

THERMAL MANAGEMENT SIMULATION APPROACH FOR PARALLEL HYBRID VEHICLES

Filip Kitanoski¹, Günter Lang¹, Wolfgang Puntigam¹, Christian Kussmann²

¹ The Virtual Vehicle Competence Center GmbH (vif),
8010 Graz, Inffeldgasse 21a/I, Austria

² Magna Steyr Fahrzeugtechnik AG & Co KG
8041 Graz, Liebenauer Hauptstraße 317, Austria

filip.kitanoski@v2c2.at (Filip Kitanoski)

Abstract

The most challenging goals facing the automotive industry are reducing emissions and increasing fuel economy. These requirements are not only imposed by the society, but also by different cooperative agreements and legislative efforts such as the PNGV Program (USA), the ACEA (Europe) commitment to reduction of CO₂ emissions to 120 grams and the California Low Emission Vehicle Legislation.

The hybrid electric vehicles are seen as a solution for reducing of the pollution emissions and for improving of the fuel economy. Beside the conventional cooling system for the engine, the hybrid vehicle needs cooling systems for the electrical drive and the energy storage system as well. The thermal integration of the additional components leads to complex and coupled cooling systems. Therefore, a novel simulation model of the entire thermal management of the hybrid vehicle is required. This paper introduces an approach for the simulation of the vehicle thermal management system in a parallel hybrid vehicle within a comprehensive simulation environment. The hybrid drive train is developed by using a combination of the vehicle dynamics simulation program veDYNA and Matlab/Simulink. The simulation of the cooling system is performed by the 1D simulation program KULI. In order to carry out a comprehensive thermal calculation, a coupled simulation using the independent co-simulation environment tool ICOS is performed.

Keywords: Modeling and Simulation, Thermal Management, Cooling System, Hybrid Vehicle, Co-Simulation

Presenting Author's biography

Filip Kitanoski received the master degree from the Vienna University of Technology, Austria in 2005. Since 2005 he is a junior researcher at The Virtual Vehicle Competence Center GmbH (vif) and his research interests are in the area of the vehicle thermal management systems, as well as modeling, simulation and optimization of the vehicle as an entire system. He also works and has special interests in future ground vehicle propulsion systems.



1 Introduction

Rising demands on performance, fuel consumption, emissions and comfort lead to new power train concepts and complex thermal management systems. Hybrid electric vehicles can meet these demands by using two power sources such as fuel and the stored electrical energy as well. By recovering the kinetic energy during braking or downhill drives and by optimizing the engine operation to maximize fuel economy, hybrid electric vehicles outperform the conventional vehicles.

Regarding the mechanical and the thermal impact, passenger cars are a difficult environment for electrical components. The thermal integration of the electrical drive, the battery, and the power electronics leads to complex and interacting cooling circuits. Beside the cooling system of the internal combustion engine (ICE), the hybrid vehicle needs cooling loops for the electrical drive and for the energy storage as well. Exceeding of the maximum allowed temperature is not permitted. It leads to immediate destruction of the electrical component.

To deal with these issues and to minimize the time and the effort of the vehicle development, numerical simulation tools are deployed. The simulation methods have to fulfil the demands of the comprehensive simulation in order to manage this complex task. The main challenge lies in the consideration of the entire system. Today, the development of the different subsystems (engine, cooling system, gearbox, drive train) is done by using different simulation tools and by different departments of the company or even by diverse suppliers. To reach future targets imposed by the PNGV Program (USA) [1], ACEA (Europe) [2] or the California Low Emission Vehicle Legislation [3] a very early interaction within the virtual vehicle development is necessary. Therefore, a sophisticated method of coupling the different subsystems to an overall system "vehicle" is required.

2 The Simulation Models

In following the models of the power train and the cooling system of the simulated vehicle are discussed.

2.1 The power train

The layout of the power train is shown in Fig. 1. The conventional power train is extended by a traction module for an electrical four wheel drive (E4WD) with longitudinal mounted engine. The integrated module is placed between the combustion engine and the automated gearbox. The

module itself consists of two electrical traction motors (EM1, EM2) and four wet multidisc clutches (C1 – C4). The electrical traction motor EM1 with the implemented clutches C1 and C2 present the parallel hybrid concept and is placed on the engine side. The electrical motor EM2 is located on the gearbox side and is used for the pure electrical driving mode of the front axle.

The ICE, the gear box, the axels, the wheels, the tyres as well as the chassis with the suspension (not shown here) was modeled in the simulation software veDYNA [4].

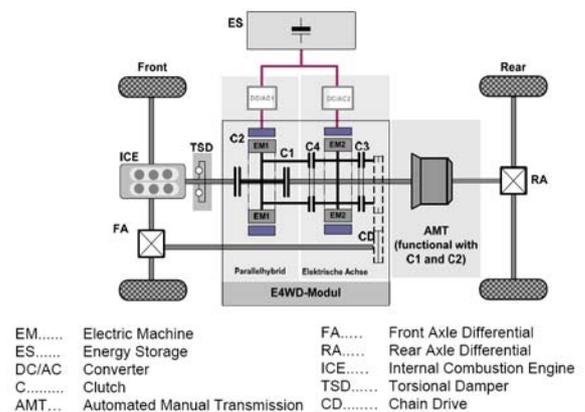


Fig. 1 Drive train of the simulated parallel hybrid vehicle [5]

The veDYNA open model architecture in a Matlab/Simulink environment offers modularity to extend the drive train model by the electrical component models. Standard Simulink interfaces are provided for the external model of the electrical drive. The model of the electrical system consisting of power converters, electrical traction motors, battery, charge / discharge controller is developed using Simulink. The quasistatic model of the electric motors is presented in Fig. 2. The input variables are the torque as well as the speed required at the shaft. The output variable is the electrical power.

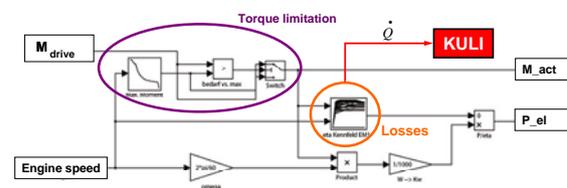


Fig. 2 Electric motor model

A positive value of the power is delivered by the model in motor operating mode. In generator operating mode a negative value is calculated. Those values are handed over to the battery model (Fig. 3). The battery model calculates the battery

state of charge (SOC) which is fed to the hybrid controller. Both models feature stationary map-based calculation of the power losses, which are dissipated to the cooling system. The simulated amount of heat is routed to the thermal model interface. The torque coordination between ICE and the electrical traction motors is controlled by a hybrid drive train controller which is also modeled in Simulink. A simple control strategy for the hybrid vehicle is applied since the principal aim of this paper is to propose a framework for the design and analysis of the interactions between different subsystems of the entire vehicle (in this case for a parallel hybrid vehicle).

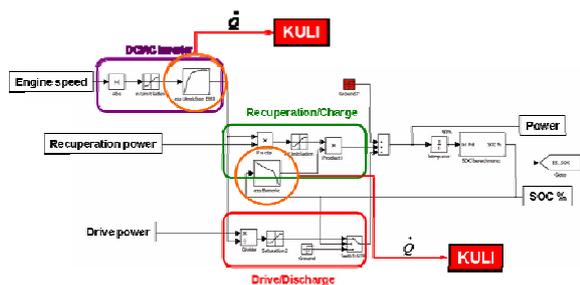


Fig. 3 Battery model

The ICE has to supply the part of the overall traction moment which is not supplied by the electrical drive. The ICE torque (driving and braking mode) is added to the torque of the electrical machines (EM1, EM2) and forwarded directly to the veDYNA model. The calculated total torque is fed to the gear box as external moment.

2.2 The cooling System

The layout of the new cooling system depends on the thermal requirements of the additional electric components for the hybrid vehicle which are heat sources and need to be cooled. The different thermal conditions of the ICE and the electrical components require separate cooling circuits. The temperature level of the ICE cooling circuit is roughly at 95°C, the one of the cooling circuit for the electrical system has an upper limit of 75°C.

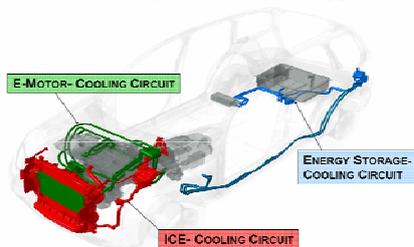


Fig. 4 The cooling system of the HySUV

The performance as well as the life-cycle costs of hybrid vehicles depends mainly on the performance and durability of the battery packs. Each battery operates over a narrow operating range to achieve

optimum durability and performance. For example the desired operating temperature for a Li-Ion battery is 25°C to 40°C [6].

For the vehicle described here, two additional cooling systems were developed:

- The electrical drive cooling circuit for the electrical machines and the power electronics
- The energy storage cooling circuit for the battery

The cooling circuit of the ICE was not modified. The battery cooling circuit is coupled to the HVAC-system which can serve as heat sink even at high ambient conditions. Besides the hoses and valves, two additional electric water pumps, one additional radiator and one coolant / refrigerant heat exchanger were applied to the baseline system. To ensure cold start capabilities, also an auxiliary heater was applied to the battery coolant circuit. These extensions require a new cooling strategy and the thermal management has to be adapted from the base vehicle. The cooling systems are simulated with the 1D simulation tool KULI [7]. Within this simulation tool, the temperatures of the structure, temperatures in the coolant circuits (water, oil) as well as on the air side of the heat exchangers (air path) can be calculated. The model consists of three partial systems:

- Cooling circuit of the internal combustion engine
- Cooling circuit of the electric machines
- Battery cooling circuit

In the following section only the cooling loop of the electrical components (Fig. 6) is described. To achieve lowest possible temperature for the power electronics the coolant is fed first to the inverter. The two electrical traction motors are passed in serial by the coolant. The focus of the thermal model was to simulate the temperatures of the different components like converter and copper coil even under transient conditions. The modeling of the structure of the components is based on the lumped parameter approach. Each component is described by two lumped masses describing the transient thermal behavior. The heat transfer coefficients between the single components and the coolant had to be adjusted by means of measured data (Fig. 5).

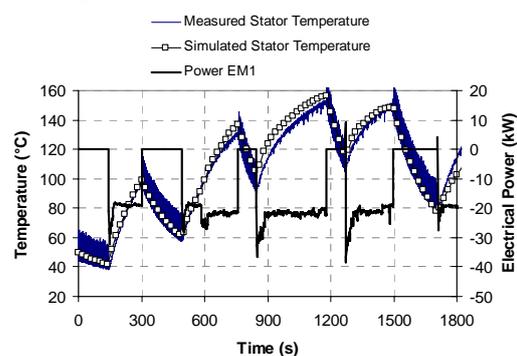


Fig. 5 Simulated vs. measured stator temperature

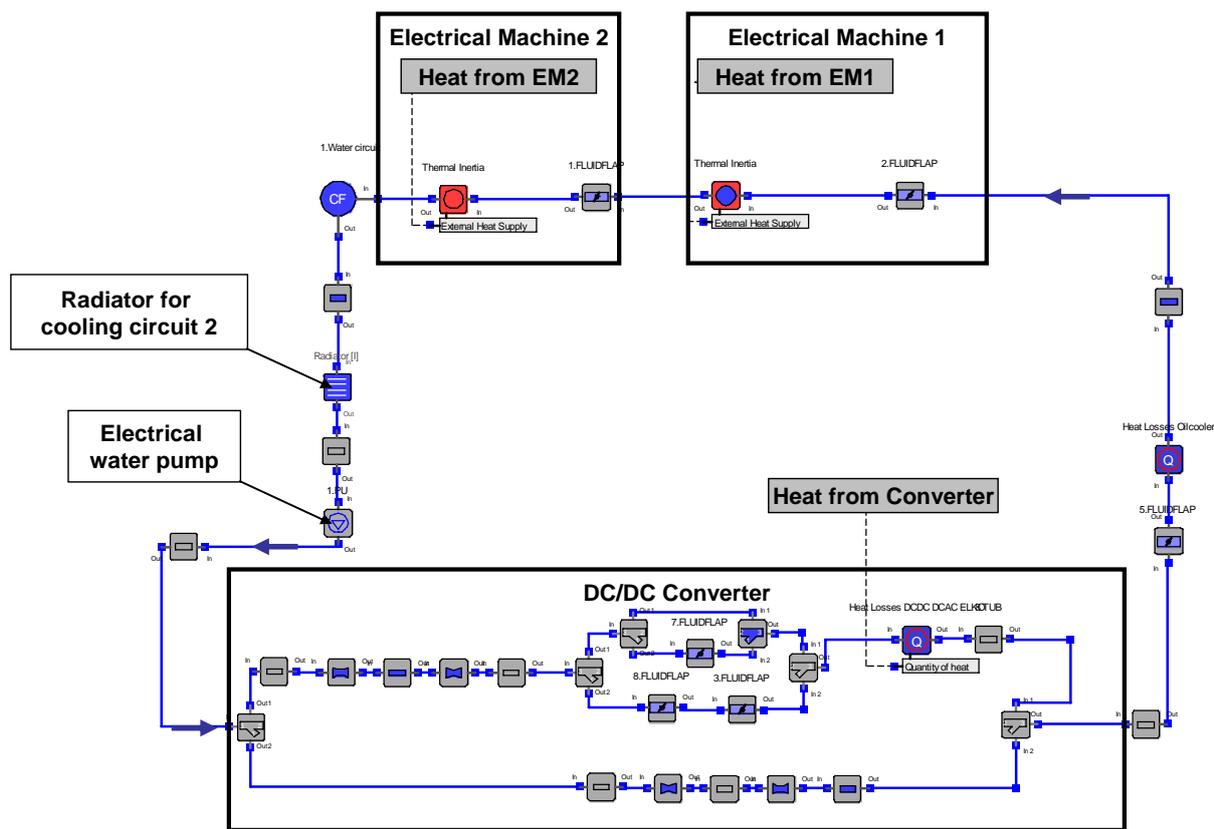


Fig. 6 Simulation model of the cooling circuit for the electrical components (simplified)

The physical parameters of the components (electrical traction motors, inverters, battery, etc.) like mass and heat capacity were set according to supplier's information. Using ICOS over the COM interface, the lumped masses in KULI are fed with the amount of heat from the electrical system modeled in Simulink. The heat is rejected to the coolant and then to the ambient air in the radiator, which is installed upstream of the condenser and the radiator of the ICE in the cooling package. The pressure losses of the whole system were carefully adjusted to measured values in order to reproduce the correct volumetric flow rates in the single branches.

3 The coupling process

To consider the interaction of the different systems within the entire vehicle the subsystems must be coupled together. The coupling of the different subsystems is performed with the connection of the physical parameters (power and heat flows) which are exchanged between them. The observance of the interaction between the different subsystems is ensured by the time dependent data exchange performed by the independent co-simulation environment ICOS [8]. In order to provide a time dependent and flexible data exchange between the

different subsystems modeled in different simulation tools in respect to the exchange of physical variables ICOS is used. The design of the independent co-simulation environment consists of three different layers.

- **Application Layer:** The application layer is the first layer. The diverse models of the subsystems modelled in different programs are included there.
- **Wrapper Layer:** The wrapper layer is a kind of translation layer between the simulation program's specific interface and the global interface specification. The wrapper is related to the specification of the application programmer's interface (API) defined by the simulation program. The wrapper of each program which can be regarded as a kind of ambassador allows the programs to communicate with other programs very easily via the communication layer (like "plug and play"). The wrapper is the only program unit which must be adapted, if the API specific for the simulation program changes.
- **Co-Simulation Layer:** The co-simulation layer is a kind of independent control unit of the coupling process. Within the Co-simulation layer different coupling

algorithms can be used. It also guarantees the conservative exchange of physical data between the subsystems to ensure conservation laws during the transient coupling process.

With the layer structure of the independent co-simulation platform ICOS (Fig. 7), the simulation programs can be coupled on different computer platform and operating systems. On a programming level, the definition of the input and output parameters and the time triggered ‘send’ and ‘receive’ of the parameters are defined by five basic communication functions. These basic functions are oriented on solving linear equation systems and are called within the wrapper:

- MTS_VAR_DEF {variable, IN/OUT, unit, boundaries, initial}
- MTS_VAR_PUBLISH {ip-adress, port}
- MTS_VAR_GET {variable, time stamp}
- MTS_VAR_PUSH {variable, data array, time stamp}
- MTS_VAR_SIM {ip-adress, port}

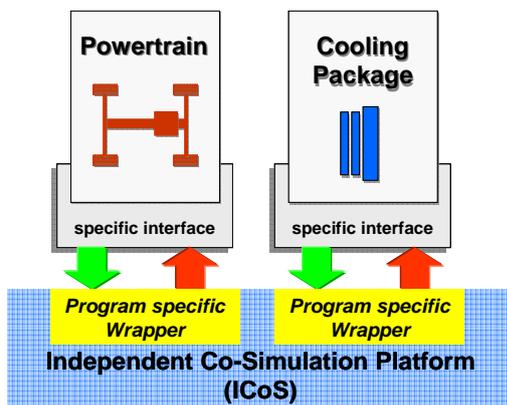


Fig. 7 Layer approach for an independent co-simulations Environment

A key issue of the independent coupling approach is the time depended synchronization process. This process allows simulation programs with different time step lengths to participate a comprehensive simulation task. The time management and synchronization processes are based on the layer structure in Fig. 7 and the five basic communication functions. To realize the synchronization process, the different time loops (integration loops) of the different simulation programs are controlled from the outside via the API (within the wrapper program). The coupling process between the simulation programs is performed on the integration level of the various simulation programs.

4 Simulation and results

The results of a simulation run using the simulation approach introduced above for the New European

Driving Cycle (NEDC) are discussed next. The NEDC is the legislative driving cycle for passenger cars in Europe, and is used to assess the emission level and the fuel consumption of passenger cars. The New European Driving Cycle consists of four repeated Urban Driving Cycle UDC (UDC) and one Extra Urban Driving Cycle (EUDC).

The parameters that are defining the relations between the two subsystems are shown in Fig. 8. Based on the parameter definition in ICOS, physical values are exchanged in a time dependent way during the coupling process.

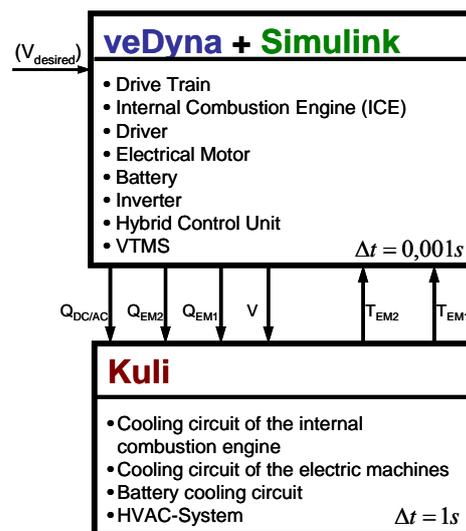


Fig. 8 Parameter flow

Fig. 9 shows the parallel simulation scheme. During the first nine seconds of the simulation both programs are performing their start up process. After the models are loaded, the wrapper sets the GetStatus Variable. Each calculation step for both programs has a common start point (parallel simulation mode). The initialization of KULI occurs just after the start of the simulation. The first calculation step of KULI (Fig. 9) is the initialization process.

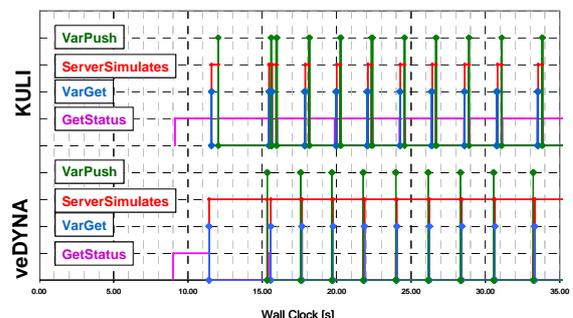


Fig. 9 Parallel time synchronization scheme

At the end of this step the physical simulation time of KULI is zero. The independent Co-Simulation environment ICOS notices the actual physical simulation time of both programs and after the calculation of the first step in veDYNA, ICOS synchronizes the both programs. ICOS starts the next simulation step for both programs once their physical simulation time is synchronized. Thus a parallel simulation is ensured. The end point on the wall clock scale of each calculation step depends on the duration of the simulation for one time step (the different simulation tools have different duration on the wall clock scale for equal physical simulation time step).

In Fig. 10 the simulation times of each application are presented. It can be figured out that 83% of the overall calculation time is consumed by veDYNA. If the co-simulation is run on a single computer platform the CPU time is shared between the two tasks. Thus, up to 17% of the simulation time could be saved by running the two simulation programs on different computer platforms.

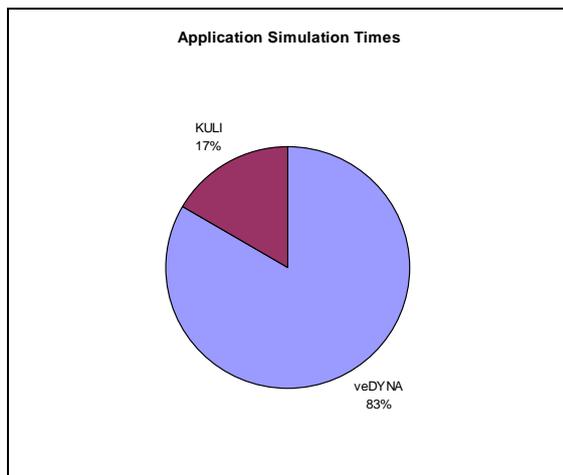


Fig. 10 Share of application simulation times

In Fig. 11 the calculated powers of the engine and the traction motor EM1 are shown. At the beginning of the cycle the state of charge (SOC) of the battery is 80% of the nominal charge. The hybrid vehicle uses only the electrical drive until the battery reaches the lower SOC limit of 65%. As soon as the limit is reached the hybrid control unit switches off the electrical power and the hybrid vehicle drives using the ICE solely. During the braking phases the traction motors are switched to generator mode and use the recuperated brake energy for charging the battery.

As result of the comprehensive thermal simulation the transient behavior of the coil temperature and the structural temperature of the traction motors during the NEDC are illustrated in following (Fig. 12). Due to the small thermal inertia the stator temperature has that particular temperature evolution for the NEDC. The rest of the

components and the structure of the EM1 are modeled as one mass.

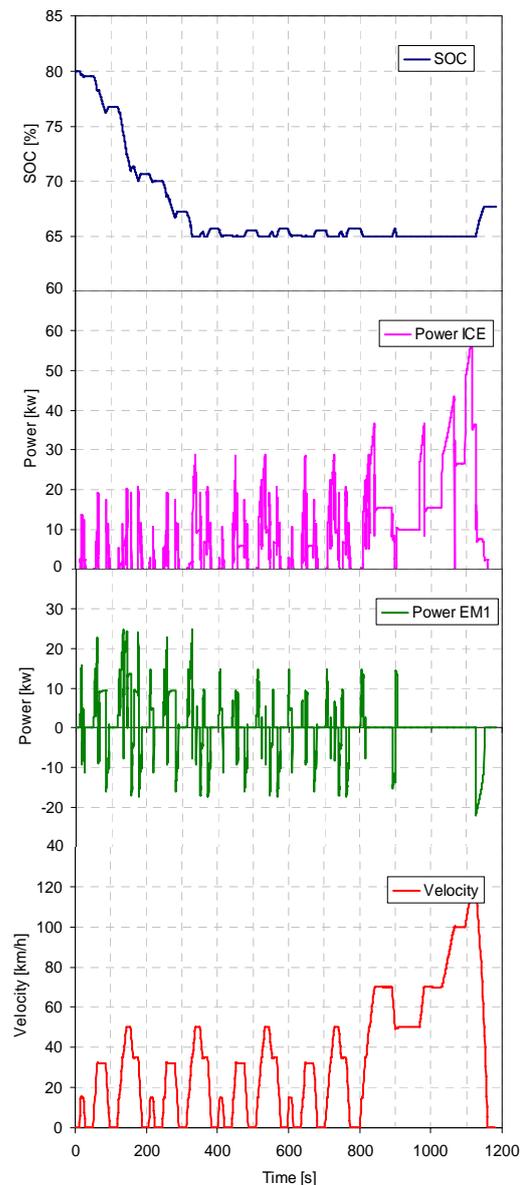


Fig. 11 Power of the EM1 and ICE in NEDC

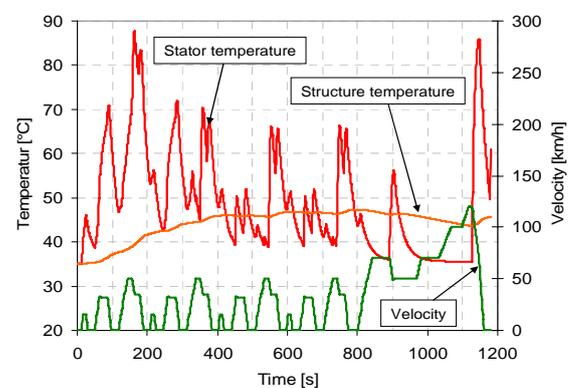


Fig. 12 Evolution of the temperature of the lumped masses

More detailed discretization is required if one is interested in the temperature of the different components of the traction motors (rotor, stator, coil, structure etc.).

5 Summary and outlook

Without the consideration of all relevant subsystems of the vehicle an efficient energy management is not possible. A framework for the design and analysis of complex coupled systems is proposed. Utilizing the approach described here the developers can achieve an overview of the energy flows within the entire vehicle. Using the models and the methodology of a comprehensive simulation, both steady-state as well as transient simulations of the thermal system, the drive train and their interaction can be performed. The simulation can be extended by additional programs for the calculation of the gas exchange process in the ICE, electrical components, gearboxes, air conditioning system etc. Furthermore simulation programs different as the ones applied here can be implemented in ICOS for the calculation of the drive train just like for the calculation of the coolant loops.

6 Acknowledgments

The authors wish to thank K plus Kompetenzzentren-Programm of the Austrian Federal Ministry for Transport, Innovation, and Technology (BMVIT), Technologie Impulse Gesellschaft (TIG), Das Land Steiermark and die steirische Wirtschaftsförderung (SFG) for their financial support. Additionally we like to thank the supporting company MAGNA Steyr Fahrzeugtechnik AG & CoKG.

7 References

- [1] U.S. department of Commerce. PNGV Program Plan. U.S. department of Commerce, Washington, DC, revised Nov. 29, 1995, p. ES-2
- [2] <http://www.acea.be>
- [3] California Air Resources Board. Low emission vehicle LEV II program. <http://www.arb.ca.gov/msprog/levprog/levprog.htm>
- [4] TESIS DYNAware. veDYNA User Manual. TESIS DYNAware Technische Simulation Dynamischer Systeme GmbH, 2007
- [5] A. Schmidhofer, J. Starzinger, G. Teuschl, F. Zöhrer, V. Hartmann: Powertrain Hybridisation of a Full-Size SUV—Development and Validation of a Multi-Functional E-4WD Traction Module. Conference New Electrical

- Drive Concepts for Hybrid Vehicles, Munich, Germany, March 20–21, 2007
- [6] C. A. Rosenkranz, U. Köhler, J-L Liska: Battery Systems for the Growing and Diversified Hybrid Electric Vehicle Market, Tagung Neue elektrische Antriebskonzepte für Hybridfahrzeuge, Haus der Technik, München. March 20 2007.
- [7] ECS - Magna Steyr; KULI Brief Description, MAGNA Powertrain, Engineering Center Steyr GmbH & Co KG, 2006
- [8] W. Puntigam, J. Balic, R. Almbauer, J. Hager. Transient Co-Simulation of Comprehensive Vehicle Models by Time Dependent Coupling. *SAE Technical Paper*, SAE World Congress 2006, Detroit, MI, USA