Introduction

Since 2011, I have been leading the Institute of Automotive Technology, which currently consists of five research groups and over 60 employees. The following groups Vehicle concepts, Vehicle Dynamics and Control Systems, Driver Assistance and Safety, Smart Mobility and Electric Vehicle Components cover all questions relating to electric vehicles and future mobility.

The research group components of electric vehicles mission is to increase driving range, reduce costs and development time along the life cycle of electric vehicles. We are covering current topics in research and industry, by investigation of all components of an electric drivetrain. Our research starts with the battery cell via the battery pack to the power electronics and the electrical machine. Each of these components is investigated in detail as well as in the system of electric vehicles. We deal with classical concepts and investigate new approaches (e.g. dynamic interconnection of battery cells). Our research is done in simulations, with help of prototypes and experiments. Our strength is modeling and simulation. Through our range of test benches and demonstrators, we are able to parameterize and validate our models with real components and vehicles. Starting with highly accurate battery cell testers via battery module tester to a powerful battery simulator at our roller test bench. Furthermore we can use various HiL environments as well as climate chambers for the according research. We developed and parameterized various component models and integrated them into our simulation library, which can be used to carry out holistic vehicle simulation.

Markus Lienkamp
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1. Group overview
2. Research topics
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4. Demonstrators
5. Test benches
6. References and acknowledgement
Research Group Electric Vehicle Components

Research goals: increase driving range, reduce costs and development time

- Server based health monitoring and second life battery design
  - Michael Baumann
- Modular power electronics
  - Fengqi Chang
- Optimal cell connectivity
  - Felix Römer
- Overload optimization
  - Svenja Kalt
- Active battery pack circuitry
  - Philip Wacker
- Design and operation of highly loaded battery packs
  - Christoph Reiter
- Potential of HV heater
  - Matthias Steinssträter
- Optimal cell size for electric vehicles
  - Matthias Kerler, Xue Lin
- Degeneration detection, Electrical drive train components
  - Jörn Adermann
- Integration of a modular drive train
  - Katharina Minnerup
- Battery aging & load spectrum
  - Tanja Gewald
- Technical and economical analysis & evaluation
  - Stephan Rohr
- Increase of driving range
- Reduction of costs
- Reduction of development time
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### Description:

#### Problem

The dimensions and capacities of the battery cells defined in the norm DIN 91252 and that have been applied by German OEMs had been determined without any scientific basis. They have rather been derived from compromises between cost and manufacturing. However, the impact of this decision on the "battery pack" system was not taken into account.

#### Consequences

Today the market for lithium-ion battery cells is majorly dominated by manufacturers from Asia. American manufacturers are just pushing their way into the market with the help of cooperation projects. A big chunk of the total production volume consists of rather small (cylindrical) cells which are used in a variety of applications. Large cells (> 25Ah) are therefore subject to problems, such as poor availability, as well as higher costs. Due to the lack of experience in the production process, larger cells are currently at a disadvantage in areas like energy density and costs. The effects of cell size on the aging behavior, performance, efficiency and the safety of a battery system were not considered during standardization.

#### Goal

A safe, cost-effective, efficient and powerful battery pack that meets the pack’s requirements by determining optimum cell sizes tailored to an area of application clusters.

### Publications:

- Kerler, Matthias; Peter Burda, Michael Baumann, Markus Lienkamp: A concept of a high-energy, low-voltage EV battery pack. Electric Vehicle Conference (IEVC), 2014
- Kerler, M.; Hoffmann, F.; Lienkamp, M. Optimization through rapid meta-model based transient thermal simulation of lithium ion battery cells, IEEE Transportation Electrification Conference (ITEC), 2017, Chicago
Increased driving range

Electrochemical-mechanical interactions in lithium-ion cells.

Publications:
Ebert et al., *Influence of dynamic mechanical stress on lithium-ion-battery aging*, Conference on Future Automotive Technologies CoFAT, 2017, Fürstenfeldbruck
Ebert et al., *Detection of Cell-Stack Inhomogeneities via Mechanical SOC and SOH Measurement*, IEEE Transportation Electrification Conference (ITEC), 2017, Chicago

Description:

**Problem**
The influence of thermal/electrical parameters and operating conditions on battery cells has been extensively researched. Additionally, there are further effects occurring during operation such as mechanical stresses in form of vibrations, shocks and the stress caused by the mounting of individual cells in the battery modules. There are only a few qualitative statements available on the topic, all of which point out to a significant influence on the aging behavior and the safety characteristics. The effects must be investigated further.

**Consequences**
Because of the suboptimal design of the battery module construction, lithium plating can be observed even at room temperature, leading to capacity loss or in the worst case, to an internal short circuit. In addition, both vibrations, e.g. while driving or shock loads from accidents also lead to non-visible damage and decrease in the lifetime of battery cells. It is therefore necessary to build up a knowledge base on the short and long term effects as well as the detection of such incidents in order to avoid a costly exchange of the battery module due to overlaid safety concerns.

**Goal**
Determination of characteristic, damaging and mechanical influencing factors and the improvement of the battery cell- and module construction, depending on the operational- and cell parameters, including mechanical conditions.
Description:

**Problem**

In numerous studies, range is identified as one of the greatest problems associated with electromobility. Uncertainties in determination of the battery status, performance forecast of electric drive train components and/or auxiliary equipment will aggravate this problem. In addition, possible malfunctions in power electronics and the engine or failure of individual battery cells can also adversely affect the range.

**Consequences**

User acceptance declines as a result of unreliable range predictions and questionable resale values of electric vehicles.

**Goal**

Using the simplest sensor technology, the system is capable of detecting both degeneration- and aging effects, as well as malfunctions in the drive train components. This information can be used to derive an optimal discharge strategy and a reliable range prognosis or to determine the residual value of the components.

**Publications:**


Wacker, Adermann, Lienkamp, Using Active Battery Switching Technology to Improve Electric Drivetrain Efficiency, Conference on Future Automotive Technology, 2016
Problem
Although the efficiency of electric drive trains is very high at the design point, the numbers depend strongly on the actual operating point, resulting in significantly lower energy conversion efficiency rates in reality. The problem is particularly serious for electric vehicle since they are not being operated constantly, but are rather used in daily driving conditions.

Consequences
The overall efficiency of the vehicle is significantly lower than that at the design phase of individual components. Thus, the achievable range is lower than what is predicted.

Goal
The efficiency of the electric powertrain is to be increased by utilizing the intermediate circuit voltage, since the voltage has a great influence on the overall efficiency. For this purpose, the so-called active battery pack circuitry was introduced. The system allows a variable connection of the individual modules in the battery pack during vehicle use, which allows a variable intermediate circuit voltage with very low self-losses. The overall efficiency of the powertrain can be significantly increased with this system.
Increased driving range
Design of electrical machines by employing overload potential

Description:

Problem
For many years, electric machines have been designed according to common design patterns. These methods have the effect that the machines are usually designed in such a way that they can withstand even the toughest loads (such as interval accelerations) permanently. However, such a capability is not necessary in real-life driving. Because of these conventional patterns big, heavy, expensive and possibly inefficient machines are being designed.

Consequences
A machine model is to be calculated by means of a design which is limited from beginning by constructive limits. With the help of constructive data an efficiency computation is to be carried out and a thermal model (point mass model) is to be created. This model chain is used to check whether the machine reaches its thermal and magnetic limits on the road. If not, the values are lowered gradually until the limits are reached.

Goal
The aim is to design a vehicle-compatible electrical machine that provides the required (instationary) performance. It is expected that newly designed machines will be smaller, lighter and more efficient by shifting these characteristic loads into a more realistic and efficient scope.

Publications:
Horlbeck, Hackl;
Analytical solution for the MTPV hyperbola including the stator resistance;
IEEE ICIT, Taipei 2016
Horlbeck, Lienkamp;
Design of Electrical Machines for Automotive Purposes Considering the Overload Potential,
Conference on Future Automotive Technology, 2016
Adermann, Wacker, Horlbeck, Baumann, Lienkamp,
Alternative methods for detecting the degeneration of electric drive train components,
Conference on Future Automotive Technology, 2016
Horlbeck et. al.
Description of the modelling style and parameters for electric vehicles in the concept phase, Researchgate 2016
Increased driving range

Optimal cell circuitry

**Problem**

Singular battery cells have differing capacities within the scope of production. In an automotive application, it is necessary to connect a certain number of cells in series and in parallel, because of the small single-cell voltage. By means of safety and lifetime, usable voltage windows are defined, which in such a wiring limits the usable cell capacity to that of the worst cells.

**Consequences**

The worst cells experience the highest loads and age faster, which further decreases the usable total capacity. Good cells can not use their full potential. Minimizing the differences requires a higher effort in cell production. Active and passive balancing attempts to compensate for the cell load conditions caused by capacity differences, but this always results in a loss of energy.

**Goal**

With the help of an optimal, potentially active cell circuitry, different cells are to be connected in such a way that they can all use their full potential and the load is evenly distributed. Such a system can also be capable of providing adapted DC link voltages.

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**Publications:**

**Problem**

The partial load efficiency of inverters used in vehicles is low, even with state of art circuit designs. This problem can be addressed on three levels: IGBTs have a diode-like behavior on the component level. Moreover, the parallel connection of IGBTs requires high redundancy and a precise control. On the topology level, the high DC voltages lead to constantly high switching losses. On the control side, the switching frequency should be more than 20 kHz to reduce motor noise and harmonic distortions, which then again results in higher switching losses.

**Consequences**

The overall efficiency of inverters is currently around 85% in an urban driving. On the other hand, the overall efficiency of a typical MOSFET inverter is over 95% in the same testing conditions. Furthermore, MOSFET inverters (<100 V) are cheaper and have a lower outlet resistance. Therefore, MOSFETs have a great potential to be implemented in future electric vehicles.

**Goal**

Low-voltage MOSFET inverters have a great potential in EVs. However, to be able to use them in a vehicle inverter, a suitable topology and methodically selected components are necessary. And this design should be compared to the SiC technology in terms of cost, efficiency etc.
Problem
The actual, load-dependent aging of lithium-ion cells, especially in series and parallel circuit, is difficult to predict. The electrical and thermal design of battery packs for electric vehicles is often based on reference values or data sheets. Maximum currents, temperatures and temperature gradients are scaled to continuous loads and the cooling system of the traction batteries is dimensioned appropriately.

Consequences
Particularly with high-performance vehicles, the issue leads to a largely oversized cooling system which then leads to additional costs, weight and energy consumption. At the other end of the spectrum are uncooled battery packs, which require a premature performance reduction, depending on the design. However, the ideal time to reduce the performance and its precise influence on aging behavior is currently unknown, since there are only reference values to work with.

Goal
Through a more precise determination of the actual load and actual aging behavior on a single-cell-level within the battery pack, detailed statements for the calculated design of the cooling system and the operation strategy of the battery pack should be made (in the context of complete powertrain too). Depending on the required driving performance, the thermal mass of the battery pack and its components should also be considered.
Description:

Problem
To maximize the efficiency of an electric drivetrain the components of the drivetrain have to be kept in the range of their optimal performance and have to interact with each other in an optimal fashion. To ensure this an energy management strategy, which takes a variety of factors into account, has to be implemented. For designing such strategy, different issues have to be addressed: For example: Which objective functions can be applied? Which parameters in the car can and should be influenced by an energy management strategy? Which methods can be applied to find a satisfying solution to the problem.

Consequences
In my work I try to answer these basic questions and come up with a holistic energy management strategy for purely electric vehicles.

Goal
The goal is to design a holistic energy management strategy, which can be applied to electric drivetrains with different components. This strategy should improve the range of the electric vehicle and minimize aging mechanisms of the components.
Reduced development time and cost reduction
Accelerated aging characterization of battery systems

Description:

Problem
Lithium-ion traction batteries age during operation in electric vehicles due to loads from daily usage, environmental conditions and various other aspects of the system design.

Consequences
Various characteristics of traction batteries change as a result of aging which influences the further usage of the battery. This reduces the range and performance of the electric vehicle which ultimately makes it necessary to replace the battery. Therefore, the prediction of aging behavior is very important for various actors along the value chain, e.g. suppliers and manufacturers in the automotive industry.

Goal
For the efficient and cost-effective prediction of battery aging, a simulation model on cell and system level is developed. By this means, the aging progress for each cell and the entire system can be predicted. For the simulation model's validation, laboratory testing is carried out and the influence of stress factors is analyzed. To accelerate the time-intensive testing, a synthetic load cycle is developed which intensifies the characteristics of real driving cycles and thus accelerates the effects of aging.
Reduced development time and cost reduction
Cloud-connected parameter estimation and prediction

Description:

Problem
The current practice in Second-Life applications of used EV batteries is a highly time- and cost intensive process with uncertainties regarding the cells’ conditions and their further aging progress and expected lifetime.

Consequences
These disadvantages, especially with the falling costs of new energy storage systems, are an obstacle towards the future of a second-life battery market.

Goal
To reduce the high repurposing costs of vehicle batteries especially for the necessary electrical measurements a new approach is being developed, in which the current state of the battery is characterized and continuously updated within an electrical-thermal battery pack model on a server backend. In addition to the current battery parameters, the so-called battery pass also contains a compressed vehicle usage profile, which helps simulating further vehicle aging behavior. At the same time, potential second-life scenarios can be simulated simultaneously and the resulting aging behavior of the batteries can be analyzed and compared. By doing so, different second-life applications can by monetarily evaluated and chosen accordingly.

Publications:
Baumann, Rohr, Lienkamp, Development and Investigation of a modular stationary Second Life Storage System, CoFAT 2016
Rohr, Müller, Baumann, Kerler, Ebert, Kaden, Lienkamp, Quantifying Uncertainties in Reusing Lithium-Ion Batteries from Electric Vehicles, GCSM, 2016
Adermann, Wacker, Horlbeck, Baumann, Lienkamp, Alternative methods for detecting the degeneration of electric drive train components, CoFAT 2016
### Cost reduction

**Analysis on possibilities of manipulation on electric vehicles**

**Problem**

The trend in the vehicle market is currently pointing to a significant increase in electric vehicles - vehicles that have new core components with an electric power train. The new technology also results in new manipulation-goals and possibilities. Contrary to the practical values from conventional vehicles, current manipulations and their potential effects are currently unknown in electric vehicles.

**Consequences**

The lack of knowledge is critical in particular with regards to the expensive electrical energy storages, since this is subject to usage-induced aging and has a decisive influence on the residual value of the vehicle. In sum, electromobility is thus a major challenge for security.

**Goal**

The goal is the systematic identification and analysis of potential, motivated manipulations of the core components of electric vehicles. A special focus is on influencing the aging process through manipulations compared to the influence of the usage behavior. With a risk analysis, critical systems are to be identified at an early stage and the basis for focused security measures should be created.

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**Publications:**


Cost reduction

Technical-economical evaluation of battery degradation and second usage scenarios

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$R^2 = 0.8346$

Publications:
Rohr, Wagner, Baumann, Müller, Lienkamp, A Techno-Economic Analysis of End of Life Value Chains for Lithium-Ion Batteries from Electric Vehicles, EVER, 2017
Müller, Rohr, Werner, Lienkamp, Analysing the Influence of Driver Behaviour and Tuning Measures on Battery Aging and Residual Value of Electric Vehicles, EVS30, 2017
Rohr, Müller, Baumann, Kerler, Ebert, Kaden, Lienkamp, Quantifying Uncertainties in Reusing Lithium-Ion Batteries from Electric Vehicles, GCSM, 2016

Description:

Problem
The lithium-ion traction battery is the most expensive component of an electric vehicle and contributes significantly to resource consumption and emissions during production. Increasing electrification and battery upgrades for existing vehicles will lead to an increase in already used and degraded traction batteries.

Consequences
In addition to the conventional recycling of batteries, increasing secondary usage scenarios such as the use of vehicle batteries in stationary energy storage systems or the remanufacturing of specific components are helpful to create additional ecological and economic added value. Due to the complexity and the many technical, economic and regulatory influencing parameters, it is not yet known how these second use scenarios will evolve in the future. Through a parameter-based technical-economic assessment of the Eo1L of batteries in the vehicle and second usage scenarios, future developments, potentials and challenges are investigated.

Goal
A technical-economic assessment of battery degradation in the battery electric vehicle, future second-usage scenarios as well as the derivation of decision-making advice for automotive manufacturers, waste disposal companies and stationary energy storage producers and policy.
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6. References and acknowledgement
There are still many unanswered questions regarding the interpretation of electric vehicles. A comprehensive vehicle model was developed by the Chair of Automotive Technology for a fast and comprehensive analysis. Here it is necessary to examine the vehicle together with the driver and the environment. An examination enables, for example, the calculation of the driving performance, the energy consumption or the dimensioning of the powertrain. Among others, lifespan examinations can be carried out depending on vehicle user behavior or environmental conditions. However, the detail level of the simulation model is always a compromise between the amount of required parameterization data and the resulting outcome quality. To individually control the detail level for each component and at the same time to be able to vary different components in an optimization process, the model was designed modularly. A component library makes it possible to find adapted component models, depending on the application.
Modelling
Full vehicle simulation with Velodyn

Description:

The Velodyn model is a commercial longitudinal full vehicle simulation model of an electric vehicle in the MATLAB / Simulink environment Velodyn of the project partner IAV GmbH. Velodyn works with transmission blocks. The signals of from blocks are integrated into a bus structure consisting of the signal and the control bus. The signal bus transmits the physical and model-specific signals. The control bus transmits the control and feedback variables.

In cooperation between the Chair of Automotive Technology and IAV GmbH, the Velodyn model was expanded by a LI-ION battery block, an electric motor with voltage switch block and a model-based range prediction.
Modelling
Holistic battery system model

Description:

The battery system of electric vehicles consists of a number of interacting, complex subsystems such as the lithium-ion battery cells, the module or the cooling system. The interactions of these subsystems are crucial for the successful design of electric vehicles. These interactions must be analyzed thoroughly for meeting realistic design decisions regarding performance, efficiency, service life, package and safety.

The research group Electric Vehicles Components have integrated sub-models, both integrated from the literature and self-developed, into a complete battery pack model. The smallest unit here is the cell model, which maps the electrical-, thermal- and aging behavior of an NMC cell. A reliability model is used to quantify the possibility of a cell failure by counting the number of critical operating events. By means of a parametric design of the series and parallel circuits as well as the cell size, a battery system is created automatically. This step to the system level allows the analysis of compensation currents between the parallel circuits and their effects on the parameter dispersion. The uncertainties regarding parameter dispersion and temperature gradients in the battery pack can therefore be analyzed and evaluated.
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Description:

Within the scope of the collaborative project Visio.M, funded by the BMBF, an electrical minicar was built at the Chair of Automotive Technology. The energy storage used in the car is a complete in-house-design. The monitoring of the 1296 lithium-ion cells as well as the control is carried out by a self-developed battery management system. A new contact technology for battery cells, also developed at the university, facilitates a simple and fast assembly as well as efficient air cooling via the cell deflectors. A startup, stemming from the chair, further developed this technology to series manufacturing.

With a weight of 91 kg, the battery pack has a capacity of 13.5 kWh. With a voltage range of 380 V, a maximum power of 45 kW can be achieved.

A total of 18 battery modules, each having 72 cells, are used in the battery pack and being constantly monitored by an independent battery management system. Each module has a fan to be individually supplied with cooling air.
Description:

At the Chair of Automotive Technology, a Smart Fortwo with an electric drive was developed as part of the research project "User-Oriented Electric Mobility - NEmo", funded by the Bavarian Research Foundation. The energy storage system uses an innovative active battery pack circuitry. It operates with a nominal voltage of 103.6 V and provides a capacity of 21.6 kWh.

The research vehicle enables the acquisition of highly accurate data from the driver, vehicle, powertrain and the environment. This allows the possibility to implement innovative systems and algorithms in a prototype vehicle and to validate their usefulness in vehicle tests and simulations.
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Description:

At the Chair of Automotive Technology, a single-axis chassis dynamometer from Renk Test System GmbH is in operation. The test stand allows a drive speed up to 250 km/h and delivers a braking power up to 280 kW.

For testing and characterization of the electrical drivetrain in the development process, the company Kratzer Automation supplies a scalable, automated driving controller in addition to the chassis dynamometer. Typical application areas for these control systems are grid recordings, efficiency tests, thermal examinations, continuous running tests and dynamic tracking tests with the vehicle simulation.

In combination with a linear actuator from Linak GmbH, the controller can be used to reproduce standardized driving cycles such as the “NEFZ” or “WLTC” accurately on the chassis dynamometer. In the future, comparisons between different vehicles can be made. The actuator controlled by CAN is able to apply a maximum force of 300 N to the brake pedal and achieve a transfer speed of 36 mm/s under full load.
Test benches

Environmental chamber / BMS-HiL-Stand

Description:

**Environmental chamber:**
Vötsch VC³ 4100
- Testing space: 990 Liters
- Temperature range: -42°C - 180°C
- Humidity range: 10% - 98% r. F.

**BMS-HiL-Prüfstand:**
Hardware-in-the-Loop-Stand for battery management systems
- Self developed based on a NI-PXI-System
- Simulation of 36 galvanically isolated cells as well as typical vehicle signals (eg. CAN)
Test benches

Battery Test Systems

Description:

Cell and Module Test System:
BaSyTec CTS Lab XL, XCTS25, XCTS50, HPS
• Voltage range: ±6V, 0-4.5V, 0-6V, 3 - 60V
• Current range: ±5A, ±25A, ±50A can be parallelized to ±300A, 60A loading / 100A unloading
• Up to 32 individual cells

Pack Test System:
Heinzinger ERS 600-500/120
• Bidirectional, liquid-cooled DC power supply
• DC Output:
  Voltage: 600 V
  Current: ± 500 A
• Number of output channels: 2
• Output per channel: ± 120.000 W
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