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## ASTERICS – advanced simulation models and accelerated testing for the development of electric vehicles

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### Abstract

The development of Electric Vehicles (EV's), either fully electric (BEV...battery electric vehicle) or different hybrids (like HEV... hybrid electric vehicles or PHEV...plug-in hybrids), is an undeniable prerequisite to fulfill the worldwide emission targets for transport even within the next 10-15 years. The conventional development methods and tools on the other hand, are so far only optimized for the development of vehicles with ICE engines only and not well designed to develop EV's at all. To close this gap, the research in ASTERICS is focused on simulation and testing methods as well as tools that enable the optimal, cost efficient and safe development of EV's. Realistic driving cycles for e-vehicles, models for e-components, test procedures, test equipment and tools as well as system simulation and evaluation have been investigated in , which lasted 3 years (Oct. 2012 – Sept. 2015) and involved 10 partners (OEM: CRV, Volvo; Supplier: AVL, Siemens SAS/SISW, Thien eDrives, GustavKlein; Research: see above).

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## 1. Introduction

The design and development process of next generation EV's requires accurate, real-time capable models of all electric components that are simulated together with the vehicle to assess the fulfillment of performance, durability and safety requirements. The co-simulation of models from different vendors is often needed or rather a big advantage, when the goal is to assemble the best component models one can get.

The involvement of high accurate simulation models with higher levels of details can help to enhance e-component development throughout all stages in the e-powertrain design process. Methodologies for e-powertrain modeling considering multi-physics including thermal and ageing effects have been investigated and developed in the ASTERICS project. Therefore the topics of research in ASTERICS were the following:

- Realistic driving conditions for EV's, to assess the performance and durability requirements. Different vehicles have been equipped with devices to collect and analyze typical EV's usage scenarios (see chapter 2 for details).
- Chapter 3 introduces the results concerning modelling batteries, e-motors and inverters, which include modelling electrical, thermal and degradation behavior over the life-time of components. Several detailed models and variants (battery, PMSM, SRM, IM, ...) have been generated and validated in the course of this project.
- In chapter 4 test procedures, test equipment and tools to create and validate models and verify the EV's performance, durability and safety parameters are described. A thorough investigation into appropriate testing methods and improved test equipment for e-components has been done.
- Finally in chapter 5 co-simulation capabilities to connect and simulate models of different vendors in parallel, even in combination with real components in HiL-(Hardware in the Loop) or XiL-(Powertrain in the Loop) environments were subject of work. Different project partners have integrated and co-simulated their models in their specific vehicle simulation environments. With this platform assessments, evaluations of applications and comparisons have been performed.

## 2. Realistic driving conditions for EV's

A driving cycle can be considered as a standardized procedure to evaluate vehicle performance in a reproducible way under laboratory conditions, such as simulation environment, power-adsorbing chassis dynamometer and/or testbeds. A test procedure has to include a time-vehicle speed signal and a large set of boundary conditions. EVs are characterized by specific, "new" criticalities in comparison to conventional vehicles, such as the possibility of energy recovery during braking, the limited range, which could determine the so-called "range anxiety" phenomena and a different "drivability" and perception of vehicle performances.

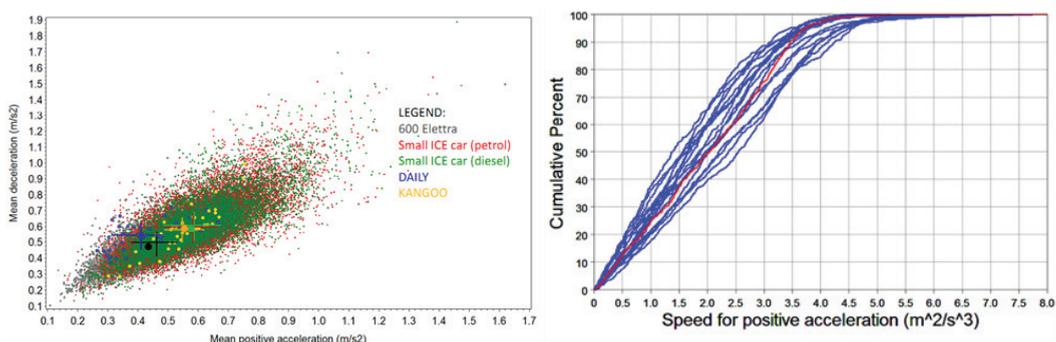


Fig. 1: (a) Comparison of typical EV-usage with ICE-usage; (b) Cumulative distribution of kinematic parameters example.

A large number of cycles (about 150) are available for vehicle type approval and within scientific literature, but only few have been specifically built up for EVs. Within ASTERICS data was acquired for many vehicles, analyzed

and synthesized into representative driving cycles adapting the major indications of common synthesis procedures (see Bishop et al., 2012), in order to cover various use conditions for electric/hybrid vehicles and components. The methodology includes:

- Subdivision of each “trip” into “kinematic sequences” (e.g. from stop to stop)
- Analysis and grouping of “kinematic sequences” using common indicators (e.g. mean positive acceleration, average speed, number of stop per km – up to 40 parameters are described in literature, see Figure 1 (a) and (b))
- Creation of synthetic cycles as a succession of representative sequences (e.g. through “random walk” approach driven by Speed-Acceleration-Probability-Matrix)

### 2.1. Case studies: Turin - light vehicle, Lyon - heavy vehicle, Florence - light vehicles

The data acquisition in the city of Turin has been performed using a Light-Delivery-Vehicle (Iveco Daily, under 3.5t) running over a predetermined route comprehending urban, extra urban and mixed urban roads, in order to explore different conditions. The mass loaded on the vehicle was varied on two levels. The cycle obtained is representative for light van driving condition in urban context, and is represented in Figure 2(a).

Data acquisition in the city of Lyon has been performed with a Heavy Vehicle (Volvo Premium Hybrid, equipped with an innovative hybrid powertrain, over 10t – GVW 19.2t) in real condition in the area of Lyon city. Due to the high mass of the vehicle, significantly different values for common indicators have been found in comparison with lighter ones (Figure 2(b)).

The data acquisition in the city of Florence was done with three different types of vehicles, Renault Kangoo ZE, a light delivery (M1 class), Renault Twizy, a quadricycle of L7 class and Peugeot iOn, a passenger car of N1 class.

According to different characteristics of the vehicles, the synthesis procedure has been applied on filtered datasets in order to generate different cycles for categories such as, representative “average” electric vehicle, small class passenger vehicle, light delivery vehicle, low powered vehicles and most “unsteady” sequences. For each category, two different distances – “long” (95th percentile trip distance) and “mean” (mean distance excluding extra-urban phases) – have been calculated. This analysis forms 10 ASTERICS driving cycles. Figure 2(c) shows the result for an “unsteady long” cycle, which has been calculated and further used for the creation of current profiles for battery testing in this project.

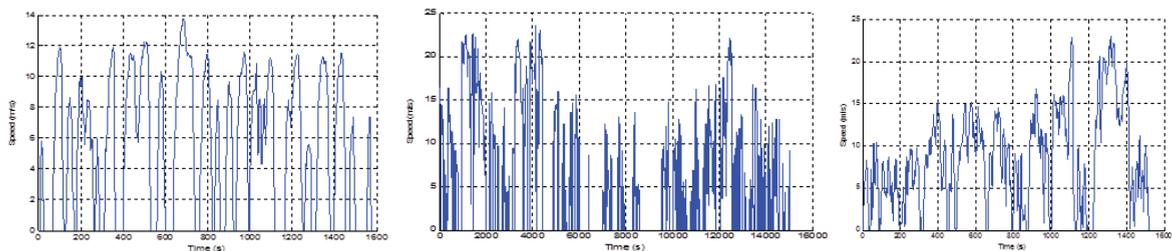


Fig. 2. Driving cycle, (a) obtained from Turin case study (b) Volvo Case study (c) “Unsteady” cycle from Florence case study.

### 2.2. Driving data management

In order to overcome the limitations of “fixed” representative cycles, the creation of pseudo-random cycles for vehicle testing activities has been applied in recent researches (Schwarzer and Ghorbani, 2013; Souffran et al., 2012). Such data can be used during testing (e.g. or SIL/MIL/HIL environment) or for preparation of vehicle energy management strategies, usually verified over a large number of use cases. A tool for the recombination of measured driving data has been developed; it is particularly suitable for batch simulation activities, offering multiple inputs aimed to represent real driving style variability.

Different driving cycles have been generated thereof and used in this project depending on the vehicle application (see also chapter 5).

### 3. Best of class models for battery, e-motor and inverter

E-component models for battery, inverter and e-motor are a substantial prerequisite for the intelligent design and layout of the e-powertrain in electric or hybrid vehicles. Not only the exact model of the steady state behavior is needed, but also the dynamic behavior and lifetime degradation effects are of high importance. The following chapters give an overview and some insight into the complexity of the modelling activities as well as results that have been reached in the ASTERICS projects. The models are capable of modelling electric, thermal and degradation behavior over the life-time of components. Several detailed models and variants (battery, PMSM, SRM, IM, etc.) have been generated and validated in the course of this project.

#### 3.1. Battery Models

In the project, two different approaches have been investigated: an equivalent circuit model approach, and a semi-empirical electro-thermal model approach based on the theoretical background of Shepherd. The purpose for developing the ASTERICS electrical battery model has been to provide a smart battery simulation model with easily adjustable parametrization for the use in dynamic load cycle simulations, taking ageing of the battery cell into account. The model is built on empirical data from accelerated ageing testing of a Li-ion battery cell (LG Chem 41 Ah, NMC blend).

The user defined inputs and model outputs are current, temperature, SOC (State of Charge), SOH (State of Health) and pack configuration, and voltage, power loss, SOC and SOH as output. The SOH describes the ageing status of the cells, which is reflected by reduced capacity, higher impedance and lower energy throughput respectively. There is also the possibility to tune some of the physical parameters of the model related to ageing, energy throughput, internal resistance, and SOC window which enables the simulation of different battery types and driving cycles.

The battery model is based on a dynamic battery cell model, reflecting the cell performance at BOL. In order to take ageing into account, a separate simulation block sets ageing conditions of the original battery cell characteristics in relation to the number of cycles and SOH. The comparison of experimental data and results of both models (the Shepherd and the equivalent circuit model) is presented in Figure 3(a). One can notice that the trends of both simulated voltage curves coincide well with the experimental data over the entire analyzed interval.

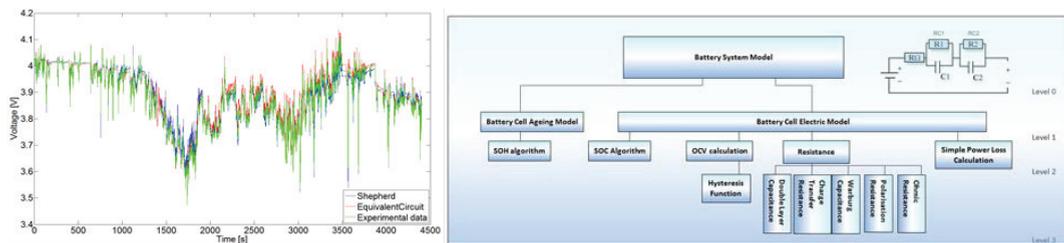


Fig. 3 (a) Comparison of the experimental data to the results of the Shepherd and the equivalent circuit model calibrated with experimental data (b) Block diagram of battery model.

During operation the battery pack generates heat. It is well known that besides electrical parameters, cell temperature decisively influences battery performance and aging. Therefore a cooling system that efficiently dissipates generated heat is of importance for ensuring high performance of the battery pack and in particular its longevity. Combining the electrical model with a thermal model is therefore essential. This model behavior is implemented in the AVL software tools FIRE and CruiseM.

#### 3.2. Inverter Modelling

Development of inverters used for the automotive environment requires adaptations to the conventional inverter design process. State of the art component models operate at very low time scales as they have to resolve the switching pattern of the inverter. They reach high accuracy in power loss assessment, which is the basis for efficiency analysis of this component. Due to their computational effort these models cannot be used in system analysis.

System simulation tools use data map based inverter models that are sufficiently accurate for vehicle efficiency and cooling layout simulation but lack the level of detail needed for ageing investigations, which is caused mainly by thermal stress of the power electronic elements is a key factor for ageing. Hence, more detailed models must resolve the power electronic elements of the inverter and provide localized temperatures. Simulation effort has to be acceptable for driving cycle analysis of several minutes real time or more.

Two approaches for loss power evaluation were identified using input data from manufacturers. The averaged model considers the vast majority of losses in common operation conditions. The switched model additionally considers the impact of current ripple on losses. This is relevant for customized torque controllers or turndown operation at high speeds. The power loss information serves as input for a thermal inverter model that is fed back to the temperature dependent parameters of the electric inverter model.

### 3.3. E-Motor modelling

For automotive applications, an electric powertrain must comply mission profiles constraints for integration, efficiency, power density, weight and cost targets. Electric motors in automotive applications experience transients at very high-speed. Accurate electric motor dynamic models are needed to improve the performance and accelerate the industrial development process. Depending on the system simulation needs, high frequency (short timescale and high accuracy) simulation models up to high level simulation models (long timescale, typically for full driving cycles) are needed. The research addressed the main basic electric motor technologies available: Permanent Magnet Synchronous Machines (PMSM), Induction Machines (IM) and Switched reluctance Machines (SRM). The studies all follow the same scheme: electro-magneto-mechanical modelling, magnetic losses modelling, loss of lifetime or degradation or ageing (when applicable) evaluation, parameterization methodology and validation.

For PMSM, a new methodology was developed to calculate iron losses and induced eddy current losses in permanent magnets using a combination of analytical approach and magneto-static finite element calculation. Demagnetization in PMSM due to increased temperature was also evaluated.

A new IM model describing electric, magnetic, mechanic, thermic and ageing behavior was developed. The thermal model is based on lumped circuit theory. The temperature distribution as output of thermal model feeds back to the electro-mechanic model to calculate proper values for temperature dependent stator and rotor winding resistances. An ageing model shows loss of life-time depending on winding temperature distribution. A new method to calculate the induction machine parameters covering the nominal shaft power from 5 kW to 100 kW was established and tested and showed little differences between modelled results and measured quantities.

Switched Reluctance motor was studied using 2 complementary approaches. Reluctance network has proven to be a good compromise between the Finite Element method and analytical calculation regarding simulation speed and accuracy of the results. This method was validated on a first design both on static and dynamic operation. The accuracy of the SRM model was further improved using a co-energy based approach accounting for coupling between the phases. The workflow for generating these SRM-models is shown in Figure 4.

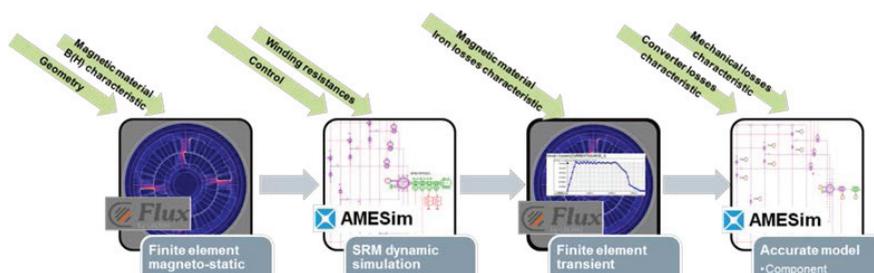


Fig. 3. Workflow of model generation for e-motors, e.g. SRM-engine.

## 4. Test procedures, test equipment and tools to create and validate models and verify the EV's performance

Testing is often seen as an activity carried out at the end of the development process to finally validate the functional and safety requirements of a given system. Due to the need of agile development processes this paradigm has changed and testing happens meanwhile in all phases of the development process, starting in virtual model

environments, further in HiL and XiL environments. In order to validate and verify the EV performance, durability and safety parameters over the entire life-cycle, a thorough investigation into appropriate testing methods and improved test equipment for e-components has been done in the ASTERICS project.

#### 4.1. Battery testing

Cell Testing is the basis for understanding the cell behavior. Beside cell data sheets and safety specification sheets, the standardized test procedures developed in the project allow a benchmark of different cell chemistries on the one hand, and allow the fitting of simulation models on the other hand. In ageing tests the adaption of certain test parameters may be needed in order to respect the changes in the physical properties of the battery and to enable to detect ageing trends that depend on single stress factors. To not make an adaption of test parameters to respect the ageing of the cell may result in ageing effects that depend on multiple and combined stress factors. Since the purpose with testing is to enhance the knowledge about the cell that can be applied in prediction and modelling, there is a clear benefit if at least the stress factor is kept under control. EIS and DC (direct current) tests performed along with the cycling have provided empirical data of how the cell performs at some different temperatures, SOC-levels and Charging-rates. The performance in terms of power and available capacity can in turn be related to the impedance of the cell. This data is taken as basis for model calibration for the thermo-electrical models.

Test methods which were defined in the project consider feedback loops for automated adaptive testing of battery cells over life-time. The consideration of changing limits for e.g. c-rates and cell-limits reduces failures and test time as well as cost intensive test interruptions and stand still times. In terms of the formulated project objectives of ASTERICS this contributes significantly to the envisaged reduced testing time.

#### 4.2. Inverter testing

Inverter testing in the ASTERICS project focused on the generation of test data to validate the inverter models. The inverter was tested together with the real e-motor on the e-motor testbed. The behavior of the battery was emulated through a battery emulator that used the generated battery models. The measurement procedure was carried out in following sequence:

- In the basic characterization of the system, all relevant sensors were calibrated, idle runs were executed, electrical and mechanical angles were synchronized, and the AVL xEV box (fast data acquisition system) was calibrated.
- For vibration analysis, surface velocity measurements were carried out, using ten 1D acceleration sensors (8 on the machine, 1 on the inverter, 1 unattached as reference). Velocity levels were measured at 4 stationary operation points with different speed and load configurations in thermal equilibrium, with parallel measurement of electrical quantities.
- For power flow analysis, dynamic electric measurements for power loss assessment at different speed and load configurations at constant DC voltage were executed in stationary motoric operation. Additional measurements were executed at reduced DC-link voltage for inverter behavior assessment without entering field weakening.
- For thermal analysis, thermal equilibrium response at different speed and load configurations was measured in stationary operation plus cooling down into cold in transient resolution. Measurement with high dynamic resolution at thermally stationary condition was executed, followed by a measurement of the electro-motive force with inverter shut down time resolved measurements quantities for voltage, current, speed and torque were taken for model validation.

#### 4.3. Test procedures for e-Motors

The striving for environmentally more benign transportation has led to invigorated interest in electric drive train components. A review of the most recent literature (Ji (2015), Wanli (2014), Gyftakis (2015), Penrose (2014), Li (2010)) about electric component reliability and durability formed the basis for the work carried out in ASTERICS.

In the field of insulation life prediction of electric machines, for instance, the variety of stresses seen by the electric machine's insulation and the many possibilities of small but acceptable defects, leads to a considerable complexity. For that reason, the main influencing factors of ageing have to be captured, such as electrical and

thermal stress. By Arrhenius' formula, the temperature factor can be approximated at least. Combined with the voltage stress formula, the simplest multi-factor approach is conceived. In addition to such static descriptions, thermal gradients – or even thermal shock – poses a considerable problem for the mechanical endurance of insulation layers.

Approaches in multi-factor stress analysis have not led to unified models independent of manufacturers or even base configurations of the insulation system. So the only way remains to test the insulation system in the ambience and under the conditions it was developed for. That does not only include the ambient conditions, such as temperatures, humidity, contaminants but also electrical and mechanical conditions. If the controller and the inverter is known, then it should be used during the test as well since insulation ageing heavily depends on the terminal voltage gradients determined by the inverter's switching pattern. The same is true for vibration levels and thermal conditions. Component temperatures are not only influenced by ambient but predominantly by their operational regime, i.e. the driving cycle of the vehicle. By taking driving cycles and component ageing into account, several important findings were obtained in ASTERICS. First, the inclusion of component ageing models in behavioral vehicle model gives important insight how driving patterns affect components' longevity (Figure 5(a)).

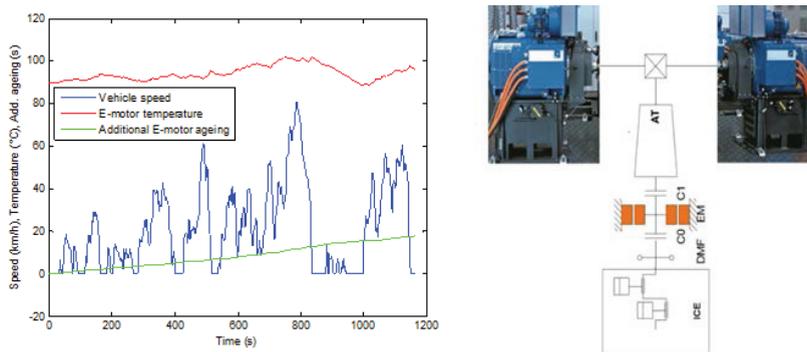


Fig. 4 (a) E-Motor ageing depending on vehicle speed, (b) E-Drive components on a Power Train (PT) test bed.

Designed experiments can be used to derive maximally damaging tests for the components based on vehicle dynamics. Secondly, future tests of e-drive components will not only take static load and ambient conditions into account. They will mimic the situation in the vehicle as close as possible, for example on Power Train test beds (Figure 5(b)). By the Load Matrix™ approach, the tests will be limited to the most significant load conditions thus achieving optimal test acceleration while keeping focused on the factors determining durability and reliability.

## 5. An advanced multi-domain system level modelling platform

In addition to the advanced and novel component modeling approaches presented in section 3 the paper also presents an advanced multi-domain system level modelling platform capable of coupled treatment of the vehicle, mechanical driveline, electrical powertrain, VTMS (Vehicle Thermal Management Systems) and control system domain as schematically depicted in Figure 6(a). Full integration of all components allows for a coupled assessment of energy consumption and their interactions, therefore supports optimization of global energy consumption in realistic driving conditions. This multi-domain system level model also serves as a very efficient plant model for model-based control optimization allowing controller development for increased component efficiency through efficient control.

Full coupling of the VTMS domain with thermal as well as performance models of the battery, EM and inverter is indispensable for accurate performance prediction of e-components and prediction of component ageing being a complex interaction of electrical, thermal and mechanical phenomena. In addition, coupled treatment of the electric, thermal and mechanical behavior including stress factors, enables improved component sizing of EM, inverter and battery, as well as the associated auxiliaries.

Moreover, coupled treatment of all relevant domains results also in significantly shortened powertrain development times through frontloading. Virtual system level integration in the multi-domain modelling platform enables analyzing thermal and ageing phenomena in the same model that is used also for vehicle performance and powertrain layout analyses. This results in reduced effort for setting up the model(s) and in the reduced effort for vehicle concept development as all system level relevant design constraints can be considered and virtually tested in a single model.

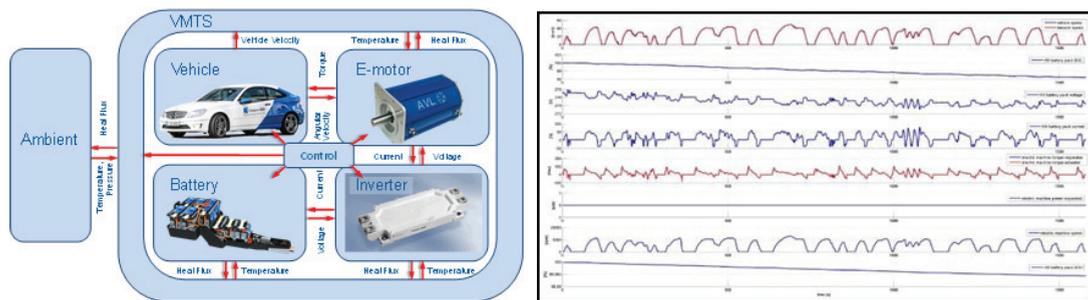


Fig. 5 (a) A multi-domain system level model of the AVL Coup-E vehicle; (b) Simulation results of light commercial vehicle with e-motor and battery FMU's - ASTERICS cycle.

Many simulations have been performed to check that FMU components generated by different environments and can be integrated in each vehicle model. In each case, both numerical efficiency and accuracy of the different methods (CS and ME) have been performed. The simulation presented in Figure 6(b) has been performed to verify that different FMU components (CS and ME) can be used within the same environment. As for the e-motor model, the battery model has been also scaled regarding reference battery output voltage and battery capacity.

Different configurations of the vehicle in each environment have been created and seamless coupled between Global Simulation Environment (GSP) from Volvo Group, GoFast from CRF, AVL Cruise and LMS Imagine.Lab Amesim Vehicle Simulation platforms.

Physical models of electric subsystems (e-motor or battery) have been imported from other environments and simulated successfully in a full vehicle model of each partner. The Functional Mockup Interface has proven to be an efficient and flexible tool for exchanging models.

### 5.1. Multi-domain efficiency analysis in interaction with thermal and aging aspects

Two different vehicles were used to demonstrate the applicability of the developed models for electric components (see section 3) for efficiency analysis and simulation of thermal as well as ageing aspects. With the light commercial vehicle IVECO Daily and the sportive Mercedes Coup-e (800V design study by AVL) two very different full EVs in terms of mass and performance were selected. Electric powertrain, mechanic driveline as well as vehicle models were built up in different system simulation platforms. The common model integration platform, co-simulation platform with FMI (function mock-up interfaces), served to integrate the developed electric component models.

The simulation models were validated by comparison to road as well as roller test bench measurements. Comparison of electric as well as mechanic quantities showed satisfactory quality of the simulation after refinement of certain vehicle control functions (anti-slip, recuperation, brake pedal characteristics).

With these baseline models power flow analysis was performed to assess the efficiency improvement potential. For the commercial vehicle the most profitable measures were the change of the electric machine from induction machine to permanent-magnet synchronous machine together with an increase of the battery voltage. This led to higher electric powertrain efficiency in combination with an increased recuperation potential that yielded in an overall efficiency increase of 14% based on the EV-driving cycle "unsteady" long. For the passenger vehicle it turned out that downsizing of the machine together with introduction of a gear box was the most effective measure.

Powertrain efficiency was increased by around 20% depending on the gear box variant (fixed ratio, automated manual 2 speed or 6 speed gear box from conventional powertrain), see Figure 7(a).

It can clearly be seen that only the EUDC and the EV driving cycle ‘ASTERICS unsteady long’ that incorporate an urban driving profile distinguish the characteristics of the transmission.

In a next step, the impact of efficiency increase on driving pleasure was assessed, which is especially critical when downsizing the powertrain. Time for maximum acceleration from 0 to 100kph increased from 6.4s by 2.4s, which is a significant performance reduction that could be remedied by an all-wheel version with four machines at the wheels.

The efficiency improvement studies for the two test vehicles showed that the simulation platform incorporating the advanced electric component models is a capable tool to assess different design potentials at very low development times and early development stages.

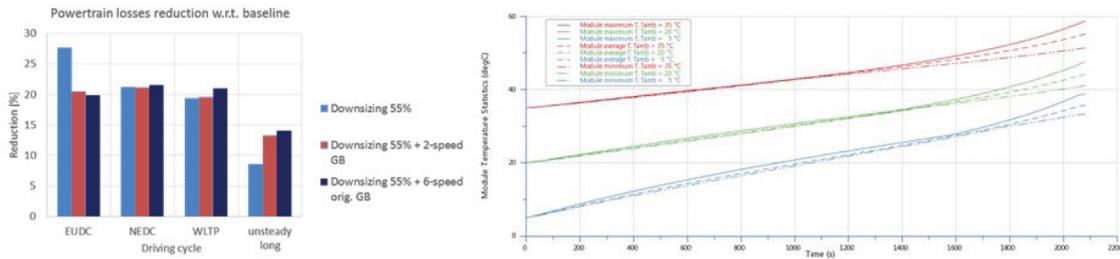


Fig. 6 (a) Powertrain loss reduction for different transmission variants and driving cycles; (b) Comparison of battery modules with different cell and ambient characteristics.

In a second step a model of the VTMS was established for the passenger vehicle. Here, the thermal component models and the cooling systems of the vehicle (oil for the machine, water/glycol for battery, inverter and compartment) were coupled with the driveline system model by individual sub-models of the model integration platform.

The temperature behavior of the cooling system and the electric components were investigated for different driving conditions and ambient temperatures (winter, mid-season, summer). It could be shown that due to increased efficiencies the local temperatures of the downsized machine increases by less than 2 °C, which is an uncritical amount for aging of insulation and demagnetization of the permanent magnets.

Comparisons to thermal test bed measurements showed the capability of the model to predict temperatures including local variations, which are critical for the power electronic elements of the inverter. For the IGBT-modules these variations make up to 30 °C. The thermal component model in combination with the cooling system and vehicle performance model can predict this thermal stress under realistic conditions. This allows to rate the thermal stress and hence further reduce the vehicle development time as the number of powertrain endurance tests can be decreased.

The thermal models for the battery are operating on module level and are hence capable to assess temperature variations between different modules due to cooling system inhomogeneities or variations of the battery cell characteristics. These temperature differences feed back to the cell characteristics with potential increase of power loss inhomogeneity. Figure 7(b) shows three modules with cells of different quality (low/average/high internal resistance) at three different ambient conditions (winter/mid-season/summer). Temperature difference between modules is predominant towards end of battery capacity. In winter conditions (5 °C) module temperature difference is up to 2 °C also for the mid capacity range (80% to 40% SOC). Power loss is reduced in warm conditions causing a smaller temperature increase over the cycle for summer conditions.

For aging this trend is reversed. During summer cell degradation is twice as high as with the mid-season condition. For winter conditions the cold start strongly stresses the cells, however for longer drives this is compensated by the moderate cell temperatures during the rest of the cycle. This leads to a similar overall reduction of state of health for winter and mid-season conditions for drive cycles longer than approximately 1000s. Cell variations lead to minor differences in cell aging in contrast to differences in the power loss.

It can be concluded that the multi-domain approach for electrical, mechanical and thermal behavior of electric components embedded in the system simulation platform delivers valuable predictions that can be used by the development engineer to study design variants for their energy economy as well as thermal impact and aging behavior.

## 6. Summary and outlook

The ASTERICS project delivered solutions to significantly enhance the development process of EV's in short-term, so that faster development cycles with 50% less effort than before are feasible. Further, these methods and tools can be used to improve the performance, reliability and safety of EV's and also hybrids, as similar modeling and testing capabilities are needed in all sorts of EV-variants.

Overall the ASTERICS project made a huge step forward in enabling the development of EV's, which are more competitive in the transportation sector and compelling for end users, which finally helps to reduce global emissions.

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