ISEA/PGS Joint colloquium: 60 years of modern power electronics

To mark the 60th birthday of institute head Prof. Rik De Doncker, ISEA and the Power Generation and Storage Systems (PGS) institute at the E.ON Energy Research Center (E.ON ERC) of RWTH Aachen University held a colloquium on the history of modern power electronics, which only stretches back 60 years. Scientists, researchers, and practitioners from all over the world attended and took the opportunity to discuss the latest developments. Brief summaries of the content of their contributions appear on pages 2 through 5 of this issue of ISEA News.

Dear Readers,

The exciting history of modern, i.e. silicon based, power electronics stretches back six decades. Indeed, the market introduction of the thyristor in 1958 by General Electric marked a new era of electrical power conversion systems. The rapid development of the field of power electronics led to innovative products that even experts would not have believed possible in the middle of the last century. Looking back now brings back memories and evokes a bit of pride in the many achievements that have been made in this field. But tackling future challenges is even more important. Colleagues from all over the world are hard at work on new power electronic materials, devices and system solutions for various tasks. Nowhere has this been more apparent than at our colloquium. I hope you gain valuable and exciting insights from reading the summaries.

I wish you a happy reading!

Rik W. De Doncker

Merry Christmas and Best Wishes for a Healthy and Happy New Year from Rik W. De Doncker, Dirk Uwe Sauer, Egbert Figgemeier and the entire ISEA Team
Power electronics is celebrating an anniversary. The Silicon Controlled Rectifier (SCR), the very first thyristor, was launched in the market in 1958. This date marks the start of a sweeping technical revolution in the area of electrical energy conversion systems. The rise of power electronics created a completely new field of research and work for engineers.

Power electronics semiconductor components such as thyristors, diodes, and transistors have achieved ever greater performance. Today, these silicon base devices are used at voltages of up to 10 kilovolts and more, and they switch currents with amperage in the four digits. Modern industrial drives, electric mobility, solar and wind farms, even our everyday household electrical appliances, computer power supplies and battery chargers for our mobile phones would be inconceivable if it was not for power electronics.

After 60 years of intense development work, a new era is on the horizon. Advanced semiconductor components based on wide-bandgap semiconductors such as SiC and GaN enable even greater switching frequencies, such that power density is increasing tenfold.

Prof. Rik De Doncker, who claims to be as "young" as modern power electronics, took the initiative to hold an international colloquium focussing not only on the history of modern silicon based power electronics, but also on its ongoing innovations. ISEA and PGS scientists, researchers, and practitioners from all over the world attended the colloquium and took the opportunity to discuss the latest developments.

Brief summaries of the content of the contributions of keynote speaker appear on pages 2 through 5 of this issue of ISEA News.

ISEA/PGS Joint colloquium

60 years of modern power electronics

Alan Mantooth: Emerging Trends in Wide-Bandgap Power Electronics

Power electronics of high power density require the integration of different technologies, such as power semiconductor components, drivers, protective and control circuits, and passive and voltage-insulating technologies, into individual modules. One of the keys in achieving this was the development of wide-bandgap power semiconductors made of silicon carbide and gallium nitride. Integrated wide-bandgap high-temperature circuits, such as gate drivers, controllers, and protective circuits allow for integration right near the power semiconductors. Hence, parasitic effects that negatively impact system performance are minimized. This talk described emerging trends in analog and mixed-signal IC design of silicon carbide for applications in power electronics. Advanced 3D integration techniques can be achieved through multi physics design approaches, which were described in detail.

Jingxin Hu: Fault-Ride-Through Strategy of Dual-Active-Bridge Converter Based Intelligent Substations for Breakerless MVDC Grids

With the avenue of more decentralized power generation, renewables and modern power electronics, as well as the desire to increase efficiency and dynamic performance of electrical systems, medium voltage DC (MVDC) networks offer many advantages over classical AC grids. However, interrupting DC short circuit currents, in the case of faults, requires fast DC circuit breakers. Increasingly decentralized power generation, the rising volatility of power consumption, and the growing number of storage systems require interruption-free use of meshed DC grids with regard to network topologies. Dual-active-bridge (DAB) DC-DC converters are a key component of intelligent substations for meshed MVDC grids. They are used as DC transformers to connect different voltage levels, but that isn’t all; DABs also have to be able
to limit short circuit currents in the event of a DC fault. This is achieved through a novel control strategy that makes it possible to ride-through DC faults and limit the short circuit currents in DC grids. This feature of DABs makes it possible to use low-cost mechanical disconnect switches to isolate the faulty line. Hence, there is no need for expensive DC circuit breakers to safely operate MVDC distribution grids. The “fault ride-through” phase uses a space vector-based asymmetrical duty cycle control method that allows the DAB converter to provide a controllable current while maintaining soft switching operation even in fault states where there is no current. As a result, the “fault ride-through” capability of DAB converters and the associated fault coordination concepts enable DAB converter-based intelligent substations to design and operate breakerless meshed MVDC grids.

Peter Friedrichs:
Wide-Bandgap Devices – Next Generation Power Semiconductors

Developers of power electronics solutions face the ongoing challenge of improving application-related performance capacity and increasing power density while at the same time reducing weight and volume and the number of components. To meet these often contradictory requirements, engineers are increasingly turning to solutions based on wide-bandgap materials like silicon carbide (SiC) and gallium nitride (GaN). Thanks to the higher switching frequencies that these devices unlock, power density can be increased further as passive components are made smaller. The new solutions also offer potential for savings with regard to the cooling performance needed for the overall system.

Low charge and excellent dynamic properties in reverse conduction as compared to conventional silicon components enable more efficient operation at the same switching frequency in present-day power converter applications. The high dielectric strength and heat conductivity of SiC make it possible to develop components that outperform silicon-based alternatives – a crucial concern in areas like photovoltaics, industrial drive systems, traction and electric mobility. The key to success here is the use of unipolar components, even at very high blocking voltage.

List of speakers

Alan Mantooth, Distinguished Professor, Electrical Engineering Department, University of Arkansas, Director NCREPT and GRAPES, President of IEEE Power Electronics Society

Jingxin Hu, M.Sc., PGS/E.ON ERC, RWTH Aachen University

Dr.-Ing. Peter Friedrichs, Senior Director Infineon Technologies

Christoph van der Broeck, M.Sc., ISEA, RWTH Aachen University

Dr.-Ing. Jochen von Bloh, CEO AixControl GmbH

Prof. Frede Blaabjerg, Institute for Energy Technology, Power Electronics and Drives, Aalborg University, President Elect of IEEE Power Electronics Society

Dr.-Ing. Annegret Klein-Heßling, ISEA, RWTH Aachen University

Dr.-Ing. Jürgen Reinert, Deputy CEO, CTO and COO SMA Solar

Prof. Robert D. Lorenz, University of Wisconsin Madison, Co-Director WEMPEC, M. Witter Foundation Chair and E. Kaiser Chair

Prof. Adolf Müller-Hellmann, ISEA, RWTH Aachen University

Christoph van der Broeck:
Monitoring Localized Degradation of Power Modules via In-Situ Thermal Impedance Spectroscopy

Reliable and secure operation of inverters is highly important in many applications. One conservative approach to this is to design oversized power modules. Methods that monitor the aging of power modules in real time represent a cost-saving alternative. These methods guarantee reliable, secure inverter operation through early diagnosis of critical aging mechanisms and timely initiation of predictive maintenance.

One important group of degradation mechanisms involves structural degradation of the power module, such as delamination of power semiconductors and the DCB and deterioration of the convection process. The various technologies that detect structural degradation in situ, without interrupting inverter operation, focus first and foremost on detecting thermal resistance changes in the power module. Unfortunately, these technologies do not permit precise estimation of thermal resistance. Beyond that, monitoring the thermal resistance can only detect the accumulated structural degradation of the power module, it cannot be used to identify the various aging mechanisms that emerge locally, let alone to quantify them.

To address this problem, a method that makes it possible to identify, separate, and quantify structural degradation modes without interrupting normal inverter operation is presented. The in-situ thermal impedance spectroscopy that has been introduced stimulates the power components through targeted loss manipulation, extracts the temperature behavior using an innovative filter technique, and calculates thermal impedance in amplitude and phase over a broad spectrum. The phase information in particular is an important indicator for the various structural aging mechanisms. It can be extracted without errors using the method introduced.
The extracted frequency response information can be processed effectively using artificial neural networks to identify and quantify localized degradation modes separately. Combining in-situ thermal impedance spectroscopy and artificial neural networks via the Internet of Things in this way creates an outstanding sensor for remote diagnosis of degradation mechanisms and forecasting the lifespans of future power modules in the field.

Robert D. Lorenz:
Strategic Control and Sensing Developments for Power Electronics, Drives, Electric Machines, and Batteries

Prof. Lorenz, who has been a visiting Professor at ISEA over many years, took the opportunity to look back on recent achievements in power electronics and electric drive systems and to offer a look ahead at exciting future areas of research focus. He identified several key elements for power electronics research in the coming decades:

• Reducing the energy consumption of PM electric machines through precision control
• Improving the control of electric drives through advances in power electronics
• Enhancing the reliability of power electronics through active control to support passive integration methods
• Integrating critical sensors into WBG power electronics
• Improving the accuracy of drive controls without position sensors
• Secure, highly efficient design of a wireless energy transmission charging system for EVs
• Extending the lifespan of EV Li-ion batteries through active regulation of dynamic degradation

Frede Blaabjerg:
Power electronics – quo vadis

Power electronics represents a key technology when it comes to modernizing the energy supply system, electrifying transportation, or more generally making advances in protecting the environment. This presentation focused on a number of exciting research areas, showing where things might be headed with an eye to further improving the technology itself and the systems in which it is used. The following main topics were discussed in detail:

• Evolution of power electronics components
• Renewable energy supply
• Reliability of power electronics systems
• Grid stabilization based on power electronics

Annegret Klein-Heßling:
Active DC-Power Filters for Switched Reluctance Drives under Single-Pulse Operation

Switched reluctance drives require relatively large intermediate DC-link capacitors in order to filter the oscillating machine current. As a result, compared to inverters of AC machines, weight, volume and costs of SRM inverters tend to be larger. Particularly in the case of reluctance drives with a low number of phases, the current ripple can exceed the mean value of the current during single-pulse operation. This leads to higher losses in the power supply and the machine. Hence, additional filtering is often required.

This presentation focused on the use of an active DC power filter to minimize intermediate circuit capacity in switched reluctance drives. The control algorithms for the filter and the implementation thereof were presented in detail. To improve filter performance, the machine parameters are measured and continuously estimated during operation. The entire control is implemented in an FPGA-chip. This presentation concluded with an examination of the dynamic behavior of the active filter.

Jürgen Reinert:
Sustaining Power-Electronic Production in a Dynamic Market with Fast Technical Changes

The market for photovoltaics has always been a fast-moving one. Aid programs, overall conditions set at the policy level, and customer needs are in flux, and new market models (private consumption, storage systems, etc.) are arising. Solar energy today costs just a fraction of what it did 20 years ago. Survival in the decentralized energy supply market requires that new business models need to be developed.

With this in mind, SMA Solar’s activities currently focus on integrated PV systems with storage solutions, comprehensive service packages, and processing of large volumes of data. Alongside the technological alignment of product development (platform mindset, etc.), the organization and the necessary mindsets are also subject to a continuous process of adaptation. Agile methods, new management principles, and new structural models are all needed in order to assert and defend a position as a top player in this environment.

Jochen von Bloh:
Custom Power – Challenges and Opportunities for SMEs

Early on, as the number of industrial contract research projects at ISEA was growing, it became clear that project partners expected more than just providing research reports. In particular, industry partners expect that the knowledge acquired will be transferred professionally and that the prototypes developed at ISEA will be revised into products for pilot production. To bridge the gap between academic contract research and industrial product development, AixControl GmbH was founded in 2002 as a spinoff. During the realization of a wide range of different projects in cooperation with AixControl, researchers at ISEA had an opportunity to gain engineering experiences and develop a sense of what characteristics are necessary to successfully develop a product.

Typically, in projects the concept phase calls for both experience and creativity. In close cooperation with small teams at small and medium-sized enterprises (SMEs), each employee learns from colleagues on an ongoing basis expanding his or her knowledge of the subject. Having the opportunity
to contribute his or her own ideas is a major asset to innovate. During the design phase, the focus is on maintenance issues and the possibility of remote diagnosis. Features like these are especially important to SMEs that do not have a global service network. Close integration among individual departments also helps to ensure that products are commissioned quickly and efficiently. These characteristics make AixControl an appealing development partner to medium-sized customers, but that isn’t all. Global players also tap into the Aachen-based company’s expertise to support their own product development processes.

Adolf Müller-Hellmann: Modern Power Electronics – An Outstanding Way to Pave the Way for Optimization of Railway Drives

Railway drives face particular requirements with regard to system capability, traction behavior, efficiency, power to weight ratio, and service and maintenance costs. Advanced power electronics has allowed continuous optimization with respect to these requirements. Inverters used to adjust power and frequency have made it possible to replace AC commutator motors and direct and mixed current machines with induction machines. At the same time, four-quadrant control has virtually eliminated reactive power from the rail network. To reduce the heavy weight of the 16.7 Hz transformers on the rail vehicles, several concepts were developed with an increase in the frequency on the high voltage side. The evolution of these systems over the past sixty years was presented in detail.

Numerous friends, acquaintances, and former doctoral students took the event as an opportunity to address personal messages, some of them sent by video and many featuring anecdotes, looking back on their time with Prof. Rik De Doncker.
Dissertations

Susanne Lehner:
Reliability Assessment of Lithium-Ion Battery Systems with Special Emphasis on Cell Performance Distribution

Large storage systems have entered the limelight due to the growing storage demand in the field of regenerative energies and the electrification in the vehicle sector in the last years. This results in the need for considerably longer lifetimes as well as high reliability and availability of lithium-ion batteries in comparison to consumer applications.

The main objective of this thesis is to address aging on system level taking the cell-to-cell variation as well as the influence of boundary conditions into account. A vast experiment on module level is carried out, applying varying topologies and temperature gradients. Moreover, the impact of failures in a parallel connection is investigated.

Based on the measurement results, a system model is developed to estimate the lifetime expectancy of different battery architectures. The Boolean model is based on distribution functions such as a Mixed Weibull distribution for the lithium-ion cells.

Dr. Susanne Lehner (maiden name Rothgang) has been research associate at ISEA from 2010 to 2012 and from 2012 to 2017 chief engineer. Currently she is working as head of hybrid and battery systems at MAN Diesel & Turbo SE.

This dissertation was published by Shaker Verlag as vol. 88 of *Aachener Beiträge des ISEA* and is available under ISBN 978-3-8440-5090-5.

Stefan Käbitz:
Investigation of the aging of lithium-ion batteries using electroanalysis and electrochemical impedance spectroscopy

This work takes some steps towards a more complete description of aging effects in lithium-ion batteries and also on the EIS in combination with other electroanalytical procedures.

In the experimental part of this thesis a complex test matrix is evaluated, which shows the dependence of the aging of the cells from different depths of discharge and mean states of charge, covering a test duration of several years. It is a comprehensive study of the electrochemical properties in various aging conditions which can be measured without destruction of the cell.

Dr. Stefan Käbitz was associated from 2010 until 2018 as a researcher and chief engineer at the ISEA and later on at HI MS. Currently, he works as development engineer at Jungheinrich.

This dissertation ist published as vol. 89 of *Aachener Beiträge des ISEA* and is available under this [link](#).

Dr. Susanne Lehner (maiden name Rothgang) has been research associate at ISEA from 2010 to 2012 and from 2012 to 2017 chief engineer. Currently she is working as head of hybrid and battery systems at MAN Diesel & Turbo SE.

This dissertation was published by Shaker Verlag as vol. 88 of *Aachener Beiträge des ISEA* and is available under ISBN 978-3-8440-5090-5.
Dissertations

Julia Drillkens:
Aging in Electrochemical Double Layer Capacitors – An Experimental and Modelling Approach

Electrochemical double layer capacitors (EDLC), also known under the brand names supercapacitors or ultracapacitors, are energy storage devices that offer high power density, very high cycling capability and mechanical robustness. Although the energy storage principle is purely physical parasitic chemical reactions might occur during the storage process of EDLCs and lead to accelerated aging.

This thesis investigates the ageing processes of EDLCs and their impact factors such as elevated temperatures and cell voltages. Extensive test matrices of cyclic and calendric aging tests were performed with test periods up to more than three years. Post-mortem analysis of selected cells was performed to achieve a deeper understanding of the different aging processes at single electrodes.

Finally, a model was developed to simulate the electrical and thermal behavior of single cells as well as different module configurations. Additionally, an approach to represent the aging behavior as well was developed. This model is a useful tool for optimization of system design and operating strategies.

This dissertation is published as vol. 93 of Aachener Beiträge des ISEA and is available under this link.

Alexander Gitis:
Flaw detection in the coating process of lithium-ion battery electrodes with acoustic guided waves

The energy hunger of nowadays applications such as smartphones, drones, and electric vehicle, forces the lithium-ion cell manufactures to increase the energy density of their cells relentlessly. Under demanding conditions even small variations in the production of lithium-ion cell electrodes significantly affect the cell’s performance and durability. Therefore, a permanent monitoring of process parameters and of output quality is required.

In the current work, a novel non-destructive evaluation method is developed, which bases on ultrasonic Lamb waves and horizontally polarized shear waves. The correlation between the flaw types and the wave parameter changes are investigated experimentally and theoretically. Later the method is utilized for flaw identification and classification. Overall, the proof-of-concept for the proposed methodology and the mechanical set-up is successfully provided.

This dissertation is published as vol. 101 of Aachener Beiträge des ISEA and is available under this link.
Dissertations

Grzegorz Pilatowicz:
Failure Detection and Battery Management Systems of Lead-Acid Batteries for Micro-Hybrid Vehicles

Micro-hybrid vehicles (µH) are currently starting to dominate the European market and seize constantly growing share of other leading markets in the world. µH require accurate battery diagnostics to ensure the vehicle reliability, prolong service life, reduce warranty costs and maximize fuel savings. The latter refers to reducing number of premature restarts and missed stop-start opportunities.

This thesis presents battery state detection algorithms of lead-acid batteries developed for operation in µH applications. Their novelty is defined by improved accuracy, reliability, robustness and applicability for different types and sizes comparing to the known solutions. It was possible thanks to conducted comprehensive experimental and analytic study, allowing a better understanding of the relevant electrochemical processes. Result of these studies were the foundation for each of the described methods and allowed finding optimal simplifications without significant loss of performance. Reduced complexity is of high importance for implementation of these algorithms into the low-cost hardware, which is responsible for real-time estimation of the battery state, current, voltage and temperature of the terminal as well as communicating these values to the body computer of the vehicle.

This dissertation is published as vol. 92 of Aachener Beiträge des ISEA and is available under this link.

Heiko Witzenhausen:
Electrical battery models: modelling, parameter identification and model reduction

The aim of this work is to find out as much as possible about a battery through the current and voltage behavior, without being able to look inside. For this purpose, an electrical model description of the processes inside a lithium-ion battery is developed and successively simplified. The novel parameterization method uses electrochemical impedance spectroscopy (EIS), a correlation analysis for process identification (DRT) and measurements with DC excitation. Thus, the separation of the individual processes occurring in the battery and the assignment to positive and negative electrode succeed.

Finally, the method described is applied in two studies: An example of a full parameterization based on the battery cell of the Mitsubishi iMiEV and that of the BMW i3 and the parameter convolution during a cycle aging test. With this model, a completely new operation strategy of batteries becomes possible.

This dissertation is published as vol. 90 of Aachener Beiträge des ISEA and is available under this link.

Dr. Grzegorz Pilatowicz worked as a researcher and team leader at ISEA between 2010 and 2015. Today, he works as technical expert for LEM Switzerland SA in the field of battery diagnostics.

Dr. Heiko Witzenhausen worked from 2011 to 2017, first as a research assistant and then as chief engineer at ISEA. Today, as a systems engineer, he develops battery electronics at Daimler AG.
Dissertations

Jan Becker:
Flexible Dimensionierung und Optimierung hybrider Lithium-Ionenbatteriespeichersysteme mit verschiedenen Auslegungszielen

Today’s traction battery systems of electric vehicles consist of a series- and parallel connection of one kind of battery cells. By using an additional dc-to-dc converter, battery cells of different kinds can be combined to a so called hybrid battery system with multiple individual packs. This approach offers significantly more flexibility during design of the battery system since the characteristics of the individual battery kinds can be combined advantageously.

In this work a method has been developed which automatically dimensions an optimized battery system for defined vehicle requirements and a given set of battery cells. The developed tool has been used for several vehicle classes to analyze the approach of hybrid storage systems in terms of costs, system mass, volume and further categories and to compare the hybrid batteries to common single pack battery systems.

This dissertation is published as vol. 104 of Aachener Beiträge des ISEA and is available under this link.

Dr. Jan Becker worked as a researcher from 2011 until 2018 in the department for battery system design and vehicle integration. Since June 2018 he has been heading the energy storage competence center at A. Kärcher SE & Co. KG.

Johannes Schmalstieg:
Physico-electrochemical simulation of lithium-ion batteries: implementation, parametrization and application

Physico-electrochemical models provide an insight into the internal state variables of lithium-ion batteries, which cannot be measured, but are very important for safe operation. For this purpose, the fundamental processes of the battery reaction are implemented in the model and parameterized with material data.

This work first describes the basics of such a model and a specific implementation. Using the example of a commercial high-performance cell, the determination of the various material data by sample collection and measurements is presented. The parameter set determined in this way is verified by comparing numerous measurements with simulation results.

Finally, the application possibilities of the model are illustrated by the simulation of effects observed in ageing tests and the validation of the theories behind these effects. Such a concretely parameterized model thus enables optimal operation even under extreme conditions such as fast charging.

This dissertation is published as vol. 96 of Aachener Beiträge des ISEA and is available under this link.

Dr. Johannes Schmalstieg worked as a research assistant at ISEA from 2011 to 2017.

He is now working as a systems engineer in the battery development department of Daimler AG.