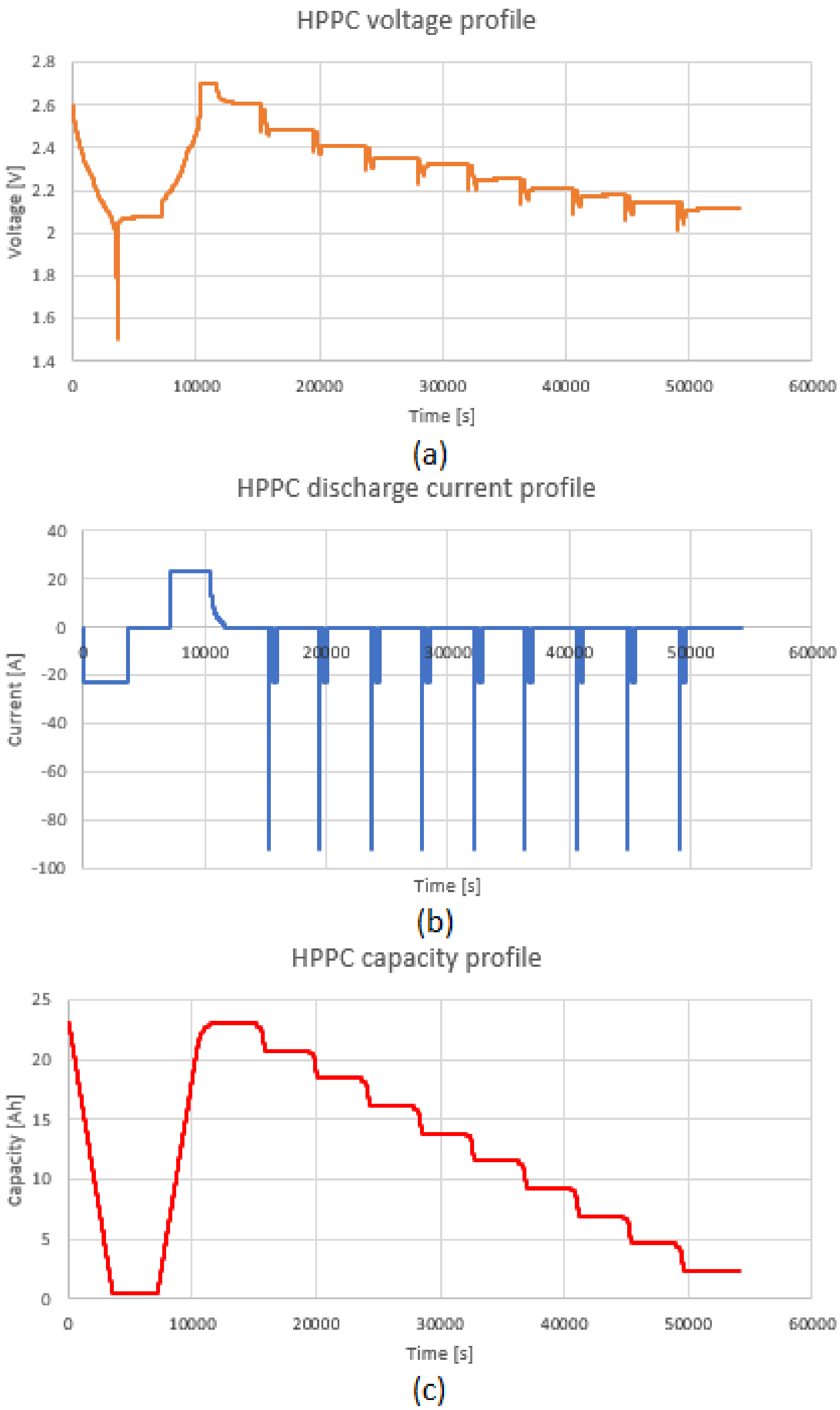


Figure 4. HPPC voltage profile (a), HPPC discharge current profile (b) and HPPC capacity profile (c) (based on Turku University of Applied Sciences, 2020).

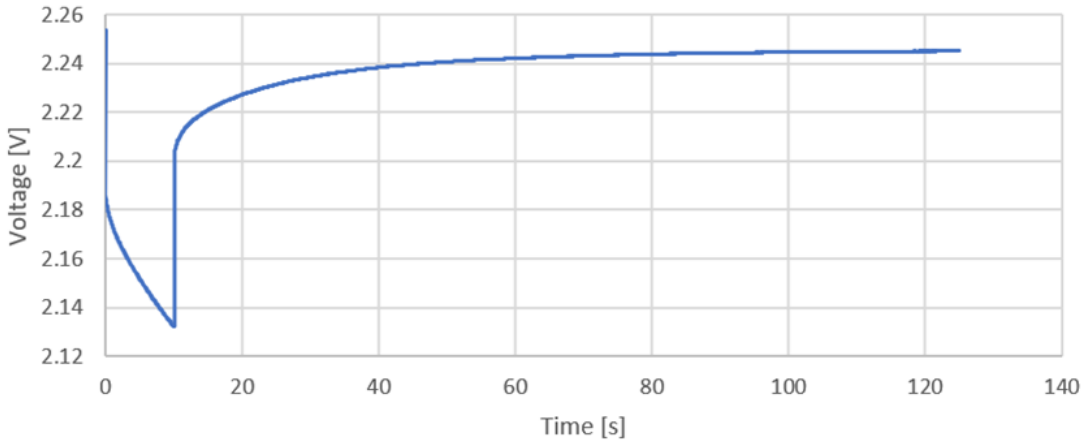


Figure 5. Cell voltage as a function of time during the higher discharge current pulse when SOC is 50 % (based on Turku University of Applied Sciences, 2020).

The cell measurements utilized in this study is done on a Toshiba 23 Ah High energy SCIB cell with a nominal voltage of 2.3 V and energy density of 202 Wh/L. The measurements were executed by TUAS battery laboratory in April 2020. The HPPC test was executed only in room temperature due to limited availability of test cells. SOC levels are chosen from 100 % to 20 % with a 10 % interval. Higher discharge C-rate level of 4C-rate (92 A) is used and the current pulse width is 10 seconds. For the SOC reduction parts a lower 1C-rate (23 A) discharge current is used. The measurement frequency is 50 milliseconds during higher discharge pulse. Test equipment used at TUAS for HPPC test is Chroma 17011 Battery Cell Tester. The temperature measurement error is about 2°...3° Celsius. The temperature of the cell is measured close to the positive pole. The preferred operating temperature range for lithium-ion cells is approximately between +15°...35° Celsius (Liu, Liao, & Lai, 2019). The Toshiba LTO cell specifications accept an operating temperature range between -30°...+55° Celsius. The charging process of the battery pack is not considered in this study and therefore, the higher C-rate charge current pulse is excluded in the HPPC measurements. In the system model it is assumed that the battery pack of the eRallycross car is initially fully charged. (Turku University of Applied Sciences, 2020)

3.3 Interior permanent magnet synchronous motor physics

In comparison to ICEs the advantages of electric machines are many. Features of electric machines are free of emissions, good efficiencies, compact designs, low vibration and bidirectional operation mode. Electric machines that are widely used in the automotive sector are the induction motor (IM) and the permanent magnet motor. The permanent magnet motor is more expensive than the induction motor since the use of permanent magnet material. Characteristics of the permanent magnet motor are high power and torque production. Therefore, the machine type is suitable especially for high dynamic applications. The permanent magnet brushless direct current motor (PMBLDC) provides a high power density, but the alternating current permanent magnet synchronous motor (PMSM) enables better controllability and field weakening capabilities (Dorrell et al., 2011). The permanent magnet synchronous motor principles are chosen to be explained in this paper since the reference eRallycross car is driven by a permanent magnet synchronous motor originated from Borgwarner. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

The permanent magnet AC motor is a synchronous machine that is equipped with permanent magnets. This means that the machine is initially magnetized and does not require any external magnetization. The operation of the PMSM can be explained by a magnetic field created by the stator that forms a rotating field that follows the current behavior. The alternately poled permanent magnets pairs can be placed either inside the rotor or on the outer surface of the rotor. Therefore, the PMSM can be divided in interior or surface permanent magnet synchronous motors. The rotor is typically radial in automotive applications. (Chiasson, 2005)

The PMSM produces sinusoidal voltage. To make it easier to understand PMSM dynamics, a d-q synchronous reference frame is used. The direct axis (d-axis) is in the permanent magnet flux direction and the quadrature axis (q-axis) represents the torque production direction. The d-q coordinates represent the rotating frame of the PMSM. With the rotor position of an IPMSM the varying stator inductances on the d-q frame L_d and L_q can be determined. If the machine losses are neglected, the stator inductances on the d-q frame L_d and L_q are constant. The IPMSM q-axis stator inductance L_q has lower reluctance and is therefore greater than the d-axis stator inductance L_d (NXP, 2013). For surface permanent magnet synchronous motor the reluctance is the same and therefore, the stator inductances L_d and L_q are almost equal (NXP, 2013). (Ohm, 2000)

Utilizing the d-q frame a set of parameters are defined to describe the IPMSM dynamics with mathematical equations. The following representation follows a method of modeling electromechanical systems (Cellier, 1991). The mathematical equations are used for the explanation and modeling of the IPMSM. Table 1 presents the set of parameters.

Table 1. Parameters of IPMSM.

Symbol	**Description**	**Unit**
R_st	Stator resistance	Ω
L_d	Stator d-axis inductance	H
L_q	Stator q-axis inductance	H
p	Number of poles	
J	Rotational inertia of motor	$\mathrm{kg/m^2}$
Ψ_pm	Permanent magnet flux linkage	$\mathrm{kg{\cdot}m^2/(s^2{\cdot}A)}$

The stator inductances L_d and L_q can be measured by performing quite simple tests where the torque is measured (Popescu & Dorrell, 2013). The stator winding resistance R_st can be calculated from measurements of applied voltages and current responses (NXP, 2013). The number of poles p and motor rotational inertia J can be mentioned in product datasheets. The IPMSM dynamics are determined with the following equations (Tolochko, 2019). The stator voltages v_d and v_q in the d-q frame are (Tolochko, 2019):

$$v_\mathrm{d} = R_\mathrm{st} i_\mathrm{d} + L_\mathrm{d} \cdot \frac{di_\mathrm{d}}{dt} - \frac{p}{2} \omega_\mathrm{m} L_\mathrm{q} i_\mathrm{q} \tag{1}$$

$$v_q = R_\mathrm{st} i_\mathrm{q} + L_\mathrm{q} \cdot \frac{di_\mathrm{q}}{dt} + \frac{p}{2} \omega_\mathrm{m} \left(L_\mathrm{d} i_\mathrm{d} + \Psi_\mathrm{pm} \right), \tag{2}$$

where mechanical angular speed ω_m is obtained from

$$\omega_\mathrm{m} = \frac{d\theta_\mathrm{m}}{dt} \tag{3}$$

$$\omega_\mathrm{e} = \frac{p}{2}\omega_\mathrm{m} \tag{4}$$

$$\theta_\mathrm{e} = \tfrac{p}{2}\theta_\mathrm{m}, \tag{5}$$

where

R_st	stator resistance
i_d	d-axis stator current
i_q	q-axis stator current
L_d	stator d-axis inductance
L_q	stator q-axis inductance
p	number of poles
v_d	d-axis stator voltage
v_q	q-axis stator voltage
ω_m	mechanical angular speed
ω_e	electrical angular speed
θ_m	mechanical angle
θ_e	electrical angle
Ψ_pm	permanent magnet flux linkage.

The IPMSM produced electric torque T_e is calculated by the following equation (Tolochko, 2019):

$$T_\mathrm{e} = \tfrac{3}{2}\cdot\tfrac{p}{2}\cdot\eta\cdot\left(\Psi_\mathrm{pm}i_\mathrm{q} + \left(L_\mathrm{d} - L_\mathrm{q}\right)i_\mathrm{q}i_\mathrm{d}\right). \tag{6}$$

With the electric torque T_e the following equation can be determined (Tolochko, 2019):

$$T_\mathrm{e} - T_\mathrm{m} = J\frac{d\omega_\mathrm{m}}{dt}, \tag{7}$$

where

T_m	mechanical torque
T_e	electric torque
J	motor rotational inertia
η	efficiency.

The machine dynamics can be represented by the previous mathematical equations, but a more realistic definition requires control of the machine, such as appliance of limitations and smoothing. Machine control is needed for improving the stability of the drive. To avoid disturbances machine control is essential. Parameters change during drive cycle due to heating. These issues need to be monitored and fixed continuously. For system level modeling it is important to have stable components because it is challenging to find errors from a complicated system structure.

An IPMSM of BorgWarner is used as a reference for the machine modeling of the eRallycross car. An electric gear drive is integrated to the BorgWarner machine and the machine is liquid cooled. Physical measurements of the BorgWarner machine are not executed nor included in this study. Another reference used in this study for the machine modeling is an Ansys IPMSM model based on the year 2004 Toyota Prius hybrid electric drive system.

3.4 Power converter physics

Power electronics is a significant part of electrified powertrains. Converters are needed for changing the voltage levels (DC-DC converter) and for the conversion between direct current (DC) and alternating current (AC). A DC-AC converter or inverter is used in an electric powertrain when the battery power is transferred to the AC machine. The opposite conversion from AC to DC is done by an AC-DC converter. Commercial converters are equipped with control software that determines boundary conditions in order to enable safe operation. Converters generate losses within the couplings and cables and therefore, its impact on the electric powertrain needs to be considered. Converter modeling can for instance utilize efficiency maps for including the total amount of loss effects. However, the efficiency maps may not contain information about the distribution of the losses inside the converter. (Ehsani, Gao, Longo, & Ebrahimi, 2019)

4 System modeling and simulation methods in Ansys

In this chapter the modeling and simulation methods and solutions used in this study are presented. The electric powertrain is modeled initially with two main components – battery storage and electric machine. The electric and thermal behavior of the battery storage is modeled. The electric machine electrical and mechanical behavior is modeled, and the machine is verified against a reference drive cycle. The models are coupled together on a system level.

Measurement and efficiency map data is integrated to the system model in look-up table format. The battery thermal behavior is modeled as a computational fluid dynamics (CFD) model, but it is integrated to the system model as a ROM. Response surface utilization is one strength of Ansys system simulations. Since Ansys has a wide portfolio of 2D and 3D multi-physics software it is profitable to utilize the possibilities and integrate it to system level simulations.

4.1 Ansys software interfaces

Ansys Twin Builder software is suitable for system modeling and simulation and digital twin generation. The system modeling in Twin Builder can be implemented with various modeling languages and the platform enables the integration of external units from other software.

Ansys Twin Builder (2020 R1 version) software is used in this study as a main platform for the system modeling. Detailed models are built and simulated in other Ansys software interfaces and imported to Twin Builder platform as ROMs. 2D and 3D simulation software examined in this study are Ansys Maxwell and Motor-CAD. Ansys Maxwell and Motor-CAD can be used for the electric machine electromagnetic simulations and Motor-CAD generates thermal models of electric machines. In this study Ansys Fluent is used for the CFD model of the battery thermal behavior.

Twin Builder platform is compatible with functional mock-up units (FMU). The FMU functionality in Twin Builder can be implemented as a co-simulation. Model exchange FMUs are also possible to be generated in Twin Builder and imported into Twin Builder. This feature is useful if other third-party software is used. Mathworks Simulink software is commonly used for system simulations. Within the system model development during DEL project the target is to both test the importation and exportation of an FMU to and from the system model in Twin Builder environment. In system simulation environment it is profitable to exchange FMUs of different subsystems or components of a system model instead of the whole system.

Control logic and optimization are significant parts of system simulations. Ansys Twin Builder environment can utilize the integration of FMUs generated in Ansys Scade Suite software. Scade Suite is based on Scade language and it is used for advanced control logic and optimization applications. Ansys OptiSLang is an optimization and sensitivity analysis software compatible with third-party tools. OptiSLang can enable the validation and optimization of different parameter ranges and combinations of system models. The focus of this study is however not in the control and optimization of the system model.

The solutions that are presented in this study are implemented in the Ansys software environment. One motivational factor behind the developed system level platform is a demonstration of the system designs in Ansys environment. There are possibilities of offering the developed system model for tutorial purpose to ease the learning process of system modeling in Twin Builder environment. For that purpose, the visual representation of the system model shall be user-friendly. There is also an idea of utilizing the developed system model for possible powertrain design projects of system integrators.

Modelica modeling language

Modelica is a free open source object-oriented modeling language. The free Modelica standard library consists of over 1500 components from various fields such as electrical, mechanics, fluids, thermal and control logics. The Modelica programming language is versatile for the user since it enables modeling with both block diagram components and on a code level (see Figures 6 and 7). (Fritzson, 2015)

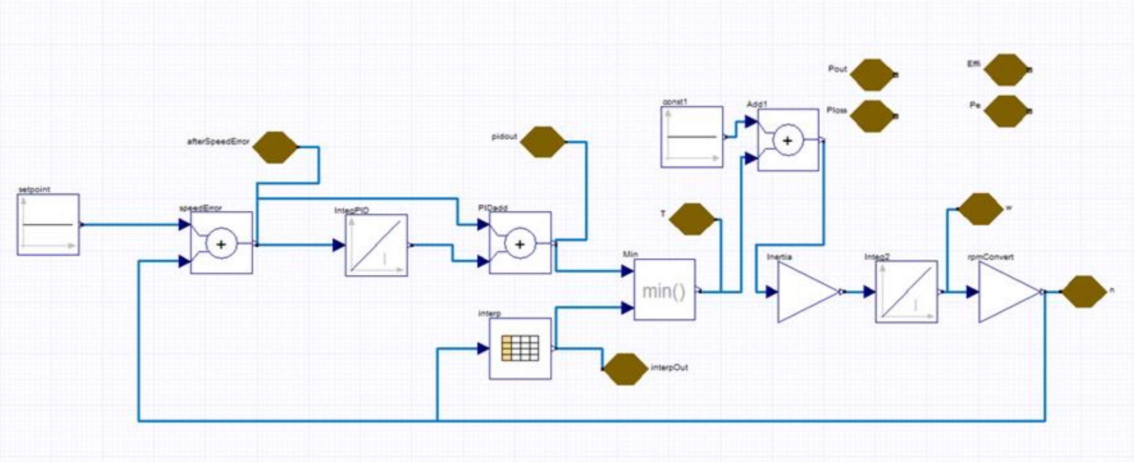
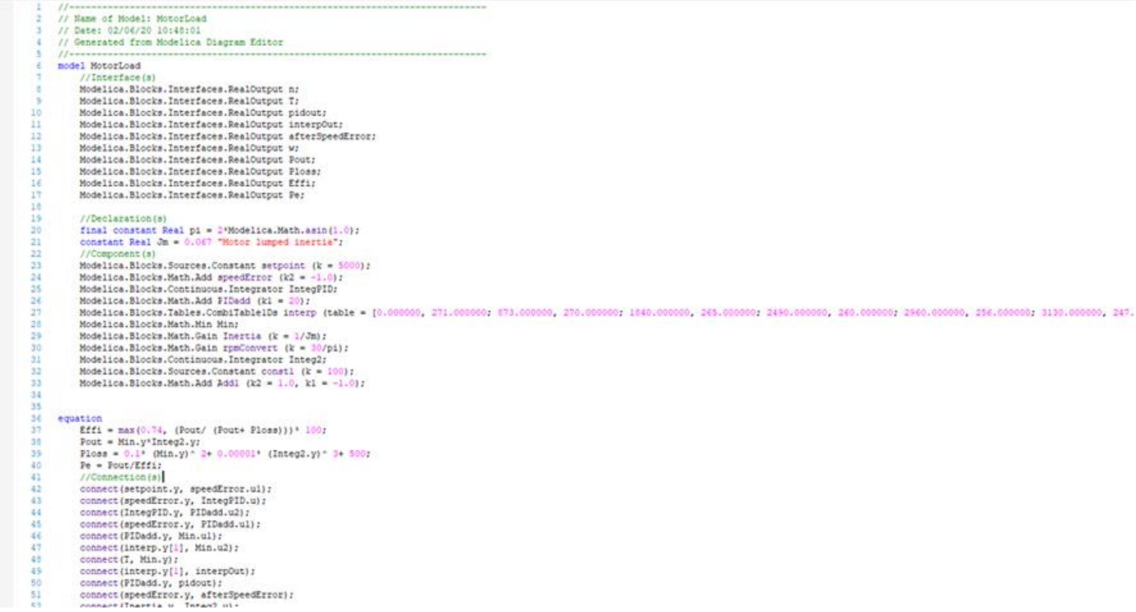


Figure 6. Modelica diagram view.



```
//----------------------------------------------------------------------------
// Name of Model: MotorLoad
// Date: 02/06/20 10:48:01
// Generated from Modelica Diagram Editor
//----------------------------------------------------------------------------
model MotorLoad
    //Interface(s)
    Modelica.Blocks.Interfaces.RealOutput n;
    Modelica.Blocks.Interfaces.RealOutput T;
    Modelica.Blocks.Interfaces.RealOutput pidout;
    Modelica.Blocks.Interfaces.RealOutput interpOut;
    Modelica.Blocks.Interfaces.RealOutput afterSpeedError;
    Modelica.Blocks.Interfaces.RealOutput w;
    Modelica.Blocks.Interfaces.RealOutput Pout;
    Modelica.Blocks.Interfaces.RealOutput Ploss;
    Modelica.Blocks.Interfaces.RealOutput Effi;
    Modelica.Blocks.Interfaces.RealOutput Pe;

    //Declaration(s)
    final constant Real pi = 2*Modelica.Math.asin(1.0);
    constant Real Jm = 0.067 "Motor lumped inertia";
    //Component(s)
    Modelica.Blocks.Sources.Constant setpoint (k = 5000);
    Modelica.Blocks.Math.Add speedError (k2 = -1.0);
    Modelica.Blocks.Continuous.Integrator IntegPID;
    Modelica.Blocks.Math.Add PIDadd (k1 = 20);
    Modelica.Blocks.Tables.CombiTable1Ds interp (table = [0.000000, 271.000000; 873.000000, 270.000000; 1840.000000, 265.000000; 2490.000000, 260.000000; 2960.000000, 256.000000; 3130.000000, 247.
    Modelica.Blocks.Math.Min Min;
    Modelica.Blocks.Math.Gain Inertia (k = 1/Jm);
    Modelica.Blocks.Math.Gain rpmConvert (k = 30/pi);
    Modelica.Blocks.Continuous.Integrator Integ2;
    Modelica.Blocks.Sources.Constant const1 (k = 100);
    Modelica.Blocks.Math.Add Add1 (k2 = 1.0, k1 = -1.0);


equation
    Effi = max(0.74, (Pout/ (Pout+ Ploss)))* 100;
    Pout = Min.y*Integ2.y;
    Ploss = 0.1* (Min.y)^ 2+ 0.00001* (Integ2.y)^ 3+ 500;
    Pe = Pout/Effi;
    //Connection(s)
    connect(setpoint.y, speedError.u1);
    connect(speedError.y, IntegPID.u);
    connect(IntegPID.y, PIDadd.u2);
    connect(speedError.y, PIDadd.u1);
    connect(PIDadd.y, Min.u1);
    connect(interp.y[1], Min.u2);
    connect(T, Min.y);
    connect(interp.y[1], interpOut);
    connect(PIDadd.y, pidout);
    connect(speedError.y, afterSpeedError);
```

Figure 7. Modelica code view.

The Modelica models are compatible with third-party tools and the models can be exported as FMUs. The Modelica language is used and supported in different software such as Dymola, Maplesoft MapleSim and Ansys Twin Builder. In this study the main powertrain components are modeled with Modelica language. The code editing feature of the language is one reason why the language is chosen. The Modelica language enables tailoring and fast modifications of component and system models. (Fritzson, 2015)

There are commercial libraries available that are based on the Modelica language. Modelon provides a wide portfolio of commercial libraries based on Modelica language from various fields. Modelon Electrification Library provides tools for electrified powertrain simulations and it is provided as an add-on library in Ansys Twin Builder (2020 R2). Modelon Electrification library is examined in this study. (Modelon, 2020)

4.2 Modelon Electrification library

Modelon Electrification library provides system level modeling and simulation components for electrified powertrain designs. The Electrification library content was examined during this study. The library components are not used in the developed powertrain since the library is not available in the Ansys Twin Builder 2020 R1 version, which is used in this study.

The Modelon Electrification library content is visually implemented and is therefore easily approachable. The Electrification library uses simplified models of powertrain components. The electric motor is represented as a generalized DC machine. The generalized DC machine is a two-phase mathematical equations-based representation of a three-phase machine (Mehta, 2016). The electric motor component does not include any motor type specific dynamic representations. In this study a specific electric motor type is modeled and therefore other more dynamic modeling solutions are examined.

The battery models of the Modelon Electrification library utilizes dynamic equivalent circuit models of battery cells. The battery equivalent circuit model (ECM) implemented in Ansys Twin Builder is presented later in this paper. The reason why Modelon Electrification battery models are not used in this study is partly since Twin Builder has a customized toolkit that generates an equivalent circuit model based on physical measurements. In this study a cell characterization measurement method is presented, and actual measured data is integrated in the simulations. The specific measured data cannot be used as it is in Modelon Electrification library, but as processed it can be integrated into the battery models of the library. The toolkit in Twin Builder can process the specific measured data with an automated curve fitting method.

The Modelon Electrification library approach to system modeling enables fast simulations. The usage of simplified component models is profitable when detailed information is not available of the component. The input parameters for the component models can be imported in table format. That feature is profitable in powertrain modeling when the available input values are efficiency maps. In system simulations a small set of essential component parameters can be accurate enough for system level analysis. However, in this paper dynamic component models are developed in order to examine what profits they can provide and for what type of application those are profitable.

4.3 Battery design using Ansys

The cell electrical performance can be measured for modeling purpose, estimations and analysis of the battery behavior. Battery cell characteristics can be examined with impedance, capacity or internal resistance measurements. With a set of cell characterization measurement data various performance models and simulations against different system applications can be run. Simulations are a good option for battery performance analysis since the physical tests cause stresses for the cell and the test cell or module availability can be challenging. Even the durations of physical cell characterization tests can be long since the cells require long cooling times between test cycles or load cycles. (Stroe, Swierczynski, Stroe, & Teodorescu, 2015)

Ansys Twin Builder 2020 R1 includes a Battery Wizard Toolkit, which is used for battery simulations. This is a tool that is easy to approach since it includes automated processes and it is built up on a simple graphical user interface (GUI). The battery simulation tool principles are based on modeling the battery cell with an electrical equivalent circuit model, which describes the battery cell dynamic behavior. The parameters of the ECM can be SOC, load current and temperature dependent and they can be determined from a transient step response. The transient step response is generated with physical measurements. In Ansys Twin Builder Battery Wizard Toolkit the battery ECM parameters are based on hybrid pulse power characterization (HPPC) measurement data. HPPC measurements of the Toshiba SCiB cell were executed by TUAS battery laboratory in April 2020.

In this study the electrical battery model is coupled with a thermal model. The thermal computational fluid dynamics battery model is calculated in Ansys Fluent 2020 R1. The thermal model is imported to Ansys Twin Builder as a ROM in order to remain the fast simulation durations, but still increase the accuracy of the battery design.

4.3.1 Equivalent circuit model of battery storage

The electrical performance of a battery can be presented with an ECM, with basic electrical circuit components, such as resistors and capacitors (see Figure 8). Ansys Twin Builder Battery Wizard Toolkit generates an ECM for both cell and module level. The cell ECM can be created either as a four- or six-parameter model. The ECM cell parameters are presented in the following Table 2.

Table 2. Electrical parameters of the cell ECM.

Symbol	Description	Units
V_{oc}	Open circuit voltage	V
R_s	Series resistor	Ω
R_1	Short-time resistor	Ω
R_2	Long-time resistor	Ω
C_1	Short-time capacitor	F
C_2	Long-time capacitor	F

Figure 8 describes the dynamic behavior of a battery cell regardless of the battery chemistry used inside the cell. The parameters are defined from a transient step response generated from an applied pulse load discharge current. The open circuit voltage V_{oc} is SOC dependent and the series resistor R_s represents the drop of voltage of the step response. The four-parameter cell ECM consists of only one pair of resistor and capacitor parallel connection and the six-parameter cell ECM of two pairs. The six-parameter cell ECM is more accurate since it considers both short and long-time constants of the transient step response (Hu et al., 2012). In Battery Wizard Toolkit the module ECM is created with an automated process that simply duplicates and couples the cell ECM in series and parallel. Battery packs can be created by coupling battery module ECM's together manually in series and parallel. (Chen & Rincón-Mora, 2006)

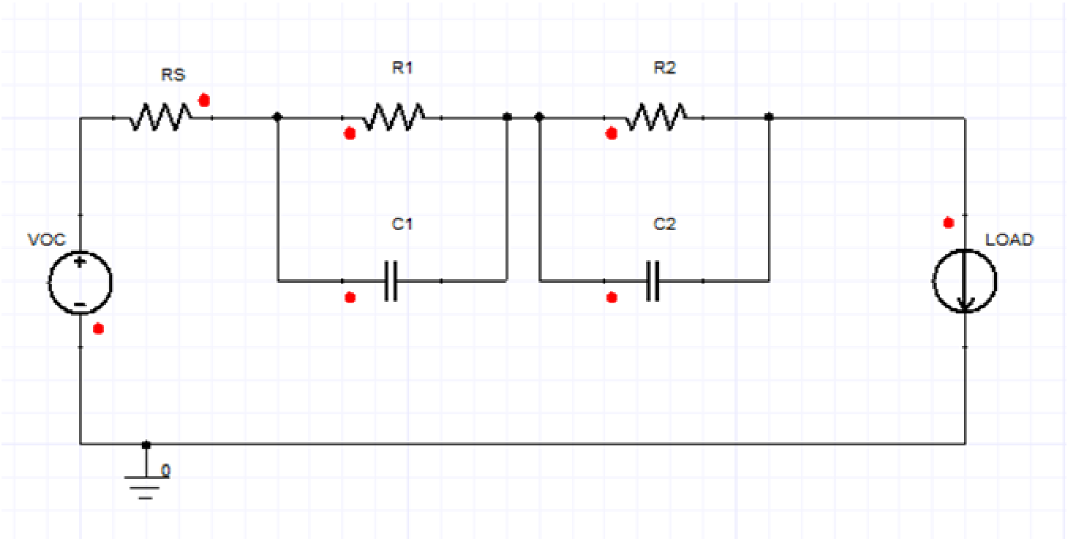


Figure 8. Cell ECM six-parameter electrical circuit representation.

The cell ECM parameter identification is done utilizing HPPC measurement data and a mathematical curve-fitting method. The part of HPPC measurement data utilized in the parameter identification is the voltage step response curve (see Figure 9) during high C-rate discharge. In Ansys Twin Builder Battery Wizard Toolkit the curve-fitting process is automated, and it follows the Jiang-Hu curve-fitting method. The Jiang-Hu model parameter identification method for batteries is a based on the Levenberg-Marquardt method (Hu, Collins, Stanton, & Jiang, 2013). The Levenberg-Marquardt method uses the entire HPPC measurement transient step response curve for parameter identification, but the

Jiang-Hu only uses the relaxation part (Hu, Collins, Stanton, & Jiang, 2013). (Huang et al., 2019)

Figure 9 shows the Ansys Jiang-Hu curve-fitting result of cell ECM parameter identification. The green curve represents the actual transient voltage step response captured from HPPC measurement data when SOC is 50 % and the orange curve represents the calculated fitted curve with similar conditions. The discharge current used in the HPPC test is 4C (92 A). The fitting results indicate the accuracy of the model in comparison to measured data. The second order ECM is used and in most cases it is accurate enough, as the results indicate. Yet, the third order ECM is more accurate since it uses three time constants for the curve fitting process. The time constant originates from the amount of resistor-capacitor loops used and it is calculated as a multiplication of the resistor and capacitor.

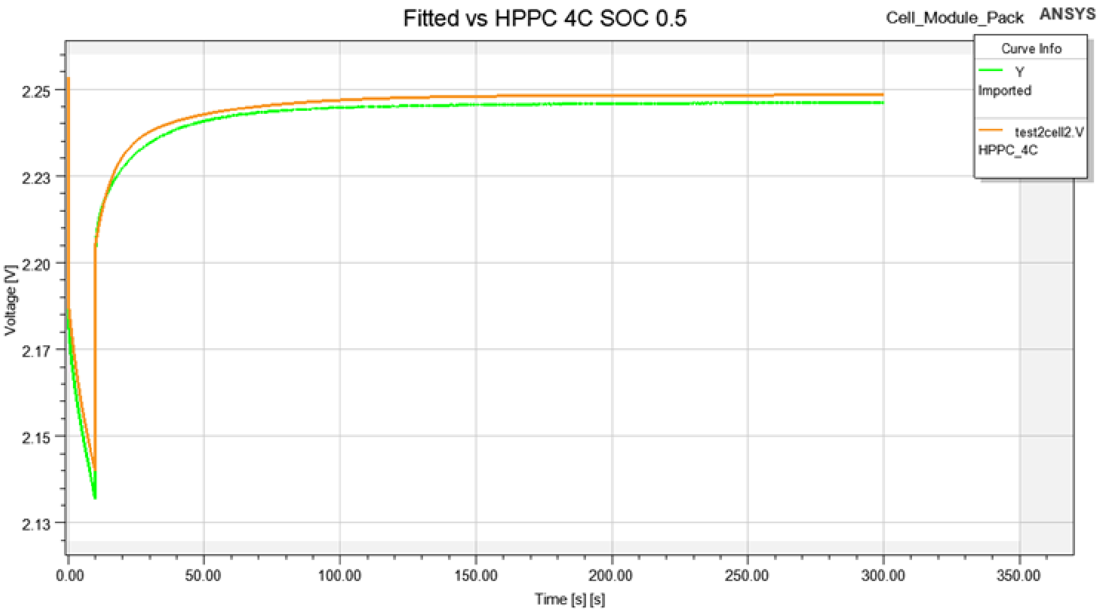


Figure 9. Fitted and measured cell response voltages as a function of time during the higher discharge current pulse when SOC is 50 %.

The Battery Wizard Toolkit generates the cell and module ECM based on Modelica language. The Modelica model enables manual changes in the code. The battery module ECM can be scaled to a battery pack that consists of similar modules easily by manual code changes. In this study an assumption is made that all modules of the battery pack behave in a similar way. In the system level presentation only the battery module level is visible. The eRallycross project is still in a development phase regarding the battery pack design and therefore, the following assumption is made in this study of the battery pack structure. There are 14 battery modules in total and they are all connected in series.

The advantage of the ECM is the ability to describe the dynamic behavior of a cell regardless of the battery chemistry. Though, the transient step response curve shapes differ depending on the battery chemistry. ECM is accurate enough from system level perspective, but for high-fidelity models the cell chemistry characteristics needs to be considered.

4.3.2 Thermal model for battery

Powerful dynamic applications require heat management. Thermal management is vital for vehicles equipped with a battery pack. Simulation software tools are suitable for the modeling of thermal effects and cooling system design. Yet the computational fluid dynamics models that are used for thermal modeling and simulation require heavy calculations and do not fit a fast system level design. In this study the target is to remain on the system level, but we increase the accuracy of detailed models by integrating them to the system model via response surfaces.

Ansys Twin Builder enables the combination of thermal battery modeling with the electrical representation of the battery characteristics. A thermal CFD model of the battery module is run in Ansys Fluent 2020 R1 and then imported to Twin Builder as a linear and time invariant reduced order model (LTI ROM). (Hu, Lin, Stanton, & Lian, 2011)

The thermal model specifications are determined based on the battery storage final application. The eRallycross project is still on a development phase regarding battery pack design and cooling. Therefore, no specific requirements exist regarding the battery pack cooling and assumptions are made considering the final application eRallycross car. The following thermal model is made for demonstration purpose. The thermal model is done on battery module level since it is imported to a system model and the compatible electrical representation of the battery is on a module level. For system modeling it is not necessary to model detailed the internal thermal behavior of an individual cell and therefore the module level is chosen. Though, this thermal model shows a lumped temperature of each cell, that enables the demonstration of cooling effects on different parts of the battery module (Hu, Lin, Stanton, & Lian, 2011).

For internal cell thermal modeling Ansys Fluent uses Newman, Tiedemann, Gu, and Kim (NTGK) models. The NTGK model describes the battery cell internal thermal behavior. Heating around the cell poles can be examined with the NTGK model. The simulations give more detailed information and make it possible to optimize the design of the battery cooling. However, as the cell internal thermal simulations are more detailed, they are executed in rather long time. Therefore, they are not included in system simulations. (Liu, Liao, & Lai, 2019)

The thermal model is created in Ansys Fluent 2020 R1 based on the meshed battery module 3D geometry. The battery module 3D CAD geometry includes twelve cells and two cooling plates (see Figure 10). The cooling plates are applied to the sides of the battery module since the thermal conductivity is higher in those areas of the battery cell.

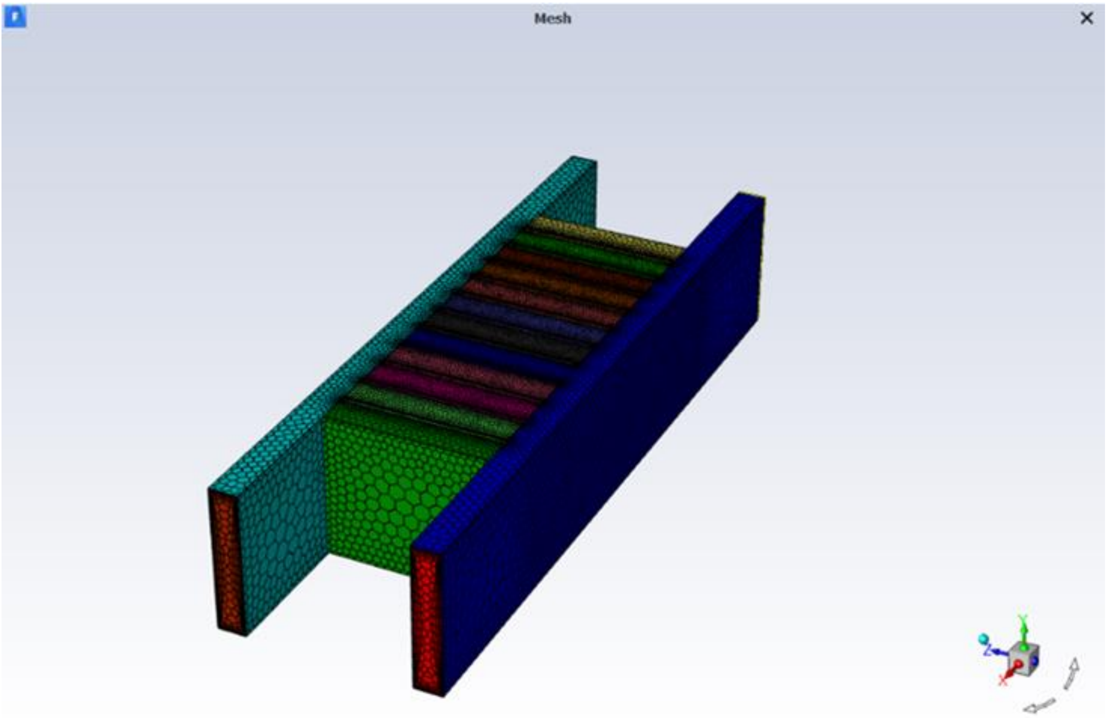


Figure 10.CAD geometry model of the battery module and cooling system.

First a steady state analysis is done to identify the initial conditions of the simulation. Battery cell material is defined with known thermal conductivity values for each axis direction (x-, y- and z-axis directions). An airflow is defined to be passing through the cooling plates in -x direction. The airflow velocity in the cooling plates is set to 21.4 m/s, which is the average speed of TUAS Hyvinkää racetrack drive cycle measurement data (Turku University of Applied Sciences, 2019). Air-cooling is chosen instead of liquid-cooling because that is the initial plan of the eRallycross project according to the battery pack cooling design.

Figure 11 shows that the airflow velocity accelerates during the steady state simulation. The reason behind the acceleration is the boundary layers. In real-life the airflow velocity in pipe walls is zero. In this model, the airflow inlet surface of the cooling plate sets the airflow velocity value to each element of the surface and therefore, the velocity differs from actual real-life situation. For that reason, the cooling plates are set a bit longer on both ends of the battery module (see Figure 10).

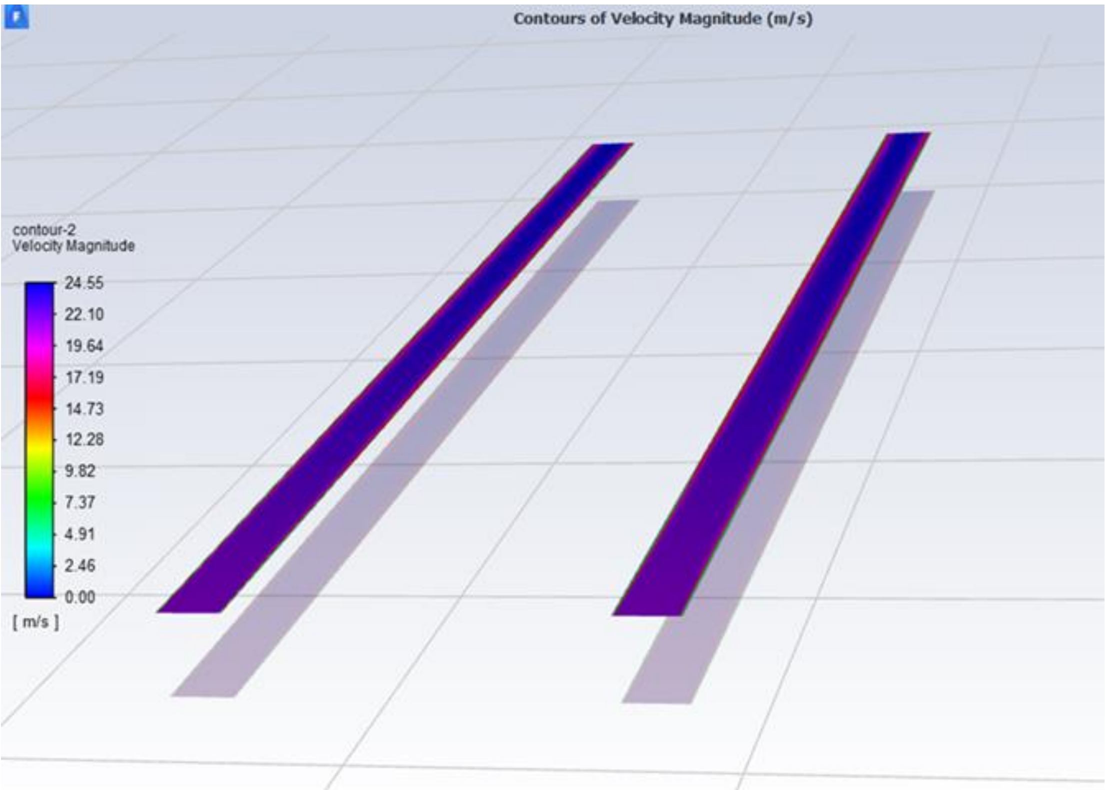


Figure 11. Final airflow velocity distribution in cooling plates after steady state simulation.

Next the transient analysis is done, and a step response is generated. A heat input power of 10 W is applied to each cell. 10 W is calculated from the internal cell resistance and the current with the following equation:

$$P_{\mathrm{heat}} = {I_{\mathrm{DC}}}^2 R_{\mathrm{int}}, \tag{9}$$

where

R_{int} internal cell resistance
I_{DC} DC cell current
P_{heat} cell heat power.

The internal cell resistance is obtained from the parameter estimates from the electrical ECM generation. For the internal cell resistance determination, the series resistor and small-time constant resistor is included in the calculations. The DC cell current is the same that is used for the ECM generation, which is 4C (92 A). (Chen & Rincón-Mora, 2006)

Figure 12 demonstrates the heating of battery module parts. Due to the cooling airflow direction the cells in the front part of the module are cooled down better than those in the back part. The cell temperature differences are about 20 degrees between the first and the last cell in line.

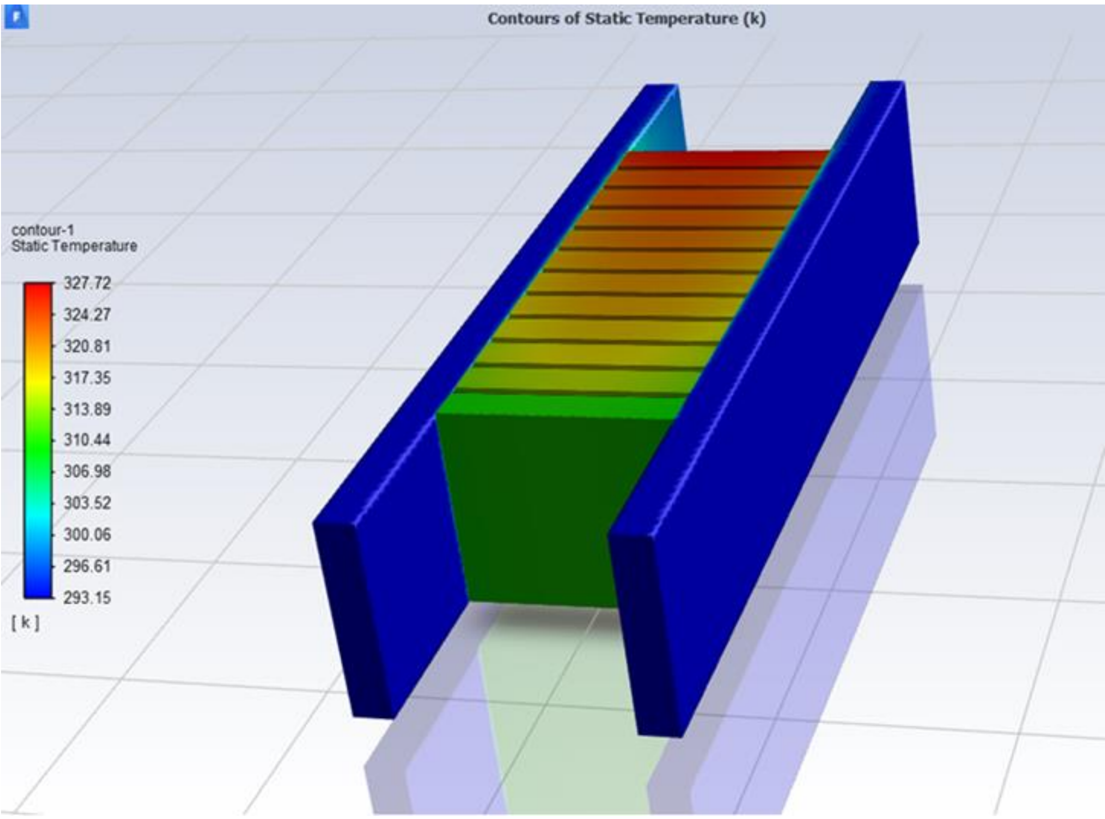


Figure 12. Final temperature distribution in each cell and cooling plates after transient simulation.

A state space model is created based on this thermal model. The state space model shall contain the essential characteristics of the original CFD model. The linear time invariant model means that it is characterized by linear behavior and that the output is not dependent of the time of in input event (Hu, Lin, Stanton, & Lian, 2011).

ROM is a simplified model of a heavy simulation, that still contains main features of the original detailed model. The LTI ROM used in this study consists simply of state space representation. In this study the thermal ROM is created with an Ansys Customization

Toolkit (ACT) in Ansys Fluent named ROM Trainer, which uses an automated process that creates text files with the information of the transient simulation. The ROM Trainer is implemented on the base of the steady state analysis. The ACT GUI is user-friendly and only a few parameters needs to be specified, such as the heat input power and time step.

The thermal LTI ROM import to Ansys Twin Builder is implemented with a Twin Builder toolkit Thermal Model Identification that reads the generated text files of the ROM. The toolkit creates a model that is based on Simplorer modeling language (SML). The electrical module ECM and thermal LTI ROM are coupled between each cell. Each cell of the module ECM is coupled to gain an input value (temperature) and the output of each cell is heat power loss. Each cell of the thermal LTI ROM is gains the heat loss of the module ECM as an input value and the output of each cell of the thermal LTI ROM is temperature. (Hu et al., 2014)

In Figure 13 the coupled electrical ECM and thermal LTI ROM in Twin Builder environment is shown. In addition, a voltmeter, ampere meter and a load are connected to the battery model. This kind of modeling is suitable when the load is not constant, which is exactly the situation in vehicle applications. The integration of physical measurement data into the model adds more value and increases accuracy to the model.

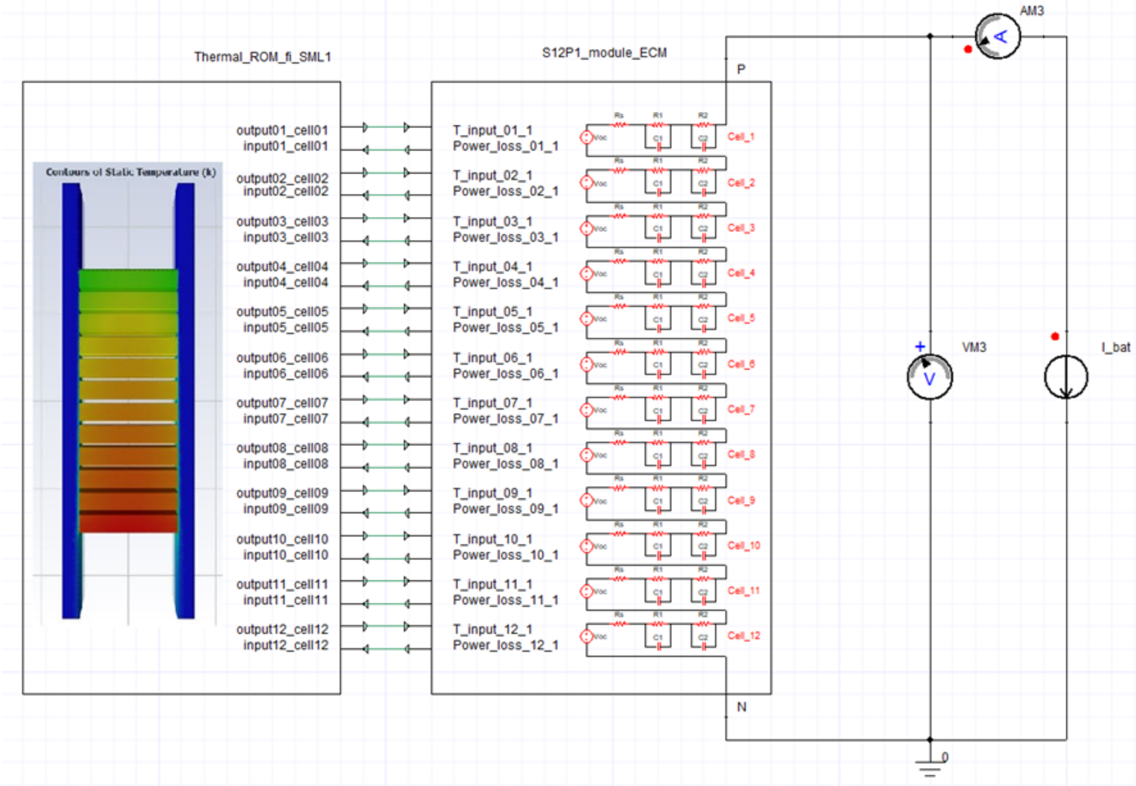


Figure 13. Coupled electrical battery module ECM and thermal LTI ROM.

Figure 14 represents the example load that is connected to the battery model. In Figure 15 the simulation results are shown. According to the simulation results, the cells in front of the module do not heat up as much as those in the back part of the module. This result demonstrates that the coupling of the thermal and electrical models is working as expected. A disadvantage of this method is the neglection of cell internal behavior, such as heat distribution across the cell, for example around the poles. The heating is determined as one lumped temperature for each cell.

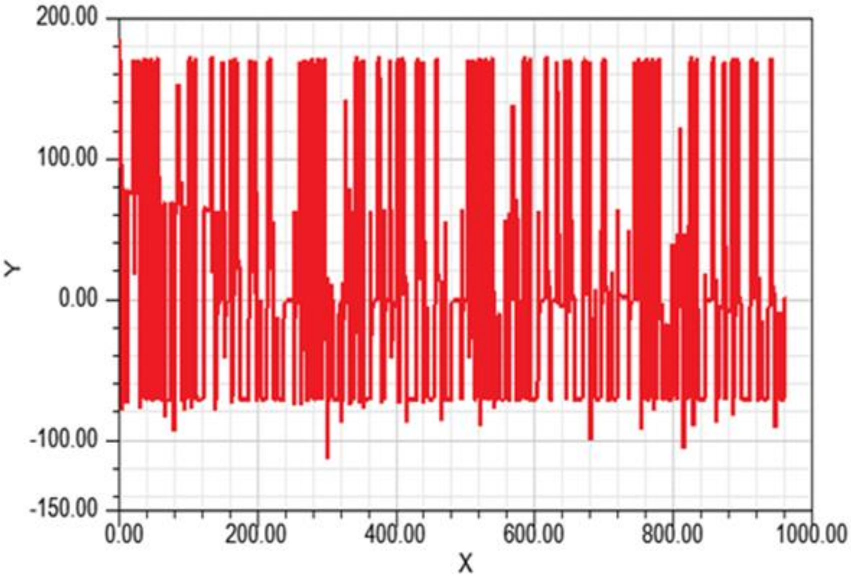


Figure 14. Example load current as a function of time.

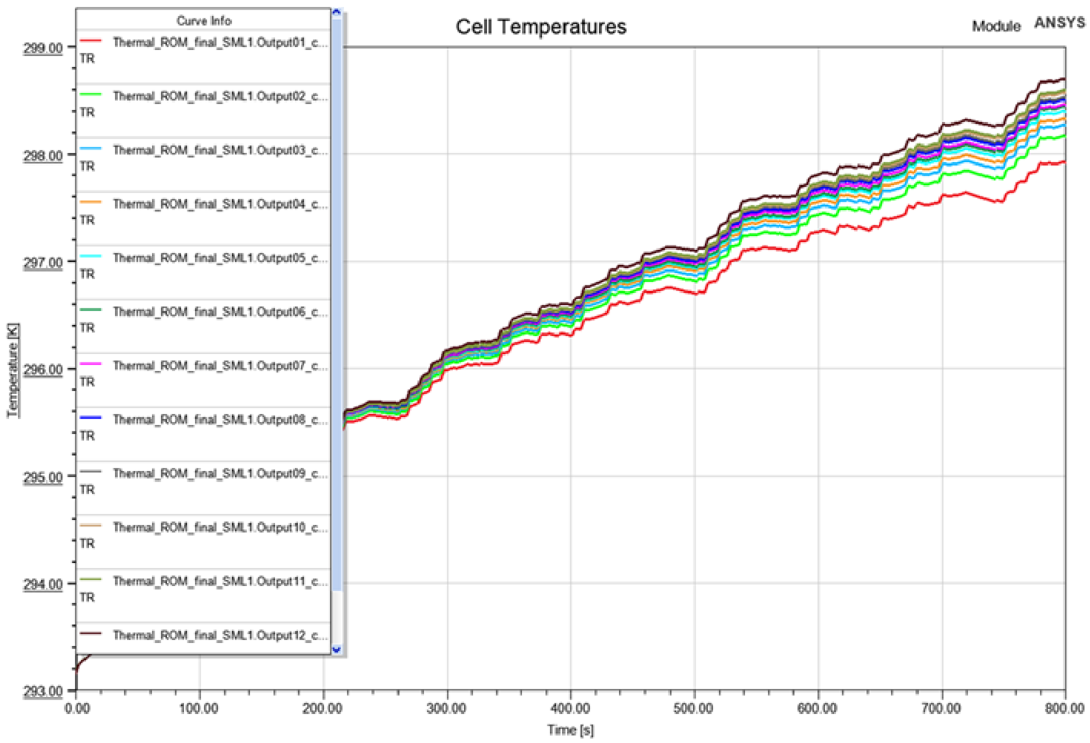


Figure 15. Temperature of cells as a function of time.

In this study the thermal battery model is included in the powertrain model since a suitable solution and physical measurements are available. However, physical measurements are only implemented in room temperature due to lack of test cells. For the demonstration of the coupled electrical and thermal model, temperature dependent input data is needed. Since temperature dependent data is not accessible, it is scaled from the physical measurements done in room temperature. The ECM parameters are scaled to a higher temperature of +45° Celsius based on the LTO chemistry. Based on the temperature dependent characterization test results presented by Stroe, Swierczynski, Stroe & Teodorescu (2015, p. 4) the scaling parameters are defined for a higher operating temperature. (Stroe, Swierczynski, Stroe, & Teodorescu, 2015)

4.4 Electric machine design using Ansys

Electric machine design with Ansys can be done with Ansys Maxwell and Motor-CAD. Maxwell enables detailed electromagnetic 2D and 3D simulations. A ROM or equivalent circuit extraction (ECE) model can be generated from the detailed electromagnetic simulations and imported to the system level. Motor-CAD is a multi-physics electric machine design software, which provides fast and accurate results and analysis of the electric machine behavior. Ansys Maxwell and Motor-CAD are not used in this study since the information about the reference BorgWarner electric machine are rather limited. Information about machine losses such as copper, iron, winding and constant power losses are required for detailed modeling.

In Twin Builder environment electric machine modeling is possible with multiple modeling languages. Modelica language and SML both have template component models for electric machines in their basic libraries. The template electric machine models of SML and Modelica language are examined, but not used in this study. The reason for not using the template models for motors as a base for the machine modeling is the fidelity levels of the models. The Modelica and SML machine template models are too detailed models and require heat loss data of the machine that is modeled. Since the only information of the BorgWarner machine is from the product datasheets, another solution for the machine modeling is used.

4.4.1 Parametrized model of interior permanent magnet synchronous motor

In this study an IPMSM is modeled because of the reference eRallycross project of TUAS. The IPMSM modeled is a BorgWarner manufactured permanent magnet motor. Another reference utilized in this study regarding electric machine modeling is a reference interior permanent magnet (IPM) model of the Toyota 2004 Prius HEV modeled in Ansys Maxwell. The detailed Maxwell model is used for comparison of the IPM essential parameters presented in table 1. The parametrized model for electric machine is implemented with Modelica language.

The developed model for electric machine is based on the IPM motor dynamic equations, that contain both electrical and mechanical parameters and other physics. The model utilizes the d-q-coordinate system. The model is based on five mathematical equations (Equations 1, 2, 3, 6 and 7) that represent the principles of IPM dynamics. The parameter (see Table 1) values are obtained partly from the datasheets provided by the manufacturer and partly arbitrary. The Prius IPM design provided by Ansys Maxwell is used for the determination of the missing parameter values such as the stator inductances L_d and L_q.

We had limited information about the heat losses of the BorgWarner machine. The machine is cooled with water. Efficiency maps originated from manufacturer’s provided datasheets are utilized in order to include some losses effects. Only motor mode efficiency map is provided in the BorgWarner IPM datasheets. For the simulations, a generator mode efficiency map is generated identical to the motor mode but with negative values. This assumption does not fully support the real-life situation since the generator efficiencies are lower than motor mode efficiencies. Saturation, hysteresis and demagnetization effects are neglected in the developed model for electric machine.

According to BorgWarner’s datasheets the machine is equipped with an integrated gear drive that uses a few ratios. In the developed electric machine model, the gear is modeled as a constant ratio, the ratio between the wheels and motor shaft.

The IPM parameters defined in Table 1 are obtained partly from the manufacturer's provided datasheets and the rest is arbitrary or determined based on the Ansys Maxwell Prius IPM model. The actual parameter values or results from the Prius design cannot be utilized because of the differences between the Prius and the BorgWarner IPM. The Prius IPM cannot reach the power requirements of the eRallycross car. The efficiencies are better with the BorgWarner IPM considering the final application eRallycross car.

The stator inductances and permanent magnet flux linkage change as a function of torque. The reason for parameter changes during drive can be a result of heating. In the developed model the parameters L_d and L_q are modeled as constants because of the lack of heat loss data. The simplification is suitable for system simulation purpose. The motor inertia and the number of poles are obtained from product datasheets. The stator winding resistance is arbitrary due to lack of information. Measurements of machine parameters used in this mathematical modeling method can be done for the BorgWarner IPM in the eRallycross car.

The electric machine model is built with Modelica language based on the IPM dynamics representing mathematical equations. The inputs of the electric machine model are the d-q-axes voltages and the mechanical torque requirement. If the machine efficiency information dependent of torque and speed is available, it can be integrated inside the electric machine model in table format.

Figures 16 and 17 present the BorgWarner IPMSM performance characteristics. The power and torque curves in Figures 16 and 17 indicate the machine performance within presented typical operating conditions. Figure 18 presents the efficiency map of the BorgWarner IPMSM. The efficiency map is generated using Matlab. The efficiency map of a machine provides an overlook on what power requirements can be fulfilled.

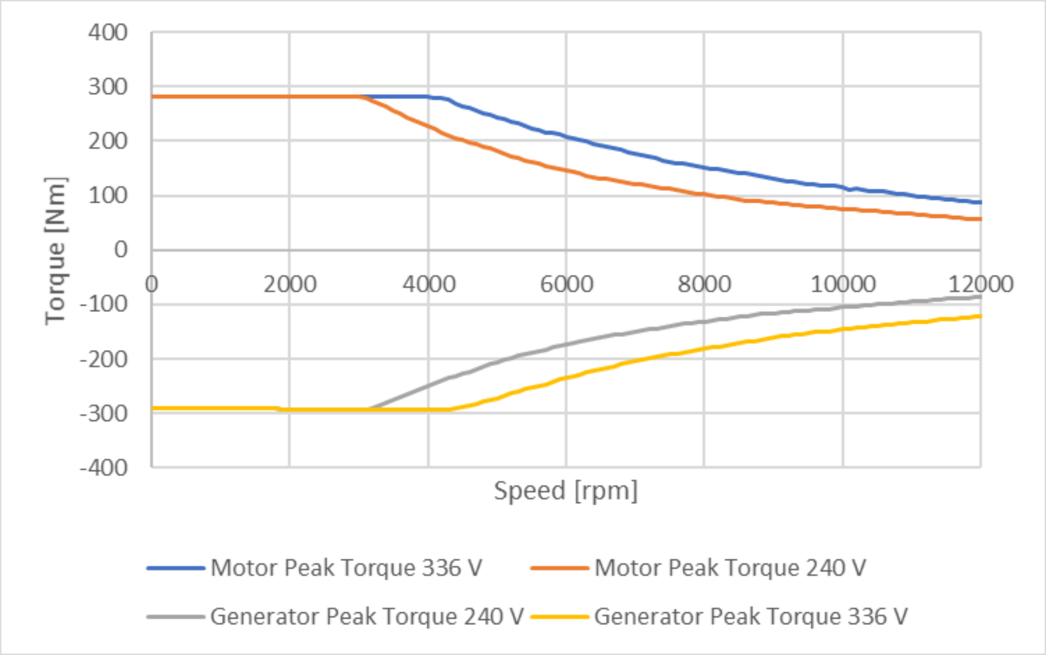


Figure 16. IPMSM torque as a function of speed (based on BorgWarner, 2017).

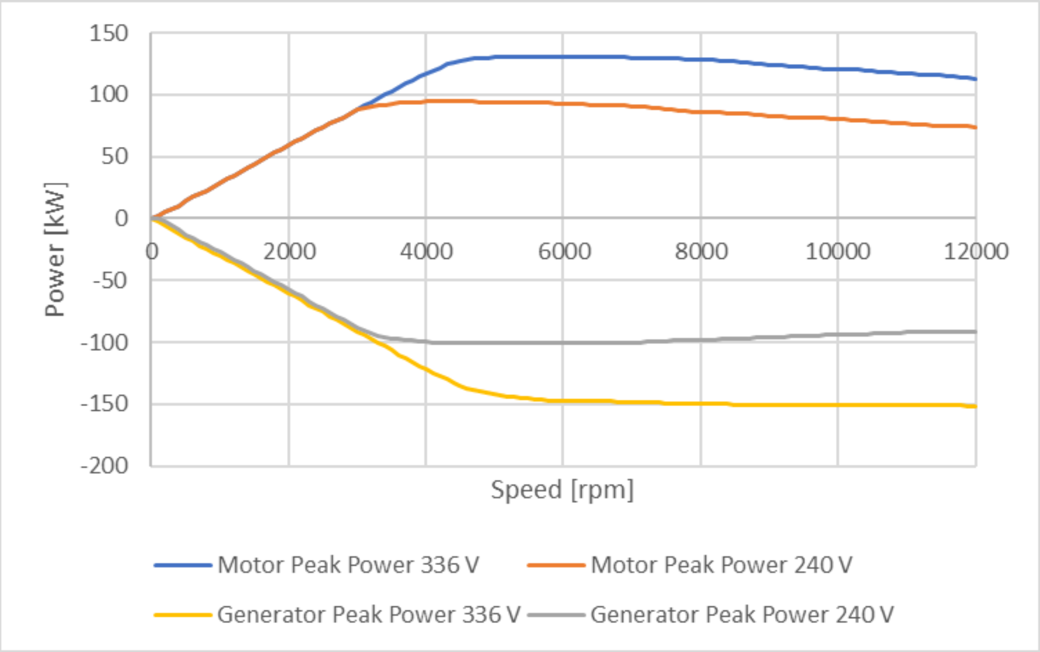


Figure 17. IPMSM power as a function of speed (based on BorgWarner, 2017).

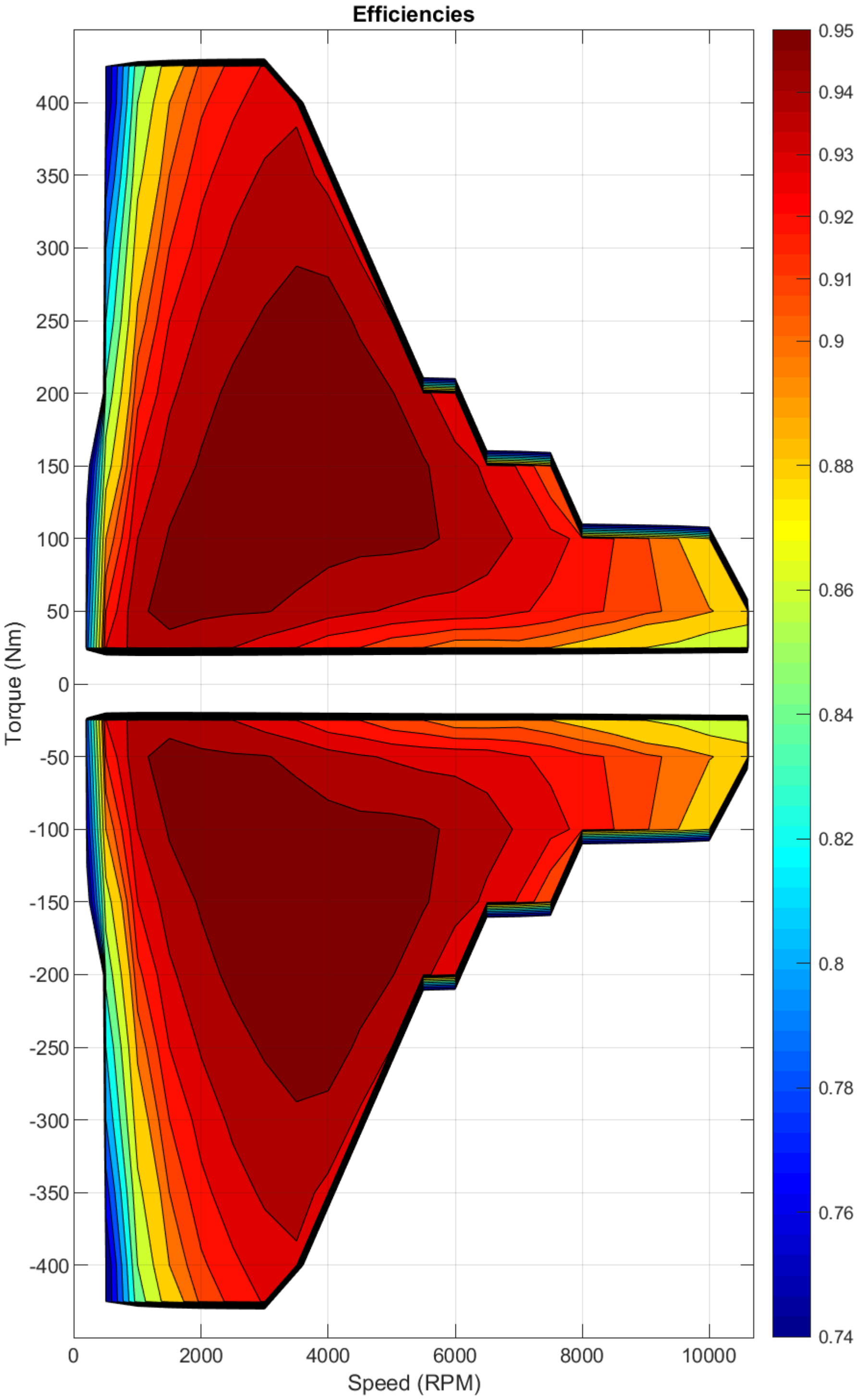


Figure 18. IPMSM efficiency map as a function of torque and speed (based on BorgWarner, 2016).

The table content is interpolated linearly in order to give an output at each point of the drive cycle. The efficiency map adds loss effects to the initially ideal model for electric machine. The outputs of the electric machine model are electromagnetic torque, speed, electrical angle of rotor and the d-q-axes currents (see Figure 19). The mechanics of the electric machine is integrated to the electric machine model in the dynamic equations by including the motor rotational inertia in the calculations. The three-phased currents and voltages of the electric machine model can be plotted for validation if needed. The transformation from d-q-axes to three-phase currents and voltages is implemented with simple mathematical equations (Ohm, 2000).

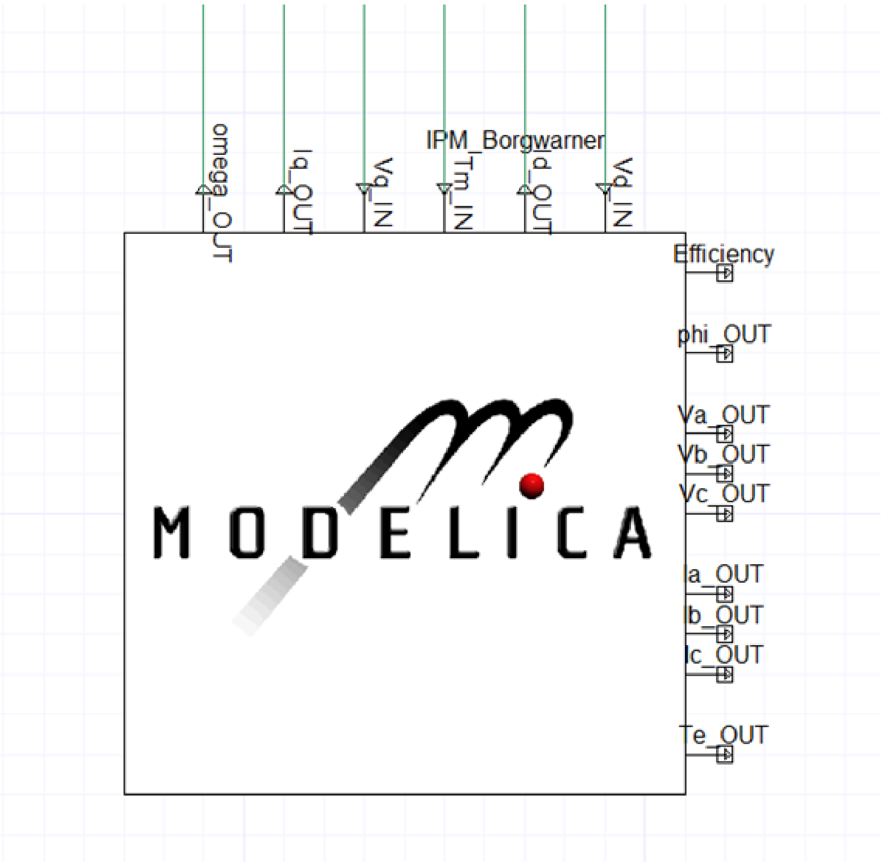


Figure 19. System level IPM model.

4.4.2 Electric machine model control

Measurement data from a driven lap at Hyvinkää racetrack by an ICE driven race car is used as a load drive cycle for the electric machine model. The target is to achieve the same torque, speed and power demands with the electric machine model. The speed measurement data contains global positioning system (GPS) speed, altitude, longitudinal and lateral acceleration measurements at a 100 ms sampling time interval (Turku University of Applied Sciences, 2019). The Hyvinkää rallycross racetrack length is 1446 meters, of which 42 % is tarmac and 58 % gravel (Hyvinkään urheiluautoilijat, 2018). The start value of the car speed is not zero since the lap start speed is measured from a moving car.

A control of the electric machine model is needed in order to keep the output torque and speed as smooth as possible. In this study a current control method is applied to the electric machine model. Voltage control is not chosen because it is more suitable for high performance applications (Chiasson, 2005). Current controllers use proportional integral (PI) controllers (Chiasson, 2005). The control method applied to the electric machine model is based on PI current control principle. The control method is chosen due to equal parameters used in the control method as in the machine model, such as stator inductances in d-q-coordinate system and stator resistance. The control of the machine is implemented in the continuous time domain. Discrete time domain or a combination of continuous and discrete time domain is suitable for motor control. Feedback and feedforward closed loops are used in the control model for correcting and avoiding disturbances. (Hinkkanen, Awan, Qu, Tuovinen, & Briz, 2016)

The PI current control method is applied separately for the d- and q-axis. The d-axis current reference follows a maximum torque per ampere (MTPA) method (Tolochko, 2019). The q-axis uses the speed measurements of TUAS as a reference input for the current control (Tolochko, 2019). A transfer function is applied to the speed reference in order to get the q-axis current that needs to be controlled (Tolochko, 2019). Since the d- and q-axes are dependent on each other, a cross-coupling factor needs to be included in the control model (Tolochko, 2019). The cross-coupling is implemented by adding a cross-coupling block to both of the PI controller circuits (Tolochko, 2019). The reference torque requirement data is obtained from the TUAS measurements of the GPS longitudinal acceleration data. The GPS longitudinal acceleration value at each sampling time is multiplied with the ratio between the torque on motor shaft and the GPS longitudinal acceleration. The ratio is dependent of wheel radius, the mass of the vehicle and the gear ratio of the motor and the wheel. Used wheel radius r is 58 cm and mass of the vehicle m is 1400 kg.

The time step of the controller needs to be small in order to catch essential changes of the dynamic model for electric machine. The time step of the controller has an impact on the system level since it is the smallest time step of the system components. In order to remain the stability of the control, the system level time step needs to be defined following the control time step. The size of time step effects also the simulation time. The system simulations are required to be fast and therefore, a small time step is suitable. In several hours lasting simulations larger time steps are used. In addition to the time step variable, the current control method includes an arbitrary integral time constant and bandwidth that effect the stability of the simulation (Hinkkanen, Awan, Qu, Tuovinen, & Briz, 2016).

The machine control is implemented with SML block components in Ansys Twin Builder environment (see Figure 20). The SML components are compatible with Modelica models, which enables the coupling of those two elements. The pins that connect the electric machine model and the control must however match. In this implementation the connecting pins are time variant real outputs and inputs.

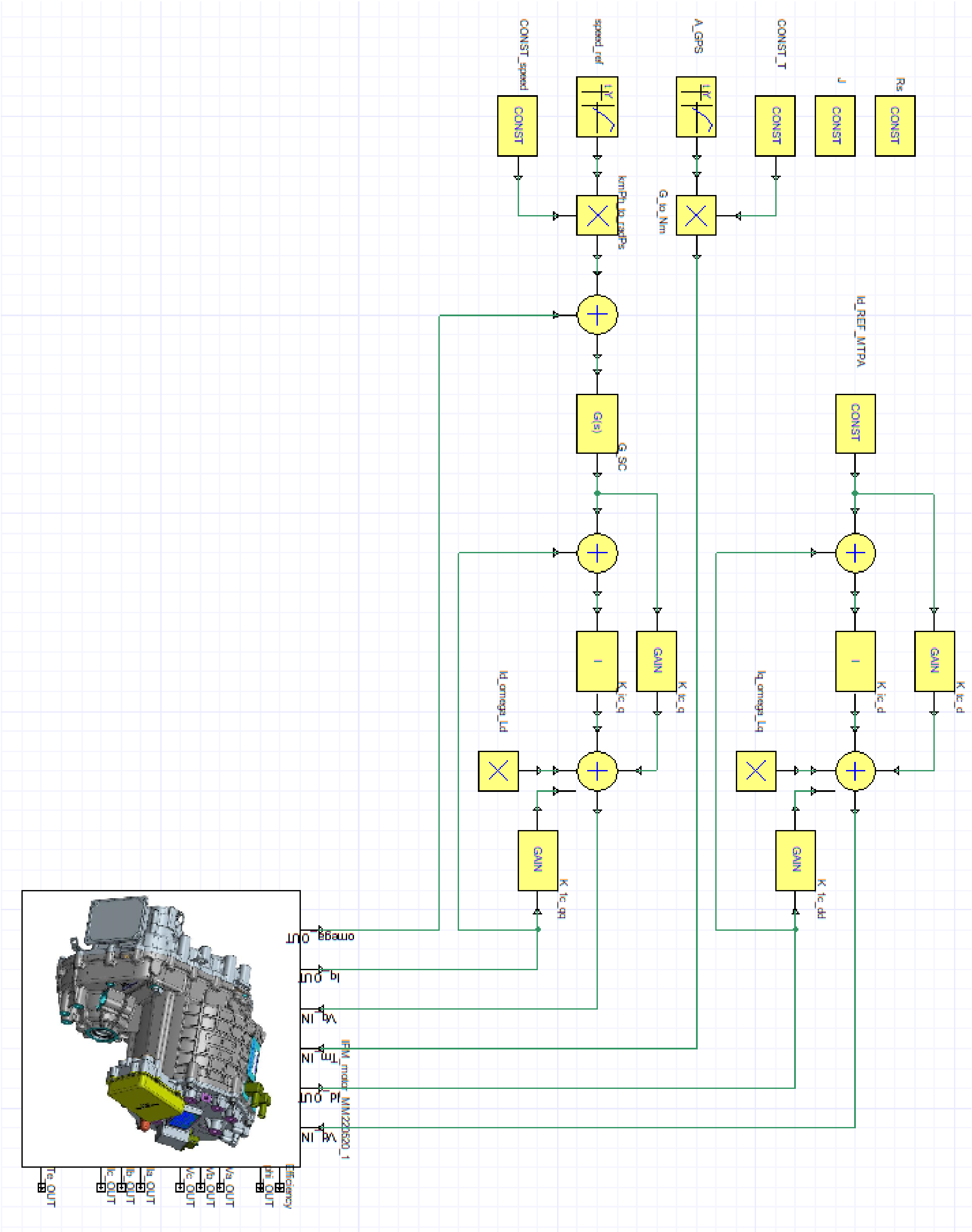


Figure 20. System level IPM model with current control.

In Figure 21 the results of the required and actual output electric machine model speed and torque response are presented. The red curves represent the output speed and torque values and the black curves represent the required speed and torque values. The required speed and torque values originate from the measurement data of a lap run at Hyvinkää racetrack. The reference lap time is about one minute. The transient simulation results of IPM model with current control show that the output values match the required values. However, according to the reference data the car does not start the lap from standstill, but from a speed of approximately 100 km/h. For that reason, a peak can be noticed at the beginning of the speed and torque output curves. The machine initial conditions are set to zero and the high input value at the beginning of the simulation causes unbalance.

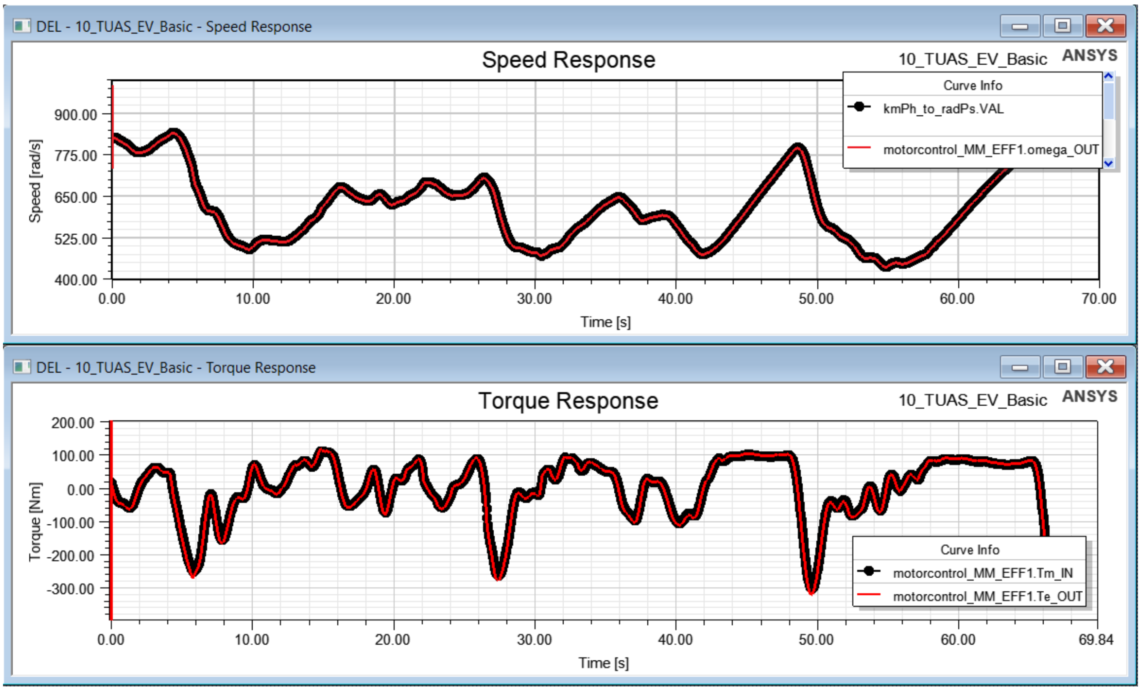


Figure 21. Speed and torque of electric machine model as a function of time.

Figure 22 is generated in Matlab and the efficiency points are based only on the measured data and the efficiency map provided by the manufacturer. Figure 23 represents the model output efficiency, which is calculated based on the efficiency map integrated to the electric machine model. The speed and torque values are obtained from the machine output electrical torque and angular speed.

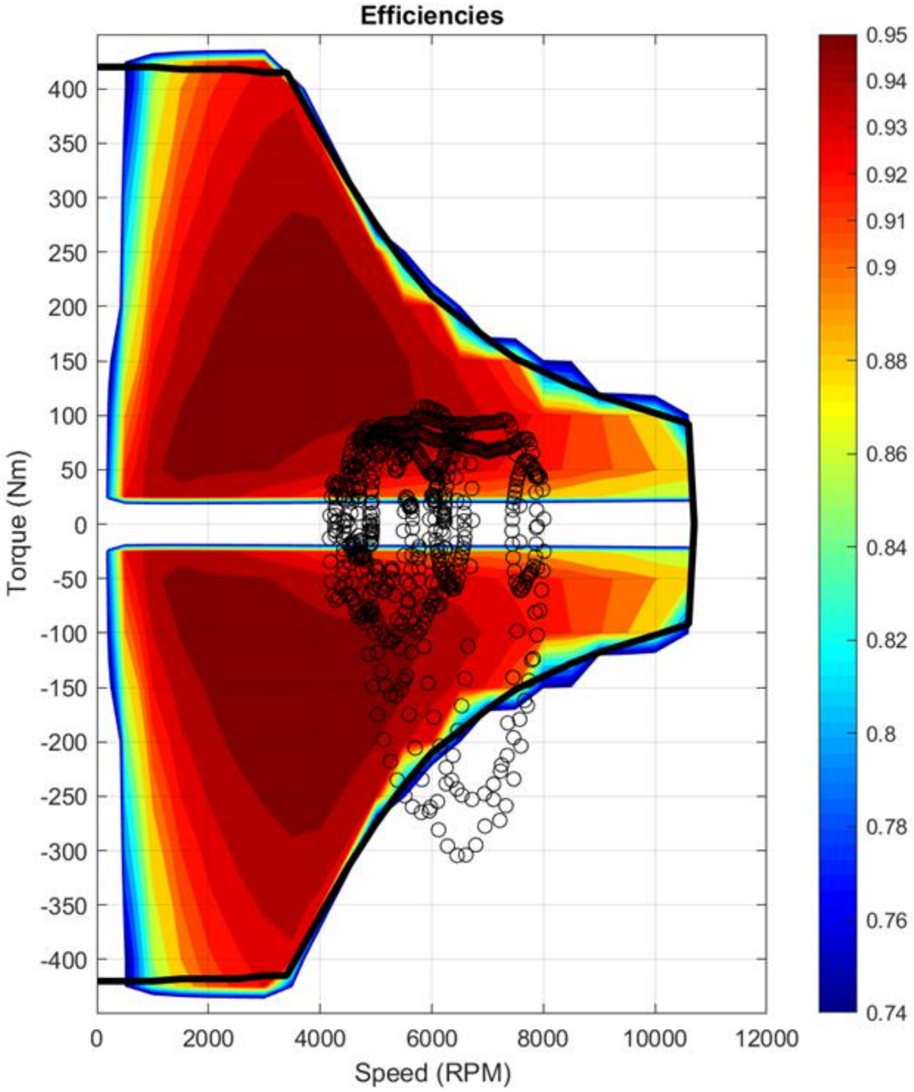


Figure 22. The reference efficiency distribution as a function of torque and speed during the drive cycle.

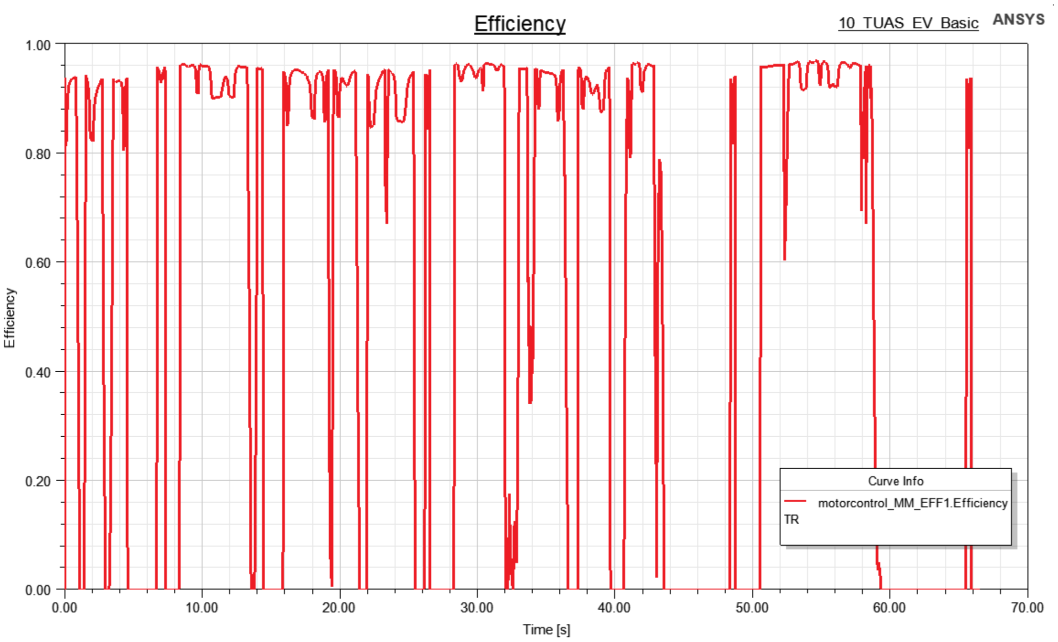


Figure 23. The output efficiency of the electric machine model as a function of time.

5 Electric powertrain design

The coupling of the battery storage and electric machine is implemented in Ansys Twin Builder. The individual components and parts are modeled either with SML or Modelica modeling language, which is beneficial for the coupling phase.

In this system model an individual inverter component is not applied between the battery storage and the electric machine. The reason behind that is the lack of information regarding the inverter. The eRallycross project of TUAS is still on a development phase regarding the inverter and therefore, it is chosen not to be modeled as a separate component in this study. For the inverter model efficiency information is required in order to estimate the losses of power conversion. The inverter losses affect the electric powertrain performance, but those losses are neglected in this study. The essential inverter tasks however need to be included in the system model. Therefore, DC to AC conversions are considered in the electric machine model. The d-q-coordinate system usage in the model for motor enables simple coupling and DC current transmission between the battery storage and electric machine models.

The coupling interface between the machine and battery storage model is a current source that is attached as a load for the battery storage model (see Figure 24). The input value of the current source is the electric machine model output electrical power divided by the battery storage voltage. The electrical power of the IPMSM is obtained from equation (Ohm, 2000):

$$P_{\mathrm{elec}} = \frac{3}{2} \cdot \left(v_{\mathrm{d}} i_{\mathrm{d}} + v_{\mathrm{q}} i_{\mathrm{q}}\right). \tag{10}$$

The current limitations are integrated in the coupling interface. The electric power is divided by the amount of battery modules of the battery pack since the battery storage is modeled in module level. The electric power represents the power requirement of the machine as a function of time. The battery storage output current is coupled back to the electric machine model via the same current source block. In this system model representation it is assumed that the thermal and electrical behavior of each battery module is identical. For a more realistic system model the effects of the heat distribution in different parts of the battery pack is needed.

The developed system model (see Figure 24) simulations are run in transient conditions and the target of this study is to find solutions for including dynamics of the components to their models. The battery ECM is a dynamic representation of battery performance and the thermal computational fluid dynamics model is a transient condition simulation. The electric machine model utilizes dynamic equations of such machine type. In order to observe the performance effects of a system that runs against a dynamic application the transient condition is the chosen option of this study. The determination of separate static modes in the rallycross environment is challenging. Though, the quasi-static simulation can be suitable for applications that have a clear duty cycle sequence. However, regarding ICE fuel consumption analysis the difference between steady state and transient condition analysis is significant (Guang & Jin, 2018). The transient analysis outcome addresses approximately 6 % to 30 % higher fuel consumption in comparison to the steady state analysis (Guang & Jin, 2018). Whether the differences between the steady state and transient analysis of electric machine performance is as significant as for the ICE, is not straightforward.

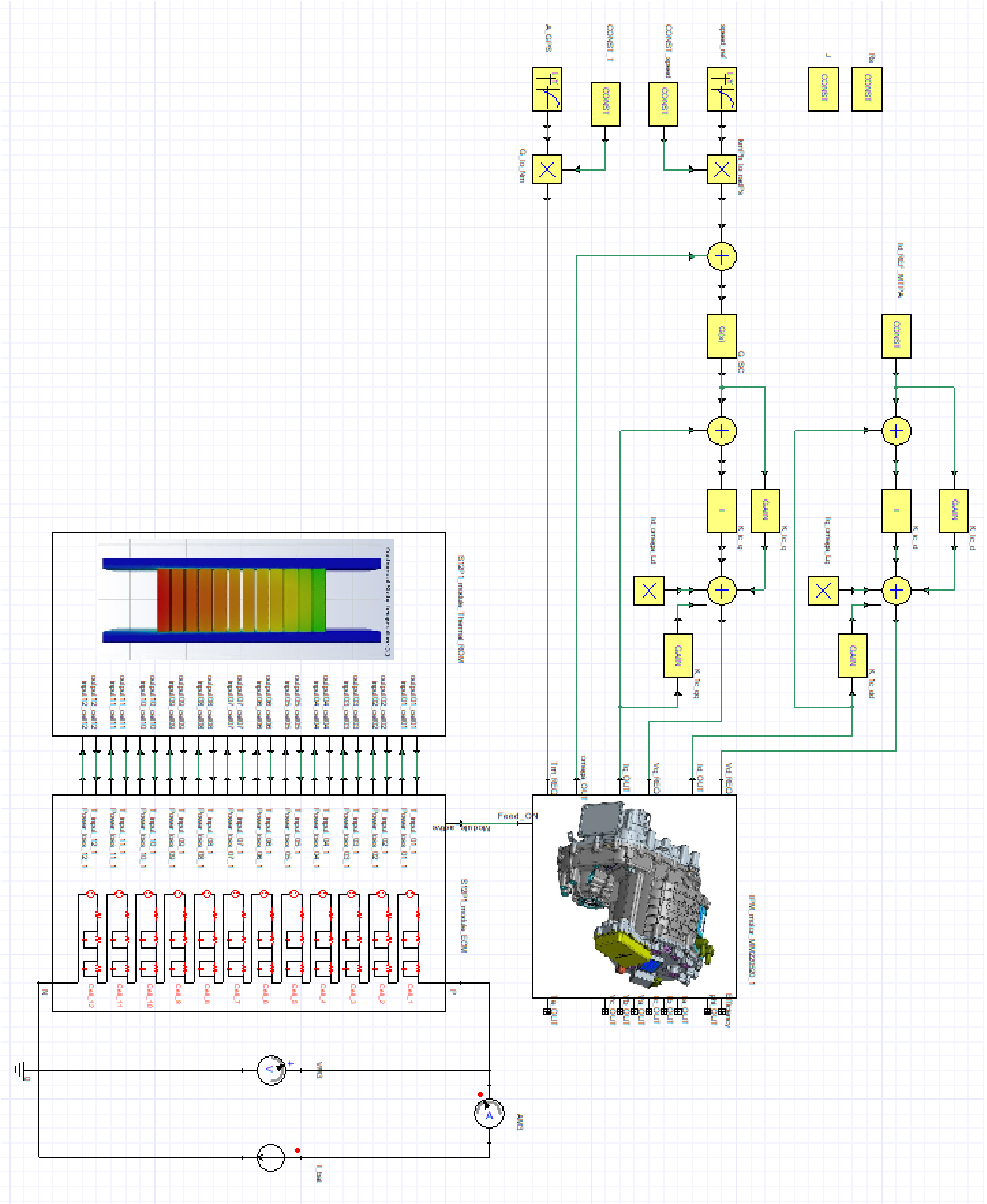


Figure 24. System level model of the battery module model coupled with the electric machine model.

In this system model the current flows in both directions. That means that the battery storage is charged during braking. Regenerative breaking is possible when the electric machine acts in generator mode. The efficiency for the generator mode is also included in the model. Though, in rallycross environment the regenerative braking is not profitable since the braking is so intense.

Additional limitations are added to the models as a result of the coupling process. The torque and speed limits of the electric machine are integrated to the model in order to ensure reliable machine performance. A lower SOC limit is added to the battery electrical model for retaining a realistic battery performance at lower SOC rates. The minimum SOC level for each cell of the battery electrical model is set to 20 %. From a SOC level of 20 % and lower the battery cell is modeled as fully discharged.

Challenges regarding system simulations in any environment are the combination of different time spaces. In this study the powertrain components are built separately with different time steps in simulations. The components are coupled together and fitted into a united time frequency. In the coupling phase the smallest timestep between the models is used. The individual battery model uses a bigger timestep than the electric machine model. In the coupling phase the electric machine model timestep 1 milliseconds is used.

Measurement data from a driven lap at Hyvinkää racetrack by an ICE driven race car is used as a load drive cycle for the powertrain model. The target is to achieve the same torque, speed and power demands with the electrified powertrain model. The start value of the car speed is not zero since the lap start speed is measured from a moving car. In the simulations a start from stand still is used to avoid peaks at the beginning of the simulation results.

The battery performance plots in Figure 25 show that the battery cell SOC levels decrease during the drive cycle. The initial SOC level for each cell is set to 100 % for the simulation. The battery temperature plot shows that the cell temperatures do not differ much in between inside such a small time frame. Though, the demanded power from the battery is high during the drive cycle. The applied cooling solution also effects the battery heating.

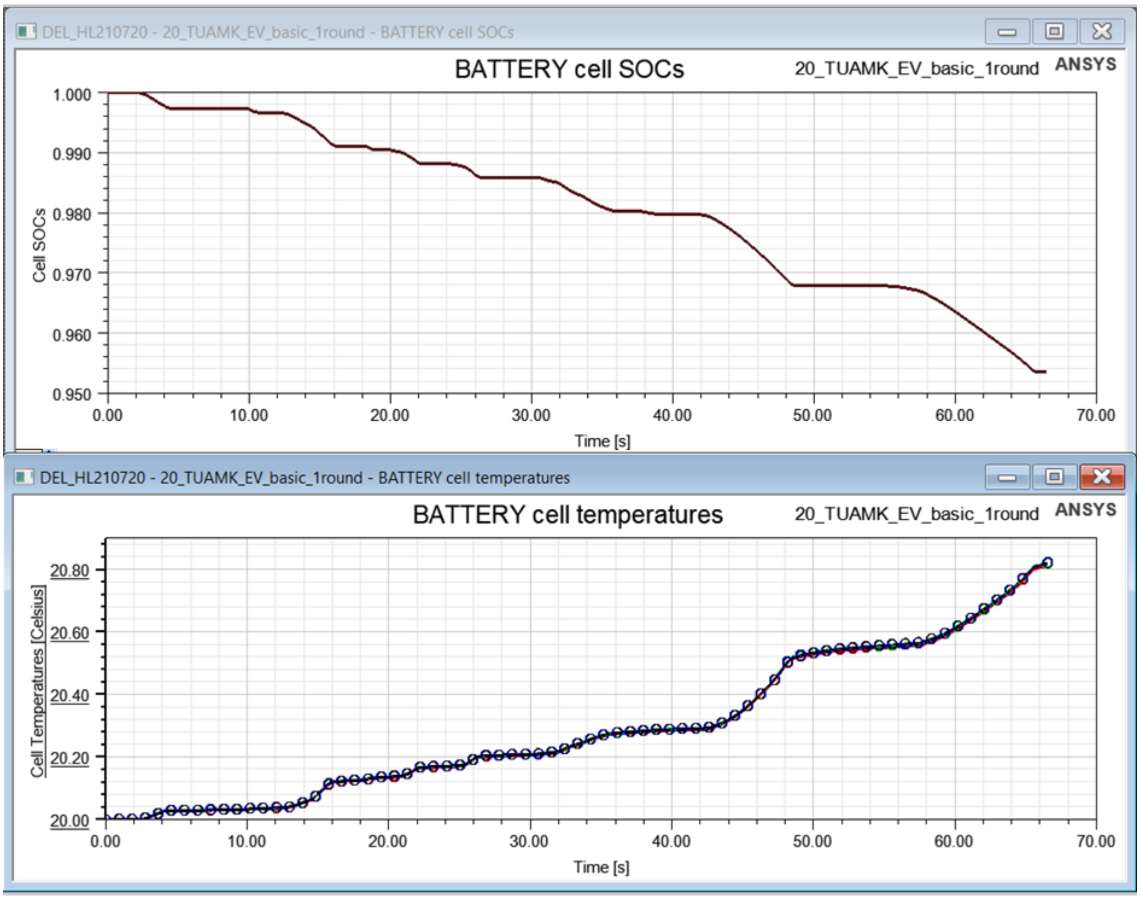


Figure 25. Battery SOCs and cell temperatures as a function of time.

Figure 26 shows how the electric machine output torque and speed matches with the required torque and speed levels. Since the demanded speed is changed to start from standstill position, no higher peak appears at the beginning of the simulation, but a balanced state is reached from the beginning. The electric machine torque plot presents three torque curves, the demanded, machine output and the setting torque. The setting torque corrects the output torque to operate inside the maximum and minimum torque values as a function of speed.

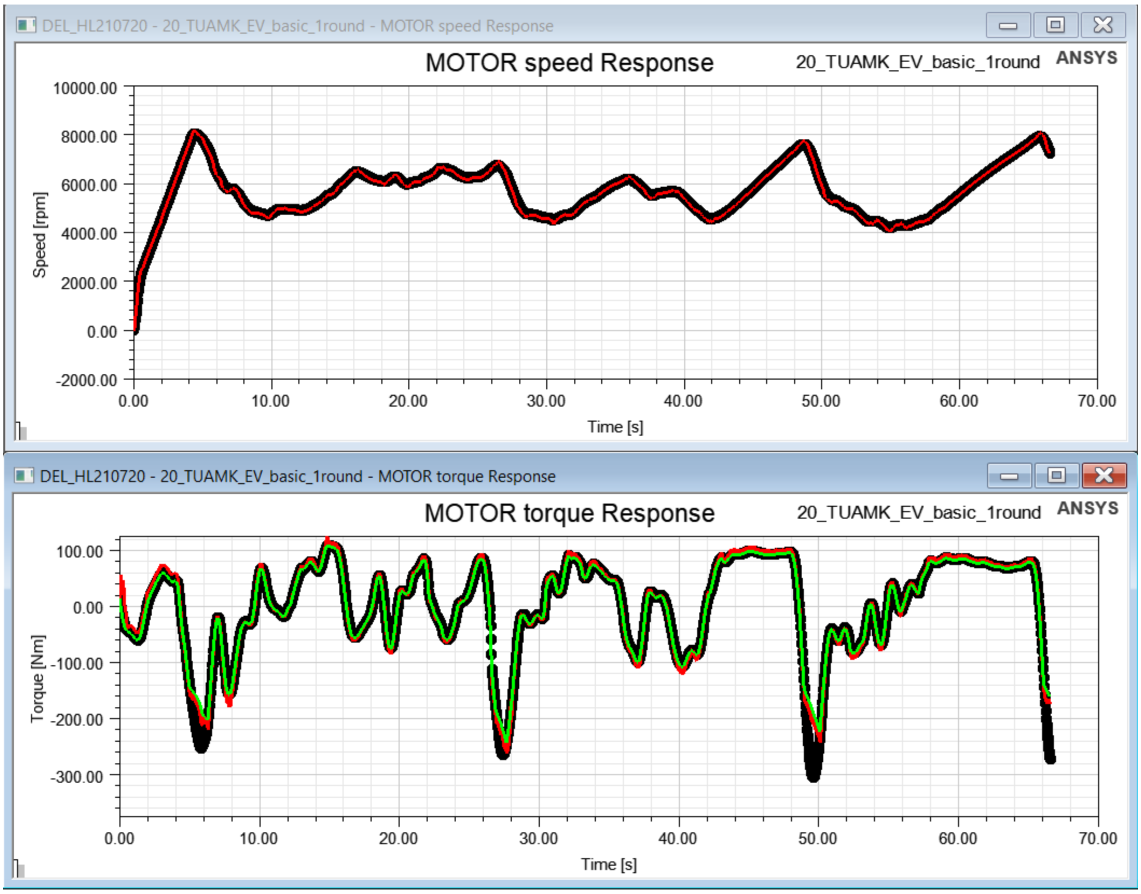


Figure 26. Electric machine speed and torque as a function of time.

The coupled battery and electric machine model simulation time is 53 seconds with a time step of 1 ms. The load drive cycle of the tested model is 66.5 seconds, which represents one lap time of the racetrack. The analysis shows that the simulation time of the system model is close to real-time. The system model time step is chosen in compliance with the used time step of the machine control circuit. Since few of the machine control circuit parameters are not optimized, the change of the time step causes unbalance. Therefore, it is chosen to utilize the determined time step of 1 ms on the system model. That means, that the system model time step cannot be freely chosen with the current system model.

The developed machine control circuit contains a few arbitrary parameters that are not optimized. Therefore, it can be assumed that the machine control circuit may have a weakening impact on the system performance. An optimized control of the electric machine could give better performance of the whole system. For comparison, a simpler electric machine model is developed and tested together with the same battery model. A simpler quasi-static electric machine model can be helpful in terms of component model validation.

Comparison with quasi-static model for electric machine

A simpler electric machine model is developed for comparison. The quasi-static electric machine model is based on look-up tables. The inputs of the model are similar reference drive cycle speed and torque requirements. The efficiency map and the torque and speed limitations are integrated into the model as look-up tables. The output of the model is determined as operation points from the look-up tables. Dynamic delays or effects between the transfer are neglected. The electric machine model is coupled with the battery model via a current source (see Figure 27).

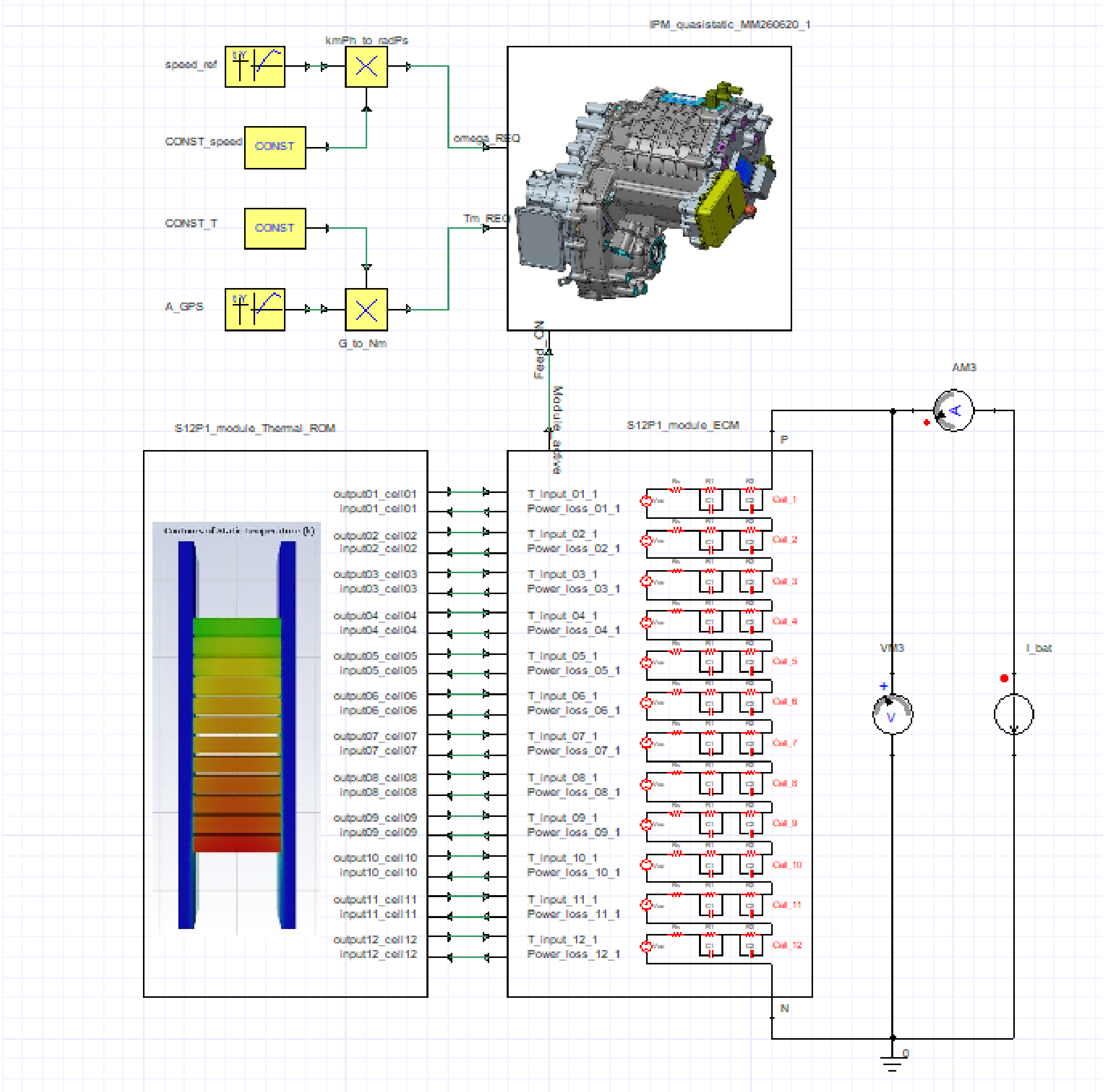


Figure 27. Quasi-static electric machine model coupled with battery model.

Figure 28 demonstrates the cell SOCs and temperatures as a function of time. Figure 28 shows that the cells heat up a little less with the simplified quasi-static electric machine model in comparison to the dynamic electric machine model. The battery output current reaches a bit higher values with the dynamic electric machine model. The battery output current peaks can be a result of delays or transfer effects between different operation points. In that case the simpler system model is not able to catch them.

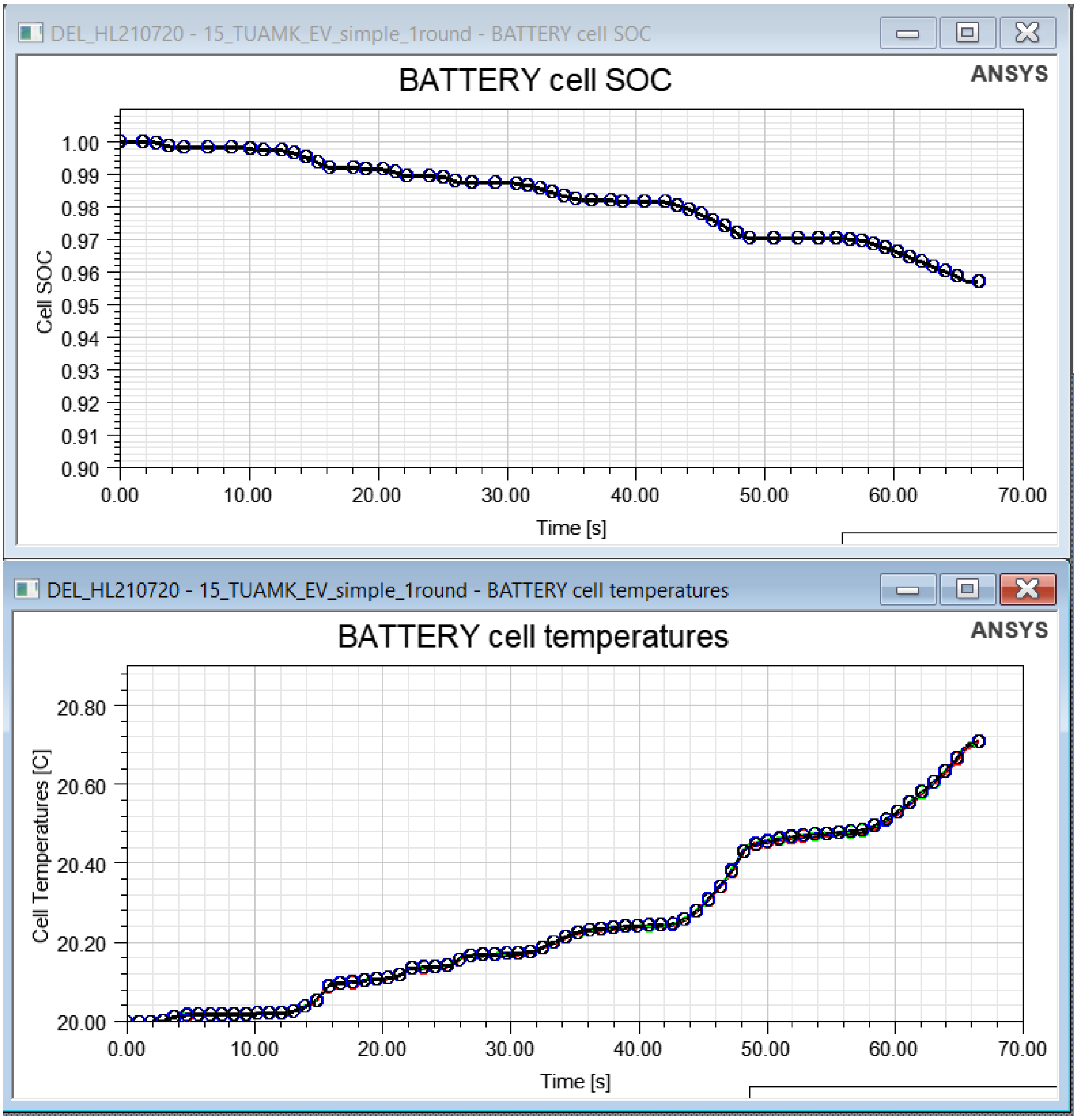


Figure 28. Battery cell SOCs and temperatures as a function of time.

Figure 29 shows speed and torque performance results of the electric machine when using the quasi-static model. The red curves indicate the model output values and the black curves indicate the required speed and torque values according to the reference drive cycle integrated in the system model. The results are very similar to those of the dynamic electric machine model. The system simulation time with the quasi-static electric machine model is 24 seconds with the time step of 1 ms. The analysis shows that the simulation time is half of the actual drive cycle time, which is 66.5 seconds. The simulation time is shorter with the quasi-static electric machine model compared to the

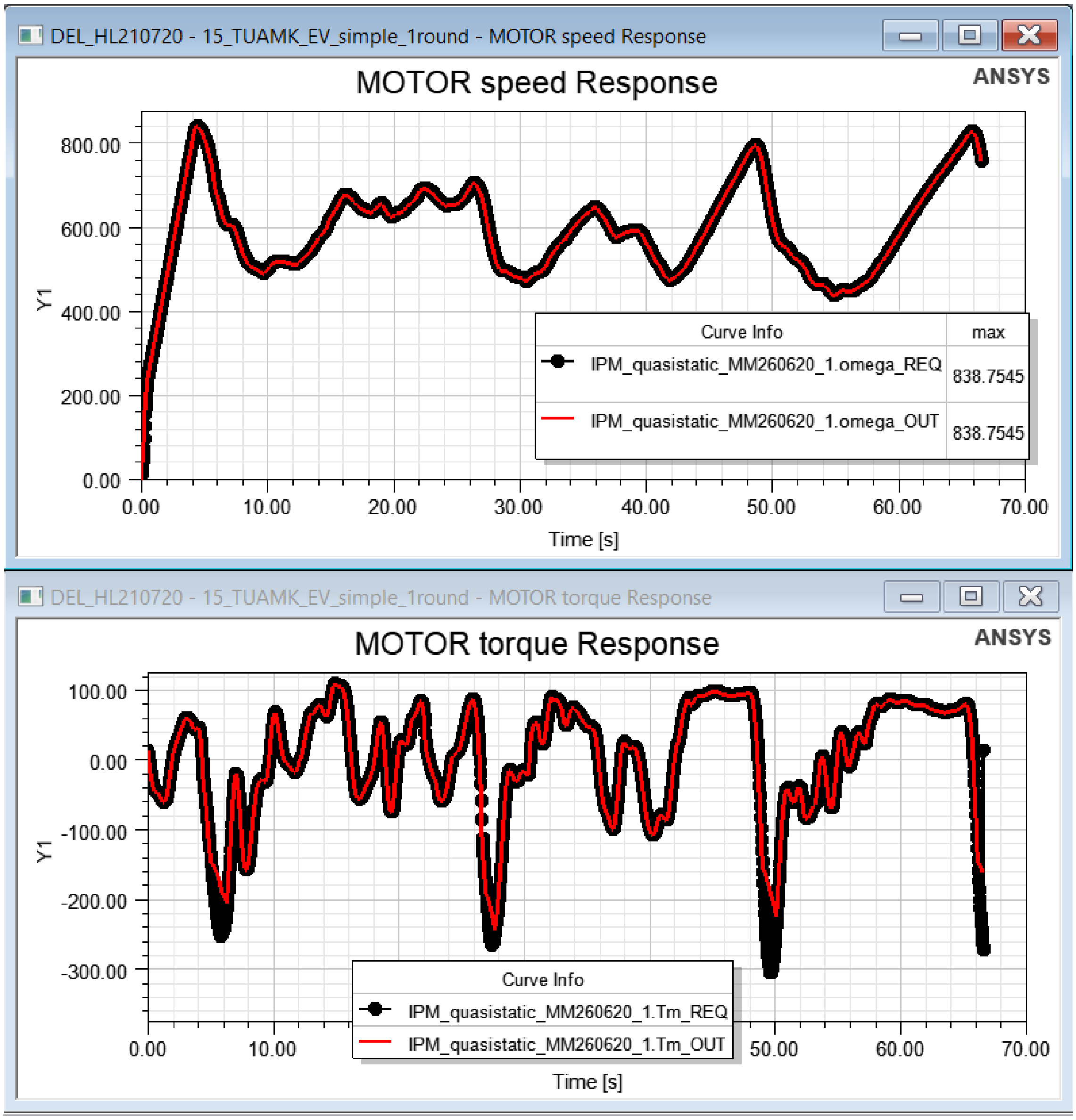


Figure 29. Speed and torque of the electric machine as a function of time, when using quasi-static model.

dynamic electric machine model. An advantage of the quasi-static electric machine model is the adjustability of the time step. The system model remains stable although the time step is changed. By increasing the system model time step the simulation time decreases.

The developed dynamic model for motor is based on commonly used dynamic IPMSM equations. Therefore, it does not necessarily add value for system designers. However, the electric motor is typically designed as a simple quasi-static model in system simulations due to shorter simulation times. In this thesis a dynamic model for motor was developed in order to examine its impact within system simulations.

The results of the comparison between a simpler quasi-static model and the dynamic model for the motor indicated similar torque and speed responses. In order to improve the dynamic model for motor, the main parameters of the model (see Table 1) can be measured and imported to the system model. The dynamic model provided more informative results such as current, voltage and power curves. The control of the model for motor appeared to have a significant impact on the performance. Since the results of both simulation cases are almost similar, the control of the dynamic electric machine is accurate enough for producing realistic results.

6 Conclusions

The following assumptions and findings can be made based on this study. The design and implementation process of the electric powertrain system model has given insight on how to proceed in the future and clarified the future development areas.

The study proves that it is possible to model and simulate complex multi-physics systems. The fidelity of each component model of the system can be determined individually in compliance with the component details available. Component models can meet compatibility requirements in a system within defined parameter ranges.

Table 3 presents the component models developed in this study. The purpose of this study was to find system level modeling and simulation methods for the battery, electric machine and load, and to connect these models into a working system. The component models utilized detailed information available in product datasheets, physical measurements and simulations.

Table 3. Component models developed in this study.

Component	**Model implementation**
Battery	• Electrical ECM based on HPPC cell measurements • Thermal CFD analysis of battery module
Electric machine	• Modelica model based on dynamic equations and efficiency map of the electric machine • SML model of machine control based on equations from a scientific paper
Load	Physical measurements from a driven lap at Hyvinkää race track

The accuracy of the system model is significantly dependent of the system model inputs and the initial information available of system components. In order to achieve accurate detailed 2D and 3D physics simulations, detailed information of the component is required. The required information can originate from the component manufacturer, physical measurements or component tear down and examination. A drawback of the study was the lack of component details from the manufacturers side and the limited amount of physical measurements available for usage. For improving the accuracy of the battery model, temperature dependent cell characterization measurements are required. For improving the electric machine model, the dynamic model parameters can be measured.

The compatibility inside the wide Ansys portfolio is utilized in this study. ROMs of detailed physics simulations integrated into system level is a good example of utilizing multiple software in order to achieve accurate results. The compatibility, however, is profitable also between third-party tools. There are many system simulation software available and the link to those can be established with FMU solutions. Based on this study, the

ROM solution is valuable, and that solution is profitable to export to other third-party software as an FMU. Exportation of the whole system model would not be profitable since the system level modeling does not differ much in between system simulation software.

For achieving the load requirements from a realistic approach, the heat losses effects of the powertrain components must be included and managed in the system simulation. The electric components increase the heat losses and they are a significant factor inside a vehicle. The heating and cooling of an electrified powertrain is a critical issue. Simulations can be a useful tool for examining that since physical measurements can be difficult. Measuring the heating of individual parts inside a rotating machine is challenging.

The ideas for further improving the system model needs to meet the demand from the possible utilizers of the model. The motivation behind the system level simulations of electrified powertrains can be the need for estimation of fuel consumption, energy efficiency or performance against a drive cycle. There are various focus areas between electrified systems. Another challenge of redesigning a powertrain and integrating electric components is the dimensioning of components. The technical implementation that considers the system output focus area and the different dimensioning combinations is complex and involves control. System control is one important aspect that is not included in this study. The goals of optimizing system structure to meet desired system outcome requires smart solutions and control. A simulation platform is suitable for proceeding in that area.

7 Summary

This thesis was done for EDR & Medeso oy. In this thesis the modeling of an electric powertrain is examined. The purpose of the study was to find suitable modeling and simulation methods for powertrain design out of Ansys simulation software portfolio. Powertrain component physics is presented, and the chosen modeling method of those components is explained. Validation of the developed powertrain model is executed.

In Chapter 1 the thesis topic was introduced by discussing the electrification trend and the driving projects behind this study. Chapter 2 provides a short outlook on what system modeling is, who can benefit from it and what role physical measurements play regarding simulations. Limitations of this thesis are considered in Chapter 2.

In Chapter 3 the physics and chemistry behind the main powertrain components – electric motor and battery, are explained. Chapter 4 presented the chosen modeling and simulation methods of Ansys simulation software that are used in this study. Validation of potential software and modeling methods are done.

Cell characterization measurements are discussed and HPPC is chosen. Measurements were executed by TUAS battery laboratory. The measurement results were used in battery modeling. A simple cooling was implemented to the battery module geometry and a thermal CFD model was generated. The electrical and thermal battery module model are coupled at a system level.

In Chapter 5 the final coupling of the battery and electric machine model is presented. The coupled model is validated through a comparison to a coupling with a simpler quasi-static electric machine model.

Challenges that were faced throughout the system model development process involved mainly lack of information about the components to be modeled. That however describes the real-life situation of system integrators very well. The solution for this problem was to initially model the component simplified, but to enable the possible future additions of detailed simulations when they are available.

One weakness of the dynamic electric machine model is the current control implementation. The control contained a combination of variables and coefficients that were affected by the load references. Though, a balanced variable and coefficient combination was found and the performance results are similar to the quasi-static electric machine model.

Physical measurements performed by TUAS were utilized in the modeling and simulation process. The integration of physical measurements added value to the system model. The battery electro-thermal coupled model gives accurate and fast results, which meets the requirements of system modeling.

In this thesis the essential parameters of system-level battery and electric motor modeling are presented. The presented coupled battery and electric machine model demonstrates how the battery pack performance is coupled with the electric machine performance.

Methods and tools for modeling and simulating complex multi-physics systems are presented in the study. The study shows that competence is required for examining different modeling and simulation processes. Different fidelity levels and parameter ranges of the component models can meet compatibility requirements at system level.

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