950 new charging points for the city of Aachen!

In order to reduce NOx and CO2 pollution in the Aachen urban area, numerous charging points will be installed in the Aachen municipal area over the next two years as part of the "Immediate Action Program for Clean Air 2017-2020". This facilitates the selective design of charging infrastructure, while also addressing future-oriented issues within the framework of increasing digitization. Against this background, measures for local and temporal flexibility as well as for the stabilization of the distribution network through solid-state transformers, battery storage and an intelligent network management system are being researched. The parallel development of business models and the analysis of all relevant communication and decision channels should anticipate possible obstacles and increase acceptance among the population.

In this context ISEA deals with the research and realization of sustainable network concepts considering transient effects on the component as well as the system level. The resulting local charging hotspots present network operators in particular with major technical challenges in terms of network utilization and stability, both in the distribution network and at the local level.

ISEA-ESS is dealing with the use of battery storage to prevent bottlenecks in distribution and charging networks. These offer an additional degree of time-related freedom in dealing with excess energy in times of high local load or feed-in peaks. Intermediate storage of excess energy from renewable energy (REN) power plants during generation peaks can prevent curtailling REN power plants, increasing the overall efficiency of the charging networks. In addition, the battery storage units enable a time-limited increase in the available charging capacity beyond the capacity of the installed power supply network at peak times.

Parallel to the installation of the charging infrastructure in the Aachen area, ISEA-LEA is developing real-time simulation models that are able to model the site-specific network conditions and requirements. This includes models for the local charging networks as well as the planned battery storage. This facilitates the selective design of individual components and operating stra-
Strategies. Critical system states and alternative network concepts can also be simulated in the model at an early stage and without risk in order to prevent possible dangerous situations and to adapt the systems accordingly. Last but not least, the simulation models developed can also be used to scale and generalize the site-specific solution approaches in order to make them usable for other companies, cities, hotspots, applications and future scenarios. With a view to the future of electromobility, the knowledge gained from the selected application example can now be applied, among other things, to the desired scenario of the widespread use of electric vehicles.

Storage systems | Electrification concepts

Analysis and evaluation of electrification concepts for long-distance truck traffic in Germany (BOB-TRUCK)

To achieve the climate targets, the transport sector must significantly reduce CO2 emissions, which requires consideration of alternative drive options for the energy-intensive use of trucks in long-distance freight transport. As part of the BOB truck project, three electrification concepts for long-distance trucks were considered that could replace fossil fuels: battery powered, overhead line powered and fuel cell powered (German abbreviation: BOB) trucks. In addition to the technical feasibility, the life cycle costs and life cycle assessment of these vehicles as well as the corresponding infrastructure of charging stations, overhead lines and hydrogen filling stations were investigated.

The model-based energy consumption of the vehicles demonstrates the advantages of alternative powered vehicles over conventional diesel trucks. On average, battery-operated and overhead-powered trucks consume a factor of 2.5 less energy than diesel trucks, while fuel-cell-powered trucks consume 1.3 times less.

The lower energy consumption of the alternatively powered trucks contributes positively to the overall life cycle costs of these vehicles. The conducted analysis revealed that an overhead line supplied truck can achieve approximately the same life cycle costs as a diesel truck. The life cycle costs of battery-powered trucks are somewhat higher in this comparison due to conservatively estimated battery costs. In contrast, the life cycle costs of a fuel cell-powered truck are significantly higher, which is attributable to the currently higher costs of the fuel cell and hydrogen. Nonetheless, all alternatively powered trucks investigated offer additional saving potentials with regard to life cycle costs, e.g. through technology developments and scaling effects based on mass production.

The life cycle assessment covers the manufacture and operation of the vehicles and infrastructure and shows that the trucks supplied by overhead lines and battery-powered can already slightly reduce greenhouse gas emissions compared to diesel trucks with today’s electricity production. Particularly if a high proportion of renewable energies is used in the electricity production mix (assumption: 80%), these truck technologies can save around 60% of the greenhouse gas emissions of a diesel truck.
Power electronics | Optimized SiC module design

SiCnificant - SiC-based traction inverters for innovative powertrain concepts

The "SiCnificant" project, funded by the Federal Ministry of Education and Research (BMBF), investigates the advantages of SiC-based semiconductors in drive converters in electric vehicles. In particular, the design of a novel power module is intended to identify the optimal use of SiC semiconductors with regard to the achievable switching speed and power density. ISEA is dealing with the design of the power module and the required drivers. The power module focuses on switching speeds of up to 50 kV/µs and a power density of up to 75 kW/liter. Innovative circuit and packaging concepts are being designed for this purpose. Within the framework of the project, comprehensive research work will be carried out and subsequently evaluated at all levels, from characterization of the semiconductor chip, simulation and assembly of components to evaluation of the effects at system level.

The project also focuses on the design of gate drivers that drive multiple SiC-MOSFETs in parallel. Due to the high switching speeds of the SiC MOSFETs, special gate drivers are required, which ensure uniform current distribution with MOSFETs connected in parallel. The drivers are designed to be highly symmetrical in order to achieve the same switching behavior in all power semiconductors. In addition, the gate drivers are designed to operate fail-safe despite the high switching edges of the SiC-MOSFETs.

Storage Systems | Market Analysis

Energy Transition in the Household: The market for home storage systems is booming

Home storage systems provide the potential to be able store solar power during the day and make it available in the evening hours. The electricity grids are significantly relieved by storing excess PV electricity during daytime. This means that home storage systems are therefore completely aligned to the trend towards energy transition. According to information provided by ISEA, more than every second newly installed PV system up to 30 kWp is currently being installed together with a home storage system. While PV systems have been already playing an increasing role for some time, home storage systems have developed from niche to mass markets in a very short space of time since 2013 and have now reached a number in excess of 120,000 installations in Germany alone. This means that a battery capacity of over 300 MW and a battery capacity of over 800 MWh have already been installed in German households. Particularly in the first few years since its inception, the nationwide market incentive program for solar energy storage has played a major, contributing role in market growth. The promotional program, which expired at the end of 2018, was launched in 2013 by the Federal Ministry of Economics and Energy in cooperation with KfW Bank and was accompanied by scientific monitoring conducted by ISEA under the name of storage monitoring. Back in July 2018, the storage monitoring organization published a comprehensive annual report, which can be downloaded free of charge from www.speichermonitoring.de.

It can be observed from this report that the end customer prices for solar energy storage systems are falling rapidly. Lithium-ion storage system prices have fallen by over 50 % since mid-2013 (see Fig. 1). The average consumer prices were already around 1,300 €/kWh (including power electronics and Sales Tax) by the end of 2017. Larger battery storage systems are now already available for less than 800 €/kWh. The market share of home storage batteries with lithium-ion batteries has risen steadily since 2013, partly due to falling prices, and is currently around 99 % for KfW-Bank supported systems (see Fig. 2). Storage systems with lead-acid batteries, which still had significant market shares until the middle of 2014, have now been almost completely forced out of the market. Alternative storage technologies, such as redox-flow or high-temperature batteries, currently play no significant role in the commercial home...
HiREX

On March 31st, 2018, the “HiREX - Highly Integrated High Speed Range Extender Module” project, which is based on a Wankel engine and a switched reluctance machine, was successfully completed. The project was funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) for a period of 3 ¼ years. The participating project partners were the companies AixControl and ENGIRO from Aachen, as well as Getriebetechnik from Ismaning (ISAR) near Munich.

A range extender is a system comprising a combustion engine and an electric generator, which enables the battery of an electric vehicle to be charged during operation. This topology therefore belongs to the category of series-hybrid electric vehicles. Since the combustion engine in the range extender is not utilized to drive the vehicle, it can be operated at its optimum operating point. This therefore improves system efficiency. A range extender enables the additional utilization of the existing gas station infrastructure and thereby provides an approach for resolving current charging infrastructure bottlenecks and range problems.

The primary task of ISEA within the HiREX project was to design a high-speed switched reluctance generator for utilization in a range extender. The generator is coupled to the combustion engine via a transmission. Utilizing a transmission opens an additional degree of freedom alongside the machine configuration (number of phases, number of pole pairs) with the free definition of the operating rpm.

The power density can be increased significantly by a high operating rpm. An additional advantage was found by shifting losses; iron losses increase while copper losses simultaneously decrease due to the higher stator frequency. This effect favors a more effective cooling of the machine via a classical stator jacket cooling, so that the increase in power density and loss density does not require additional cooling effort.

Switched reluctance drive units require a comparatively large intermediate circuit capacity in order to filter the oscillating machine current. A larger capacity thereby increases weight, volume and cost of the machine inverter. Within the scope of the HiREX project, ISEA therefore investigated and successfully implemented the minimization of the intermediate circuit capacity by utilizing an active power filter.

Storage Systems

Open battery aging tool for service life prognosis of battery packs considering uncertainties and diversities in cell quality

openBat is an open battery aging tool for predicting the service life of battery packs which are made of lithium ion cells. The battery aging tool comprises an electric model, a thermal model and an aging model. The development was executed within the framework of a research project funded by the Federal Ministry of Economic Affairs and Energy (BMWi).

openBat can be utilized by all companies, institutions and private individuals free of charge and anonymously at www.openbat.de. The individual simulation results may also be utilized for commercial purposes. Note that the project website, as well as ISEA of RWTH Aachen University, must also be cited as the source when any of the simulation results are published.

Within the framework of the project, a test matrix with more than 200 battery cells was measured in order to determine their aging behavior. For this purpose, cells were aged under different conditions both calendar-related and cyclically. The test data which was obtained in this way then forms the basis for the development of the aging model and is also published separately.
An electronic measuring system was developed for cyclic aging which permits simultaneous voltage and current measurement for 30 cells connected in parallel (Fig. 1). This therefore makes it possible e.g. to investigate the influence of parallel circuits on the aging behavior of individual cells.

An electronic measuring system has also been developed for calendar-related aging (Fig. 2). Five cells were respectively stored at a specific cell voltage (e.g. 4.1 V) and at a specific temperature (e.g. 35 °C). The external current required to maintain this voltage is measured continuously as it represents important information regarding an improved understanding of calendar lifetime of the batteries.

Fig. 1.

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Fig. 2.

**Electric Propulsion | More Electric Aircraft**

**HyFly**

In collaboration with the project partners, system investigations regarding distributed hybrid propulsion systems are executed within the “HyFly” research project. The focus is placed on propulsion architectures which not only reduce noise emissions during take-off and landing, but rather also NOX and CO2 emissions. The project is funded by the German Federal Ministry of Economic Affairs and Energy (BMWi). ISEA concentrates on the design of a high rpm reluctance generator, the associated power electronics and battery.

The tried and tested reliability and high power density of gas turbines is utilized in a hybrid solution with batteries and gas turbines as energy storage in aerospace technology and space technology. An essential challenge, which has to be mastered, is the direct coupling of the gas turbine and a switched reluctance generator. The sturdiness and high rpm capability of the reluctance machine are recommendable for this application. The electrical power generated by the generator is utilized to power the electric aircraft engines. A battery accumulator supports the electrical system e.g. during take-off and load interchanges. The design of the propulsion motors and the associated propellers will be transferred to project partners during the course of the project. New aircraft and propulsion concepts will be developed from the individual system components, which will then be measured against existing concepts.

An application in the aviation industry places higher demands on the individual components. Highly variable operating conditions must also be taken into account in the design, as well as higher requirements for the system’s safety.

**Short & Compact | IVU and ebusplan establish a Joint Venture for Electric Mobility**

Electric buses are conquering local public transport - and also fundamentally altering resource planning. In order to satisfy this demand, IVU Traffic Technologies and ebusplan are now pooling their expertise in a joint company. EBS ebus solutions GmbH develops innovative software solutions and software components which are tailor-made to the requirements of electric buses. The products from ebus solutions can be easily combined with each other and thereby enable an integrated planning process from strategic to operative planning, so that electric bus applications can be planned with foresight and efficiently. ebusplan is an ISEA spin-off which was founded in 2015.

Since early 2019, ISEA has a new research group. The research group "Reliable Power Electronic Systems", headed by Dr.-Ing. Christoph van der Broeck, develops technologies to increase the reliability and safety of power electronic systems. The new research group will become a core part of the Center for Ageing, Reliability and Lifetime Prediction (CARL) that will be built over the next two years on Campus Melaten to concentrate research activities on the aging of batteries and power electronic systems.

Our strong background in multiphysics modeling, system identification and electronic design enables addressing reliability engineering problems from new perspectives and promotes the development of disruptive technologies. This approach shall lead towards future smart power electronics by making the power module a multiphysics actuator and sensor.

For this purpose, we develop modeling and characterization tools to simulate electrical, thermal and mechanical variables for arbitrary mission cycles. Consequently, we predict the degradation, lifetime and reliability of all components of the power electronic system.

A key focus of our group is real-time monitoring of power electronic systems. By combining reduced-order multiphysics models, integrated sensors, and system identification algorithms, we develop new monitoring technologies to extract reliability critical system variables, e.g., device losses, 3-D distributed temperatures, strain as well as electrical and thermal impedances. With this information, power electronic systems are protected from overload. Furthermore, degradation modes are diagnosed and the remaining lifetime of the converter components is continuously estimated.

Another important research aspect are life-time-oriented control algorithms for converters that minimize thermomechanically-induced strain by reducing thermal cycles to increase service life and reliability. This approach allows reducing weight, volume and cost of future power electronic systems without compromising lifetime and reliability.

AABC Poster Award for Weihan Li

Weihan Li received the Poster Award for his "Cloud-based Battery Monitoring and State of Charge Estimation Platform for 48 V Battery Systems" poster. The poster was presented at the 9th International Advanced Automotive Battery Conference (AABC Europe) in Strasbourg in 2019.

Power Plant Battery Poster Award for Matthias Kuipers

Matthias Kuipers was awarded the 2nd place of the Poster Award at the 11th "Power Plant Battery - Advanced Battery Power" International Symposium in Aachen in 2019.

Authors: Matthias Kuipers, Hendrik Zapfen, Philipp Schröer und Dirk Uwe Sauer: „Algorithm for Online Electrochemical Impedance Spectroscopy (EIS) and Parameter Estimation“
**Events**

**May 22-23, 2019**
Bad Nauheim

International Symposium EEHE (Electricity/Electronics in Hybrid and Electric Vehicles and Electric Energy Management) 2019
https://eehe.de

**September 12, 2019**
Kurpark Terrassen
Aachen

FGLA-Kolloquium „Ultra-fast Charging Technologies“

**October 10, 2019**
Couvenhalle
RWTH Aachen

JARA-ENERGY Talks: Current Issues in Energy Policy
Lecture by Andreas Feicht, State Secretary BMWi

**November 26-28, 2019**
Aachen

IRSA 2019 – International Railway Symposium Aachen

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**Dissertations**

**Andreas Hofmann**

**Direct Instantaneous Force Control: Key to Low-Noise Switched Reluctance Traction Drives**

This dissertation deals with the well-known acoustic-noise issue of switched reluctance machines in the field of E-Mobility. The main noise source of the electrical machine, the breathing vibration mode 0, is eliminated by means of electronic control. The key to success of the control approach “Direct Instantaneous Force Control” is to hold the sum of all radial forces constant upon time. This zeros the excitation of the aforementioned vibration mode shape out. At first, the dissertation proofs the acoustic benefits of the control approach by the aid of simulations and test-bench measurements. In addition to the acoustical assets of the control concept, it is shown that it can compete very well with the standard control approach regarding concerns such as driving-cycle efficiency or torque ripple.

The outlook of the work states that the basic control concept is not limited to switched reluctance ma-chines but can also be applied to, for instance, permanently excited synchronous machines. It thus has the potential to essentially improve the noise characteristics of future drive trains in E-Mobility.

The dissertation is volume 83 of the Aachener Beiträge des ISEA and is available online at http://publications.rwth-aachen.de/record/673404.

Dr.-Ing Andreas Hofmann was working as a research associate for ISEA between 2010 and 2015 in the research group Electrical Drives. Ever since 2015 he is with TQ Systems GmbH holding various positions in the field of industrial servo-drive systems.
**Dissertations**

**Manop Masomtob**

**A New Conceptual Design of Battery Cell with an Internal Cooling Channel**

Cooling systems and connections of battery cells play a crucial role in the design and development of a modular battery storage system. This dissertation presents a novel concept in which battery cells with improved cooling systems are easy to assemble. In the battery cell, a liquid cooling channel is installed, which can remove heat from the inside of the battery cell to the environment. The battery cells consist of the cooling channel, the cooling connector, the electrical connector and the housing connector. They can be easy plugged together for a large battery pack. All connections can be connected at the same time. This concept allows a very modular design of the battery packs and can significantly reduce the complexity and errors in the installation of the battery storage.


**Andrea Marongiu**

**Performance and Aging Diagnostic on Lithium Iron Phosphate Batteries for Electric Vehicles and Vehicle-to-Grid Strategies: From the cell to the system level**

In this work all aspects of a lithium iron phosphate battery are explored, going from its working principle until its correct use and integration in the electric system. The work investigates firstly the battery’s electric performance and its changing during aging, demonstrating that the characteristics of the plateaus present in the open circuit voltage curve change differently based on the battery degradation. According to these findings, a novel on-board algorithm approach for the estimation of the actual battery capacity is introduced. Through the determination of the single degradation modes, the actual battery’s state of health can be assessed with an error within 2%. The proposed algorithm is part of a newly developed Battery Management System (BMS) concept designed for vehicle-to-grid (V2G) operation. Thus, a simulation tool is presented, with the aim of analyzing the behavior of the vehicle battery packs of a car fleet when additional cycle operations due to grid services are requested. The results of the simulations demonstrate that the adoption of adequate strategies allows a more uniform aging of the entire fleet, with an increase of the average battery lifetime of approx. one year.

The dissertation is volume 100 of the Aachener Beiträge des ISEA and is available online at [http://publications.rwth-aachen.de/record/709426/files/709426.pdf](http://publications.rwth-aachen.de/record/709426/files/709426.pdf).
The dissertation deals with the comparison of different packaging technologies of IGBT power modules with regard to their suitability for the use in the drive train of electric and hybrid vehicles. Two alternative packaging concepts are compared to a state-of-the-art module with DCB substrate and bond wires. The first is an IGBT press pack module and the second is a concept that uses high current printed circuit boards as an integration platform for power semiconductor chips. Prototypes of the investigated module concepts are developed and constructed at ISEA and within the scope of the joint research project HI-LEVEL.

One focus in the realization of the high-current printed circuit board module with embedded IGBT chips is the low-inductance switching cell design. A dc-link inductance of 1.5nH is achieved, which corresponds to a reduction of 90% compared to modules commonly used today.

Further aspects include simulations on converter system level, the integration of driver electronics and current sensors, the advantages of an increased dc-link voltage, the EMC characteristics of the modules and fundamental considerations regarding system costs.

The dissertation is volume 102 of the Aachener Beiträge des ISEA and is available online at http://publications.rwth-aachen.de/record/724124/files/724124.pdf.

Felix Adler
A Digital Hardware Platform for Distributed Real-Time Simulation of Power Electronic Systems

Power electronic circuits have long since permeated technology sectors that pose strict requirements on reliability and safety, calling for appropriate testing and qualification tools. In particular, high-power applications introduce possibly costly or difficult testing environments. Therefore, hardware-in-the-loop (HIL) testing is being firmly established in power electronics where the component-under-test is exposed to a real-time simulated environment. The expected future increase of the complexity of simulation models for large-scale power electronic systems render any single processing node underpowered in the long run. This thesis develops a scalable real-time simulation platform designed for the simulation of large-scale power-electronic systems. It explains the fundamentals of the real-time simulation of power electronic circuits and the principles of distributing a simulation to multiple processing nodes. It describes the real-time simulation platform and demonstrates its functionality and performance by real-world experiments: a hardware converter is compared to a simulation running simultaneously in real-time and a simulation of a cluster of wind turbines connected by a DC grid demonstrates the distribution of a real-time simulation.

The dissertation is volume 50 of the E.ON ERC|PGS and is available online at http://publications.rwth-aachen.de/record/711303/files/711303.pdf.
Dissertations

Garikoitz Sarriegi

SiC and GaN Semiconductors - The Future Enablers of Compact and Efficient Converters for Electromobility

The better physical properties of the new wide bandgap (WBG) semiconductor devices, e.g., based on silicon carbide (SiC) and gallium nitride (GaN), compared to the currently available silicon (Si) based semiconductor devices make these devices very attractive for many applications. Their properties enable reduced size converters with increased performance. This feature is of special interest for mobile applications, e.g., electromobility, where space is limited and the total weight of the vehicle is of utmost importance. In this work, the performance of commercially available WBG semiconductor devices is analyzed. The materials, e.g., SiC or GaN, and the device structures, e.g., MOSFETs, JFETs or HEMTs, are considered. The parameters of the devices are analyzed and characterized. The results are used to perform different simulations and compare the devices. Finally, the devices are mounted in a bidirectional interleaved DC-DC converter to measure their performance in real converter operation.

Dr.-Ing. Garikoitz Sarriegi was a research associate at ISEA from 2011 to 2016. Since 2017 he has been working for JEMA Energy in the Basque Country as a project manager.

Tetsuya Kojima

Efficiency Optimized Control of Switched Reluctance Machines

This thesis studies efficiency optimization to minimize the losses of switched reluctance machines for average torque control (ATC) and PWM based predictive direct instantaneous torque control (PWM-DITC). Generally, ATC is used at medium to high speed to achieve high efficiency, and PWM-DITC is used at low speed to reduce torque ripple. For ATC, conventional loss minimization methods cannot utilize zero-volt loops (ZVLs) that are additionally inserted between the turn-on and turn-off angles to improve the efficiency due to vast amount of calculation. In this work, a fast optimization method is proposed to enable utilization of ZVLs. Experimental results demonstrate that the iron loss is largely reduced by exploiting ZVLs and the loss reduction is especially large at medium speed and partial load. The loss reduction is also investigated for a city driving cycle. For PWM-DITC, this thesis proposes an optimal torque sharing function (OTSF) to minimize the copper loss through approximating the corresponding optimal torque waveform. The OTSF reduces the on-line calculation time compared to conventional TSFs as well as achieving more accurate approximation. These characteristics of the OTSF are verified by experiment.

Dr. Tetsuya Kojima works at Mitsubishi Electric Corporation Advanced Technology R&D Center since 2005. He was a guest researcher in the field of electrical drives at ISEA from 2012 to 2015.