Technische Universität Braunschweig

elenia Institute for High Voltage Technology and Power Systems

Annual Report 2022/2023

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Dear Readers,

While life at our university has fortunately returned to normal in the last two years after the Covid-19 pandemic, two new developments have brought the topic of “energy” into public focus. First, since the “Ampel” coalition agreement of December 7, 2021, the energy transition has been accelerated (e.g. through the increased expansion of renewable energies and electricity grids, the resumption of the rollout of smart meters and the controversial Building Energy Law), followed by the Russian war of aggression against Ukraine on Februaryy 24, 2022, which drove gas prices and thus also electricity and district heating prices in Germany to new heights due to the interruption of Russian gas supplies. At the TU Braunschweig, for example, this led to a threefold increase in electricity prices and a concerted effort to save energy. One example of this is the purchase of warm and cozy elenia fleece jackets for the employees on the cover picture, in order to reduce the room temperature by up to 2 degrees.

Although the demand for electrical energy engineers, for example from industry and grid operators, is increasing due to the energy transition and demographic reasons, the number of first-year students has been declining nationwide for many years. The successful launch of the new bachelor‘s program in Sustainable Energy Systems and Electromobility has only provided temporary relief for our faculty. Everyone involved must work together to change the somewhat outdated image of electrical engineering among students to one of its innovative and societal importance.

In this two-year report, we once again give an account of our research activities and the use of funds. The share of third-party funding has been further increased by many innovative and fundamental research projects. We would like to thank all persons and organizations, the TU, the companies and research institutions, the lecturers, the DFG, the project sponsors, the federal and state ministries and the PTB for the good cooperation and support of our work.

Above all, this report provides a platform for our dedicated employees to share their ideas and results with experts and society. We have included contact information for each article to to offer you the opportunity to share and exchange ideas.

In 2025 our Institute will turn 100 years old. For the autumn of 2025, we are planning the biannual elenia Energy Symposium with centenary celebrations for all our friends and partners.

We hope you enjoy reading our report and wish you good luck, all the best and, above all, good health for 2024.

Bernd Engel, Michael Kurrat
BRAUNSCHWEIG, OCTOBER 2023

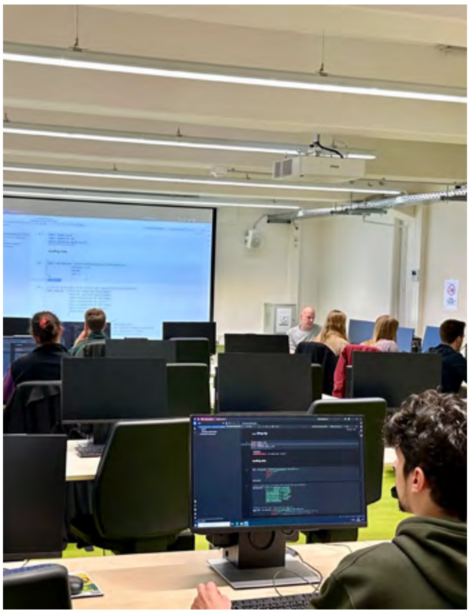
elenia

Research Reports

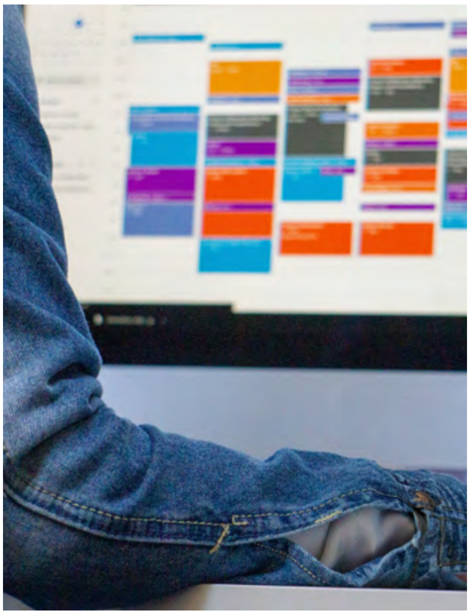
Doctoral Theses

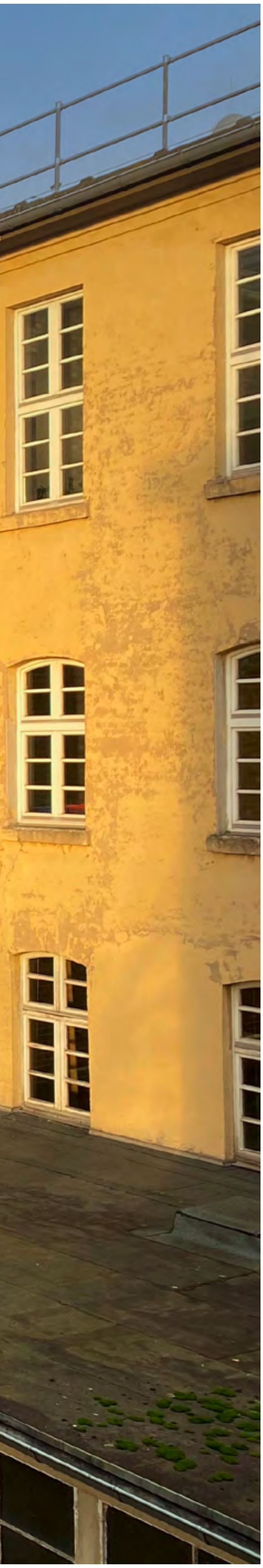
Labs and Workshops

Teaching



Chronology





elenia

Review of the Years 2022 and 2023

Back to normal? Some new challenges!

The reporting period was initially dominated by the COVID-19 pandemic. However, in early Februaryy 2023, the Robert Koch Institute downgraded the risk of COVID-19 for public health in Germany from ‘high’ to ‘moderate’. As a result, the summer semester of 2023 was the first ‘normal’ semester since the start of coronavirus infections.

It was not only the normalization of the teaching situation over the course of the reporting period; PhD examinations, project meetings with research partners and conferences also increasingly took place in person again. The following events were important for re-experiencing the Institute community: the 2022 summer party, which was perceived as a special highlight after all the Institute events in virtual space, various working group workshops in 2022/23, the 2023 Whitsun excursion with students to Switzerland and the 2023 Institute excursion to the Wind- and Watermill Museum in Gifhorn with an invitation to lunch by Prof. Michael Kurrat on the special occasion of his 60th birthday. The organization of the 12th Braunschweiger Energy Seminar followed by the elenia Symposium in October 2023 was also successful. At both events, there were many interesting presentations from fellow institutions and the participants enjoyed networking during the breaks and over dinner. The elenia was also highly involved in ETG conferences such as the High Voltage Days 2022 and High Voltage Goes Green 2023 as well as the Grid Integration Week 2022 in The Hague and 2023 in Copenhagen. A special highlight was the 2023 graduation ceremony, which honored two PhDs: Dr. Robin Drees with the Dieter Kind Prize and Dr. Dirk Bösche with the Walter Kertz Prize.

During the reporting period, the organization of the growing institute was further developed. This is mainly carried out by elenia’s Management Board, which is largely shaped by the highly motivated Project Management Office (PMO) and its members. Among other things, an administrative manager responsible for the office and other administrative processes, Dr. Frank Soyck, and a technical manager, Dr. Dirk Bösche, responsible for the mechanical and electrical workshops and IT, were appointed from among the experienced scientific staff and postdocs. The administrative office experienced a personnel renewal in 2023 due to the departure of Jacqueline Schmidt and Petra Thiele, who had been managing the financial resources for many years. Nancy Preuße and Sylvia Glowania have found new approaches to managing business processes.

The team structure has proven its worth for growth, because many questions of work distribution, scientific exchange and content development are clarified with new project applications. In both working groups at the Institute, there are teams that benefit from a certain “scientific boom” and the outstanding pioneering work. The battery technology team in the Energy Technologies working group is growing rapidly, thanks in no small part to former team leader Dr Robin Drees. In addition, battery research is concentrated in the Braunschweig region with several research centers from the Battery LabFactory Braunschweig (BLB) to the new Fraunhofer Centre for Energy Storage and Systems (ZESS) to the application in the large Salzgitter battery factory in a breadth that is unique in Europe.

Within the Energy Systems working group, the System Stability and Grid Dynamics team has been particularly successful in submitting applications for projects involving grid-forming inverters. On the one hand, this is certainly due to the preliminary work of the former team leader Dr. Florian Rauscher, among others, who completed his excellent PhD in 2023 after the highly regarded BMWK research project Grid Control 2.0 in 2022. On the other hand, the grid-forming inverter for achieving stable operation with 100% renewable energy has been the subject of much discussion between grid operators and energy policymakers since the German government’s System Stability Roadmap, of which Prof. Bernd Engel is a member of the advisory board. Another new topic represented by team leader Timo Sauer is the coupling of grid-forming inverters and hydrogen electrolysis, which he is also researching at the newly built H2 Terminal Braunschweig.

More research projects mean additional space requirements: the TU’s building management was able to rent 150 square meters of space for ten new workstations from Nord/LB in Mühlenpfordtstraße. The elenia energy lab can also be expanded with a large laboratory area that the Electrical Engineering Student Council kindly gave up when it moved to the E-Tower. In addition, the power test field with a direct connection to the 20 kV grid of BS|Netz and a maximum output of 18 MW was inaugurated in the high-voltage lab.

The faculty and elenia are particularly focused on attracting new students. According to the German Association of Electrical Engineering Faculties, the nationwide decline in the number of first-year bachelor students of -20% within four years compared to 2019 not only has a national impact, especially on the personnel requirements of the energy transition, but also leads to a shortage of young talent and tangible financial losses for the faculty. elenia played a key role in the successful introduction of the new bachelor degree programme in Sustainable Energy Systems and Electromobility (“NEEMO”) for the winter semester 2022/23. In addition, elenia is currently planning a number of student recruitment campaigns.

Bundesrepublik Deutschland

Urkunde

über die Eintragung der
Marke Nr. 30 2023 228 618

Az.: 30 2023 228 618.8

elenia
Institut für Hochspannungstechnik
und Energiesysteme

Inhaber/Inhaberin
elenia Institut für Hochspannungstechnik und Energiesysteme, Körperschaft des öffentlichen Rechts, 38106 Braunschweig, DE

Tag der Anmeldung:
01.08.2023

Tag der Eintragung:
31.10.2023

Die Präsidentin des Deutschen Patent- und Markenamtes

Eva Schewior

München, 31.10.2023

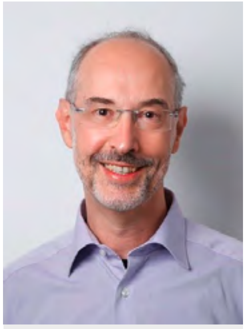
DEUTSCHES PATENT- UND MARKENAMT

Den aktuellen Rechtsstand und Schutzumfang nach dem Verzeichnis der Waren und Dienstleistungen entnehmen Sie bitte dem DPMAregister unter www.dpma.de.

We have been a registered trademark at the German Patent and Trademark Office since October 31, 2023.

Current Team

Head of the Institute



Prof. Dr.-Ing. M. Kurrat
Managing Director until 2023

Prof. Dr.-Ing. B. Engel
Managing Director since 2023

Office Secretariat and Accounting

Elke Droemer

Sylvia Glowania

Nancy Preuße

Manja Rücker

Team Battery Technology

Oliver Landrath
Team Leader

Merit Holdorf

Cedric Jackmann

Torben Jennert

Andreas Laufer

Anna Rollin

Team DC Systems and Switching Technologies

Patrick Vieth
Team Leader

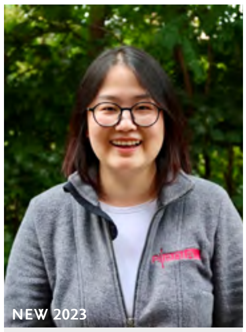
Dirk Bösche

Lars Claaßen

Melanie Hoffmann

Marc René Lotz

Fabian Witt



Fanke Zeng

→ **Team High Voltage-, Vacuum- and Plasmatechnology**

Karen Flügel
Team Leader

Maik Kahn
Working Group Leader

Muhamet Alija

Timo Meyer

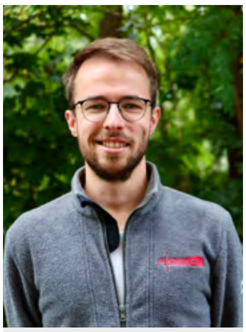
Enno Peters

Laura Tiedemann

→ **Team Energy Economics and Energy Management**

Henrik Wagner
Team Leader

Frank Soyck
Working Group Leader

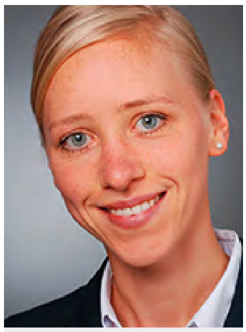


Felix Klabunde
Working Group Leader

Tamara Beck

Julien Essers

Mattias Hadlak
Deputy Team Leader



Lily Kahl

Marcel Lüdecke

Michel Meinert

Eike Niehs

Kevin Preißner

Jonathan Ries

Ajay Kumar Thakur

Carsten Wegkamp

→ **Team Grid Operation and Grid Planning**

Gian-Luca Di Modica
Team Leader

Cornelius Biedermann

Lukas Ebbert

Nils Gräfer

Robin Herman

Hartmudt Köppe

Merten Schuster

→ **Team Grid Dynamics and System Stability**

Timo Sauer
Team Leader

Max Gand

Till Garn

Johanna Grobler


Stefan Klöpping

Nelly Schulz


Frederik Tiedt


Stefanie Walujski


Björn Oliver Winter

→ IT-Department


Fabian Scholz
Head of IT


Lukas Oppermann
IT Administration

→ Mechanical Workshop


Kerstin Rach
Workshop Supervisor


Frank Haake


Julia Musebrink


Claas Narup

Matthis Grosche

→ Electrical Workshop


Christian Ryll
Workshop Supervisor

Former employees

Thank you for your cooperation.
Best wishes for your future endeavors.

Mohammed Qudaih (2021)
Tobias Kopp (2022)
Dr. Ing. Jonas Wussow (2022)
Wai Yee Choi (2022)
Melanie Hoffmann (2022),
Post-doc seit 2022

Florian Rauscher (2022)
Edwin Ariel Rebak (2022)
Julian Studt (2022)
Christian Reinhold (2022)
Dr.-Ing. Ernst-Dieter Wilkening (2022)

Frederik Anspach (2023)
Benjamin Weber (2023)
Robin Drees (2023)
Petra Thiele (2023)
Jaqueline Schmidt (2023)
Mauriz Kahmann (2023)

Student assistants 2022/2023

We would like to express our gratitude to our student assistants for their invaluable support.

2022
Faraj Abd Alraheem, Farit Ari, Harun Al-Sarea, Nikhil Arora, Alexandra Aumüller, Emmanuel-Wilson Bauni-Kamga, Robert Beyer, Jonas Biniek, Jonas Brinkmann, Max Brüggemann, Ayan Roy Chowdhury, Eray Cinkaya, Serkan Cokgün, David Cziumplik, Marcel Falinski, Felten Feldt, Max Gand, Ilja Gitin, Hendrik Grafelmann, Johanna Grobler, Janina Gottschalk, Timo Haakert, Nils Hartau, Franziska Harstrick, Pavan Ramesh Hallur, Charu Kabbalagerepura Venkatesh, Julius Kohlhepp, Felix Korff, Abdulbaki Kocabasa, Katharina Kocur, Hendrik Kösjan, Henning Krüger, Andreas Laufer, Sebastian Lindemann, Adrian Lux, Michelle Magrian, Manuel Meinecke, Shridhar Pamarish, Friederike Paul, Julius Günter Platon, Marten Probst, Xin Qi, Nils Reinköster, Julius Rieckmann, Thomas Röthig, Abbas Salamehzavareh, Salman Saleem, Stefanie Schürmann, Kristina Schwenk, Daniel Swientek, Kevin Schiemenz, Christian Schläger, Victor Schnell, Nelly Schulz, Kai Schulze, Julian Schwung, Lia Stücke, Laura Tiedemann, Julius Trützschler, Steffen Viere, Arnold Walker, Dominik Wessel, Fabian Winkler, Cathleen Wiese, Meiyan Wu, Le Xuan Thien, Fanke Zeng, Jakob Zimmermann, Hejie Zhu, Shaojie Zhu,

2023
Faraj Abd Alraheem, Jan Ackermann, Aleixo Alonso, Harun Al-Sarea, Firat Ari, Nikhil Arora, Carl Bettermann, Jonas Brinkmann, Steffen Bollhorn, Fani Cahyani, Lei Chen, Eray Cinkaya, David Cziumplik, Benedict Dammann, Marcel Falinski, Tabea Fehrs, Martin Funk, David Geißler, Niels Grafelmann, Keno Giesselmann, Johanna Grobler, Janina Gottschalk, Peer Ole Hansen, Nils Hartau, Felix Haschke, Mara Hiller, Deborah Höltje, Tobias Jesberger, Katharina Kocur, Leona Kunze, Hannes Kurzmann, Henning Krüger, Andreas Laufer, Jiakun Liu, Adrian Lux, Michelle Magrian, Jost Maenicke, Manuel Meinecke, Duc Anh Nguyen, Erdene Otgonpurev, Shivam Pandey, Marlene Pape, Emma Maria del Rosario Pensky, Vikas Poojary, Sahib Sing, Rajbeer Singh, Nils Reinköster, Julius Rieckmann, Anna Ronsdorf, Nils Rosebrock, Johannes Rothert, Thomas Röthig, Abbas Salamehzavareh, Tjark Schmidt, Victor Schnell, Eike Schwarz, Kristina Schwenk, Kai Schulze, Stefanie Schürmann, Oscar Steiner, Ajay Kumar Thakur, Zhi Teng, Julius Trützschler, Ali Vahidi, Steffen Viere, Constantin von Lützow, Sascha Wasner, Rika Webel, Maurice Weinand, Cathleen Wiese, Le Xuan Thien, Jakob Zimmermann, André Zurmühlen.

Facts and Figures

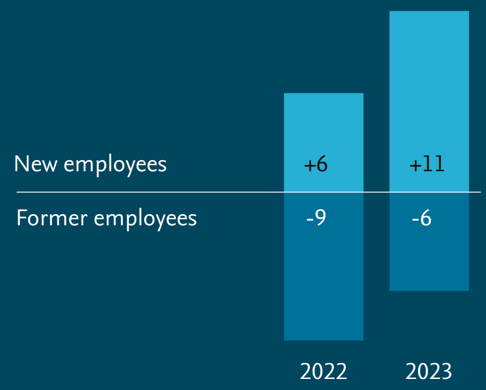
Values and goals

„Achieving excellence in research and teaching and actively shaping the future of energy technology“

The years in numbers

People

- 2 Professors
- 2 Administrative and Technical Management
- 4 Staff members of the office
- 8 Assistant Lecturers
- 5 Staff members in the Mechanical Workshop
- 1 Staff member in the Electrical Workshop
- 53 Research Assistants
- 73 Student Assistants 2023



Location

Braunschweig (Lower Saxony)
since 1925

Braunschweig
1 University
6 Faculties
104 Courses
132 Institutes
2.100+ Scientists
16.809 Students

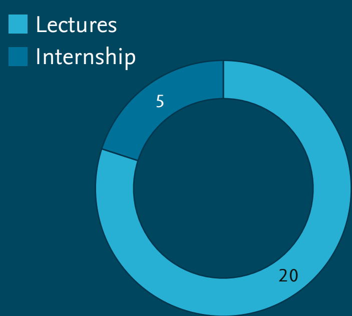
Student Work

Bachelor
16 (2022)
18 (2023)

Master
43 (2022)
54 (2023)

Studies
11 (2022)
14 (2023)

Teaching



Paths to elenia

Julien Essers

A Career Path Marked by Power Engineering

My name is Julien Essers, and I would like to outline my journey from high school graduation to my current position as a research associate in the Energy Systems group (e^3) at the elenia Institute.

After completing my high school diploma in Marburg an der Lahn, I opted for training as an industrial clerk at HOPPE AG. However, I soon realized that my interest was more inclined towards the technical field. I made the academic switch and dove into the world of technology.

Studying Electrical Engineering at the Technical University of Braunschweig, with a focus on power engineering, offered me the perfect opportunity to deepen my knowledge and interest in sustainable energy generation and use.

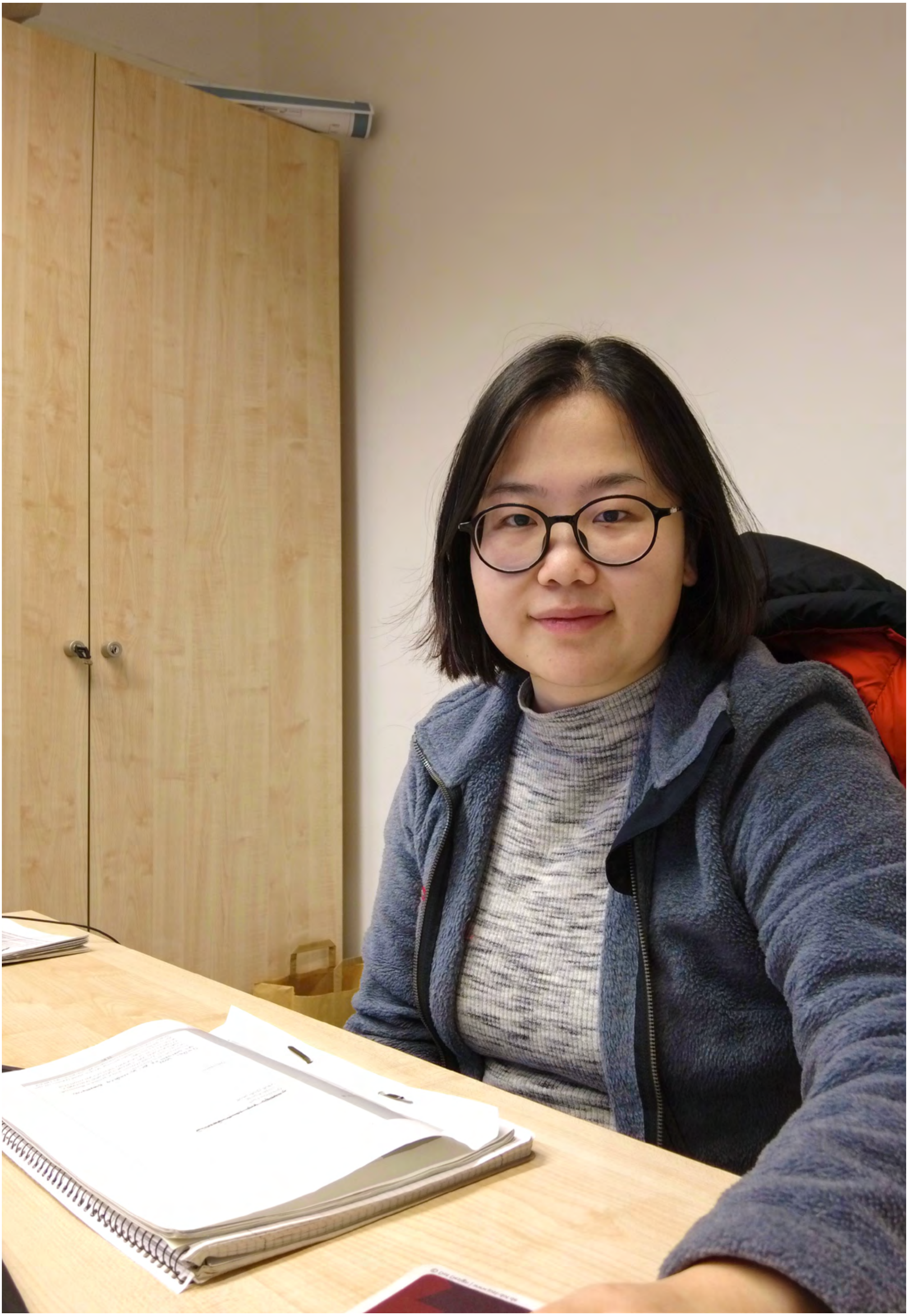
During my bachelor's degree, I had the exciting opportunity to work as a student assistant at the Institute for Joining and Welding Technology in the field of battery technology. Here, I was able to gain initial practical experience and deepen my knowledge in lithium-ion cells. My bachelor's thesis was dedicated to the influence of contamination products generated during laser separation on the performance of lithium-ion cells.

With the commencement of my master's degree, the opportunity arose to work as a laboratory engineer in the „flexess" project at the elenia Institute. This position allowed me to further expand my IT skills and work on projects in the field of energy systems in a practice-oriented manner.

After successfully completing my master's, I seized the opportunity to work as a research associate (WiMi) in the e^3 team of the Energy Systems group at the elenia Institute. I have been active here for some time now, dedicating myself to various exciting projects in the field of energy systems.

My journey from a high school graduate in Marburg to a research associate at the elenia Institute has been characterized by a clear focus on power engineering. The combination of theoretical knowledge from my studies and practical experience in various projects enables me to make a valuable contribution to the development of sustainable energy systems. I look forward to continuing to participate in groundbreaking projects and contribute to the energy transition.

Julien Essers



Fanke Zeng

From student to research assistant

Brief introduction

In June 2019, I completed my bachelor's degree in China. Three months later, I moved to Germany and completed a language program at Leibniz University Hannover. During this time, I applied for the Electrical Engineering program at the Technical University of Braunschweig and officially started my Master's degree in the summer semester of 2020.

During the Master's Degree Program

It took me about a semester to get used to the different curriculum and learning atmosphere here. After slowly acclimating, I chose to attend lectures on topics in the direction of high voltage, DC and power electronics. In this way, 80% of my lectures were taken at elenia. After the „Power Systems Engineering" lectures, I applied for the Hiwi position at the institute. In the following months, I worked as a student assistant on two projects: SE2A (Tobias Kopp) and DC-Industry (Maik Kahn). During this time, I finalized the topic of my thesis and completed my master's degree at the end of 2022.

In the Institute

While writing my thesis, I started following the job openings posted on the official website of the institute and submitted my application for DC related topics. I officially started working here in Feb. 2023.

Now, I have been working at the Institute for almost a year. The atmosphere at the institute is very pleasant. Everyone here is friendly and supportive. During this year I have learned a lot about completely new areas. I am currently working on the ETHAN project. In this project we are responsible for the development of electrical systems for electric airplanes.

Fanke Zeng

Research Components for Power Systems

Powerful switching devices and innovative protection systems for efficient energy supply in AC and DC grids

In the context of the university strategies City of the Future and Mobility, the change in energy technology is a decisive factor. The elenia Institute for High Voltage Technology and Energy Systems at TU Braunschweig makes a significant contribution to this change by developing methods for the development of components and their integration into networks. These methods are intended to meet the requirements of a flexible and environmentally friendly energy transmission system. In our teams, different aspects of energy grids are examined from the system level to the component level. The focus on components includes two teams from the Energy Technologies working group: The ‘DC and Switchgear’ team and the ‘High Voltage, Vacuum and Plasma Technology’ team. Research is being conducted on equipment and technologies for efficient energy supply in AC and DC systems. The development of protection systems and the application of ‘Model Based Systems Engineering’ form the system level. Furthermore, new methods and materials for insulation systems are being developed and investigated, for example new materials and their behaviour in the high-voltage onboard network. At the component level, circuit breakers are developed, tested and optimized for all voltage levels for AC and DC. Environmentally friendly alternatives to current techniques are being investigated, for example in SF_6-free switchgear. Our highly motivated teams implement specific goals, depending on the respective level. These goals are realized in projects in cooperation with partners from research and industry.

Methods and competencies

Our research on reliable components of energy supply is driven by a variety of methods and long-standing competencies. In this way, we contribute to new insights through scientifically secured foundations. In the planning of future energy supply grids, our toolbox for grid planning is used. With proven evaluation and selection strategies, the best topology of the future grids can be found, taking all interests into account. The Systems Engineering method offers advantages in the development of the appropriate network through the early inclusion of all interests. Validation and verification loops lead to the consideration of all requirements. Our experience with DC grids at low operating voltages helps in scaling to high operating voltages. With the help of Power-Hardware-in-the-Loop systems, even larger and more complex systems can be replicated and thus investigated in the laboratory. In the case of error handling in DC grids, AI-based error detection methods are used, which ensure safe and early detection of errors. In this way, multi-layered and functional protection systems are created through intelligent linking. Our long-standing experience with overvoltage protection and lightning current diverters thus flows into the protection systems for future DC grids. For sustainable high-voltage systems, our research on power switchgear with climate-friendly switching and insulating gases contributes. In particular, the plasma characterization during the switching-off process and the analysis of the plasma behavior after current zero with optical camera observation provide the basics of physical processes. The automated evaluation of camera images of the metal vapor arc plasma in the vacuum circuit breaker

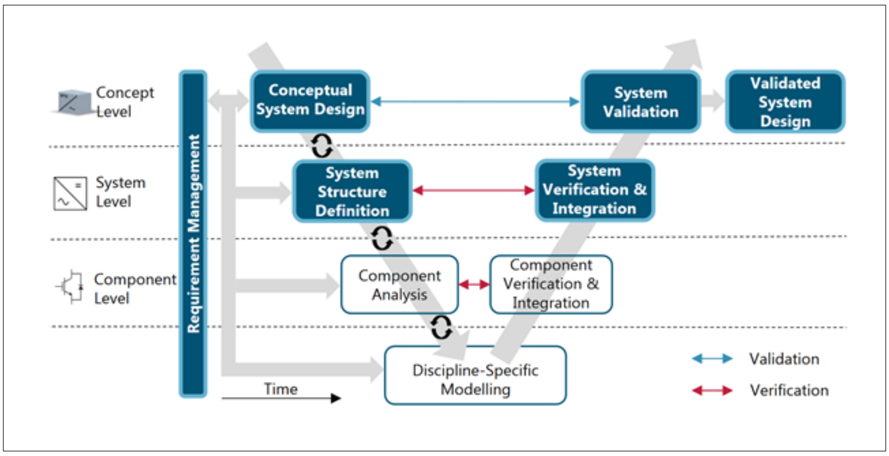


Figure 1: V-model, in reference to Melanie Hoffmann, dissertation

Figure 2: model switch, Dirk Bösche, dissertation

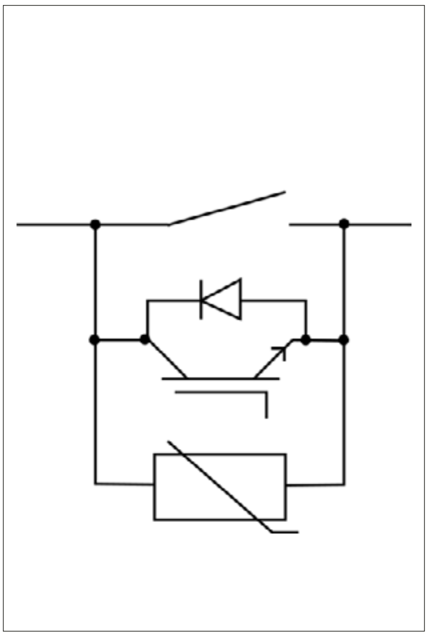


Figure 3: hybrid circuit breaker, Patrick Vieth

enables the arc detection and analysis of the rotation of the vacuum arc. For use in higher voltage levels, modular switchgear is one way to meet the requirements of electrical strength. We support these approaches with simulations and model building. The control of undefined potentials is often in focus. For the requirements of electromobility, the insulation material characterization of modern materials is important in order to meet the requirements of the insulation of battery systems and on-board networks with increasing switching speeds. We accompany the possibilities offered by additive consolidation with the systematic investigation of various printed insulating materials.

DC Systems

The use of DC grids allows for an increase in efficiency by eliminating DC/AC and AC/DC conversion losses, but it also presents new challenges for the protection system. Fault currents rise faster due to the lower grid inductance and do not extinguish, unlike alternating current, due to the lack of zero crossing. A requirement analysis is essential for the design of a suitable DC protection system. Methodically, systems engineering serves as a holistic development approach in which all stakeholders are involved in the requirement analysis. Coordinated concepts are created as a basis for the design of the subsystems and their interaction as a complete system. A central part of the requirement analysis is detailed network simulations (MATLAB Simulink), which provide a criteria catalog for distinguishing the permissible operating conditions from the fault case for the network parameters used. At elenia, modern protection systems for industrial applications, aviation, and private households are being developed. The establishment of modern laboratory facilities allows us to test and investigate protection systems up to the medium voltage range of 3000 V. Furthermore, PHIL facilities are available, which will be further expanded in the future. A promising protection concept is the use of current-limiting power electronics (switchless protection concept), which is particularly characterized by high speed and robustness. In addition, classic switchgear can be used for fault clearance. The changed networks compared to AC also lead to higher requirements for DC switchgear. To meet these requirements, switchgear is being developed at elenia in cooperation with project partners and as part of dissertations. The focus is particularly on mechanical switchgear and hybrid switchgear. In addition to development, it is also investigated how existing switchgear can be optimized. Here, the recovery investigations on hybrid switchgear as part of dissertations are particularly worth mentioning. For this purpose, modern test fields have been set up. On the one hand, industrial grids can be replicated in our test fields and protection systems can be investigated. In a test field specially set up for switchgear tests, switchgear can be tested under short-circuit conditions with up to 15 MW. Overall, the test facilities and competencies in the DC team can systematically develop, build, and test the protective devices for DC grids.

High voltage technology

The revision of the EU's F-Gas Regulation and the discussed PFAS ban result in an avoidance of the use of sulfur hexafluoride (SF_6) as an insulating and switching gas in high-voltage technology. This is important for the goal of reducing greenhouse gas emissions from energy generation and distribution. This results in a high need for research and development of climate-neutral switching and insulation systems for high-voltage grids. The HVP team is researching alternative gases that are fluorine-free and climate-friendly. The focus here is on the dielectric strength of the different gases at various pressures, electrode distances, and electrode surfaces. This is to determine which is the best alternative for a fluorine-free circuit breaker. In addition to the insulating properties of the gases, the thermal extinguishing ability is also important for successful current extinction in the switchgear. For this purpose, investigations are carried out on high current loads and the subsequent resolidification.

In particular, vacuum-insulated switchgear is suitable for replacing SF_6 switches due to their climate neutrality and non-toxicity. Vacuum circuit breakers (VCB) have been established in medium-voltage systems for decades, and intensive research is currently being carried out for high-voltage applications. The changed short-circuit currents and larger switching strokes are investigated as well as the electric strength of the vacuum insulation. Due to the degressive curve of the electric strength of the vacuum, multiple interruptions are used at high voltages. The lightning impulse voltage (LIV), the highest voltage occurring in the grid, is decisive for the investigation of the electric strength.

As part of the mobility transition, we make an important contribution with the characterization of new insulating media. The increasing on-board network voltages and increasingly high switching speeds of the semiconductors change the requirements for the insulating materials used. Thus, new sustainably produced insulating materials must be characterized over the entire lifespan and a wide frequency range. In addition to the properties of individual insulating materials, the investigation of the entire insulation system with partial discharge diagnostics is important, as each component must be precisely examined for a robust insulation system. For the safety of the components and grids, successful control of the switching plasma in switchgear is essential. The necessary plasma properties are investigated at elenia both simulative and experimentally. With various model components such as lightning arresters for lightning protection, DC hybrid switches, and circuit breakers, which enable the optical investigation of the plasmas, the plasma is investigated both in the high current phase and during resolidification. The detailed simulation and measurement data are used for model building.

Figure 4: SF_6-free switchgear, Laura Tiedemann

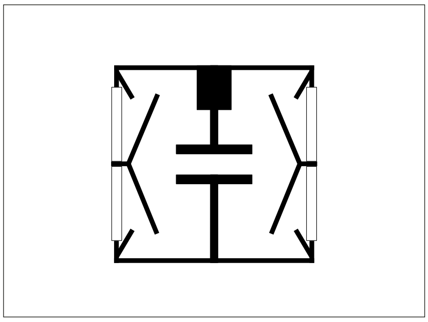


Figure 5: Schematic diagram of vacuum circuit breaker, Karen Flügel

Figure 6: insulation system for electromobility, Maik Kahn

RESEARCH NAME

Components for Power Systems

RESEARCH MENTOR

Prof. Dr.-Ing. Michael Kurrat
m.kurrat@tu-braunschweig.de
+49 531 391 7735

DC SYSTEMS AND SWITCHGEAR

Patrick Vieth, M.Sc.
p.vieth@tu-braunschweig.de
+49 531 391 9725

HIGH-VOLTAGE, VACUUM AND PLASMA TECHNOLOGY

Karen Flügel, M.Sc.
k.fluegel@tu-braunschweig.de
+49 531 391 7785

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/komponenten-der-energieversorgung

Research Active Distribution Grid

Innovative technical and economic solutions for stable grid operation and flexibilization

The energy transition is facing a number of exciting challenges in the areas of grid integration, grid technology and energy management and economics. However, from today's perspective, we can identify an absolute game changer for the success of the energy transition - the smart grid! This is where consumers, producers, storage systems and grid equipment are effectively connected and controlled.

Here at the elenia Institute for High Voltage Technology and Energy Systems at the TU Braunschweig, we are making a decisive contribution to the future of the energy transition. We focus on the active distribution grid, a central field of research that deals with a wide range of topics relating to the future role of the distribution grid and the grid operator. Here we build bridges between technical innovations, new concepts for operating the distribution grid and associated economic considerations.

Thanks to our intensive work, the elenia Institute is actively shaping the energy transition and developing smart overall concepts that steer the future renewable energy system in the right direction. Our exchange formats in the Active Distribution Grid focus area are divided into highly specialized research areas dedicated to the complex issues of our time. Together, we are committed to accelerating the energy transition!

Grid Dynamics and System Stability

The team consists of six research assistants and three laboratory engineers who work on the grid-friendly integration of renewable energies to ensure future transient grid stability. Research focuses on the electrical behaviour of generators and loads during transient grid events such as disturbances of the active power balance or grid faults. For this purpose, different control strategies (grid forming & grid following) of power converters and primary energy sources are investigated and innovative control mechanisms are designed. The core areas here are the provision of instantaneous reserve and other highly dynamic frequency maintenance mechanisms as well as the contribution to the short-circuit current and short-circuit ratio from renewable energies. In addition, the passive and active islanding detection of grid-forming and grid-following converters is being researched.

For example, it is being investigated how the comprehensive use of grid-forming power converters in the distribution grid can be realized, how prosumers can provide instantaneous reserve and how large batteries can be regulated to form the grid. Research is also being carried out into how electrolysers and innovative pumped storage power plants can be integrated to serve the grid and what metrological requirements exist for power converters to provide instantaneous reserve for certification.

In the grid dynamics laboratory, a wide variety of grid components can be simulated using freely programmable and commercially available power converters, an automated grid simulation, various loads and a Power HiL system, and their interaction and electrical behaviour in the event of grid faults can be investigated and simulative results validated.

Figure 1: Measuring systems and real-time HiL system, Photo: TU Braunschweig, Henrik Herr

Grid Operation and Grid Planning

The research in grid operation and grid planning focuses on reactive power management and power quality.

The field of voltage maintenance includes the decentralized provision of reactive power from individual PV systems or electric vehicles based on grid connection conditions for local voltage maintenance through to active reactive power management across voltage levels and grid operators. It has already been shown that renewable energy systems are an alternative and supplement to the installation of reactive power compensation systems in reactive power management. This can also have economic benefits. In the Q-Integral project, important questions regarding future reactive power management in distribution and transmission grids were answered. The follow-up project Q-Real covers reactive power management in real-life applications: Grid planning, grid operation and reactive power sources for transmission and distribution grids.

In the field of voltage quality, the team investigated the effects of increasing penetrations of PV systems, electric vehicles, home storage systems and power-to-heat systems on voltage quality characteristics in the low-voltage grid. Important findings were developed on the basis of laboratory and field measurements. In addition, regulations are being developed to maintain the voltage quality in the low-voltage grid even with an increasing number of power electronic components.

Figure 2: : Charging infrastructure for measurements of electric vehicles, Photo: TU Braunschweig, Henrik Herr

Energy Management and Energy Economics

The “Energy Management and Energy Economics” team consists of 11 research associates and three laboratory engineers who are working on the economically and technically optimal integration of renewable energies into the current and future energy system. The focus of the research is the creation and investigation of innovative operating strategies for energy management systems as well as the development of future business and market models in the context of renewable energy generation. For example, the extent to which producers, consumers and storage systems can provide system services for the grid, e.g. in the form of flexibility, and how these can be marketed is being investigated. Computer-aided simulations, laboratory and field tests can be used to model and evaluate various market and integration concepts as well as developed operating strategies. The practices of energy system modeling are used in the modelling of different tools for energy system analysis and also form the basis of many research projects, enabling cross-project collaboration at the elenia Institute. Energy system modeling covers a broad spectrum, e.g. co-simulations and HiL tests in the quasi-dynamic time domain. In elenia’s own energy management laboratory, a heat pump, electric vehicle charging stations, variably adjustable loads and generators as well as battery storage units can be used to model fully flexible prosumers.

Figure 3: Various components for experiments in the energy management laboratory, Photo: TU Braunschweig, Jonathan Ries

RESEARCH NAME

Research Active Distribution Grid

RESEARCH MENTOR

Prof. Dr.-Ing. Bernd Engel
bernd.engel@tu-braunschweig.de
+49 531 391 7740

GRID DYNAMICS AND SYSTEM STABILITY

Timo Sauer, M.Sc.
t.sauer@tu-braunschweig.de
+49 531 391 7721

GRID OPERATION AND GRID PLANNING

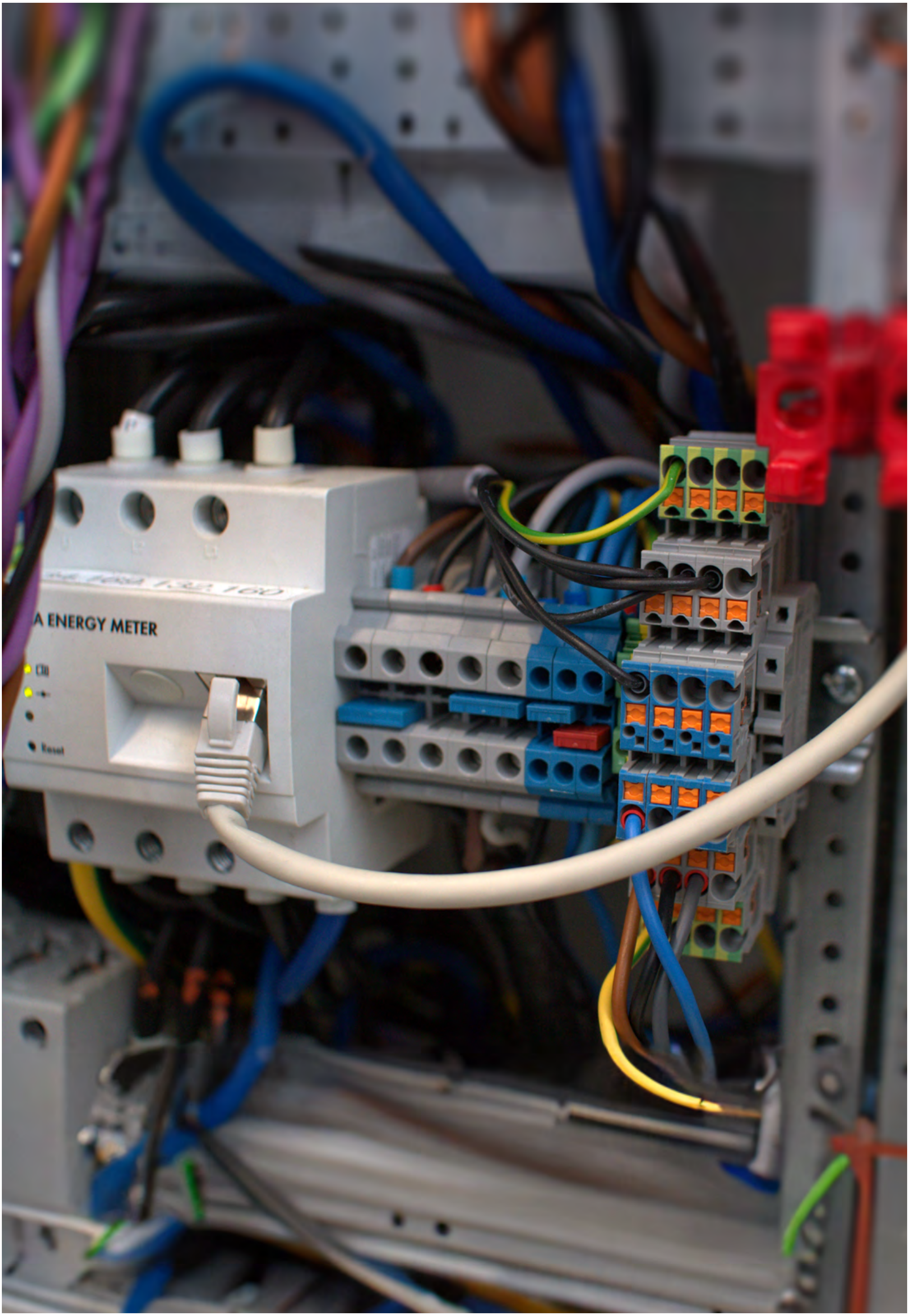
Gian-Luca Di Modica, M.Sc.
g.di-modica@tu-braunschweig.de
+49 531 391 7704

ENERGY ECONOMICS AND ENERGY MANAGEMENT

Henrik Wagner, M.Sc.
henrik.wagner@tu-braunschweig.de
+49 531 391 9718

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/aktives-verteilnetz


ENERGY METER
Reset

Research Electric Mobility

Grid and system integration of battery electric vehicles and battery technology

As part of the TU Braunschweig's strategy process, mobility has emerged as a central focus. This focus on mobility is particularly emphasized by the first introduction of the "Electromobility" Master's degree course in the 2014/2015 winter semester. elenia is actively involved in the implementation of this course through a large number of lectures. In addition, elenia is actively involved in interdisciplinary research projects on electromobility research, thanks to the research infrastructure of the Automotive Research Center Niedersachsen and the Battery LabFactory Braunschweig (BLB). Our expertise extends in particular to the areas of system and grid integration of electric vehicles and battery technology.

Grid and System Integration

Electromobility is gaining momentum in Germany. 470,559 battery electric vehicles and 362,093 plug-in hybrids were newly registered in 2022. The total number on Januaryy 1, 2023 was therefore 1,013,009 for battery electric vehicles and 864,712 for plug-in hybrids. The development of the number of vehicles is exponential. This is why we at elenia are working intensively on a wide range of issues relating to the future integration of electric vehicles into the power grid and their active role. These topics are particularly represented in the grid operation and grid planning team. As part of the research project LISA4CL, concepts for grid and generation-oriented charging of electric vehicles are being developed and examined in detail. The Netflexum project, which started in September 2022, is investigating bidirectional charging, among other things. In addition, the electric vehicle is being considered as an important component in comprehensive overall system considerations in the Energy Economics and Energy Management team.

The research field of grid integration ranges from basic grid analyses to grid-friendly charging concepts. At elenia, we primarily carry out simulations to investigate the capacity of low-voltage grids for electric vehicles. We have extensive experience with charging behavior and energy requirements in various scenarios. On this basis, we are working on the further development of approaches to minimize the impact of charging processes on the energy supply grid, which have already been developed in the past.

In addition to the grid integration of electric vehicles, we are also focusing on the development of generation-oriented charging algorithms that aim to control energy consumption based on decentralized energy generation. Electric vehicles are particularly well suited to this, as they are large consumers with considerable potential for flexibility. These developed algorithms are tested and validated in simulations, in the laboratory and in real vehicle tests.

Communication between electric vehicles, charging infrastructure and a higher-level backend plays a crucial role in the integration of electric vehicles into grid and energy systems. This communication is of great importance, for example, for controlling the charging power to support grid requirements or for implementing charging plans as part of generation-oriented charging processes. Figure 01 shows the communication infrastructure of an elenia laboratory charging station.

Figure 1: Communication infrastructure for a laboratory DC charging station,
Photo: TU Braunschweig, Henrik Herr

Figure 2: Measurement of electric vehicles at elenia charging points, Photo: TU Braunschweig, Gian-Luca Di Modica

Figure 3: Battery cell from BLB production in the elenia cell tester, Photo: TU Braunschweig

elenia has a comprehensive infrastructure for our research work in the field of electromobility and the associated grid-related issues. In addition to our laboratory facilities, we have several charging stations that can be integrated into the laboratory infrastructure via a link. Figure 02 shows an example of the use of the charging stations as part of a measurement.

Battery Technology

BLB is an important research center for battery technology at elenia. The research spectrum covers the entire value creation cycle from material and electrode production to cell production, system integration and recycling to close the material cycle (see Fig. 1). The BLB pools the expertise of 9 institutes at TU Braunschweig, TU Clausthal, Leibniz Universität Hannover, the Fraunhofer Institute for Surface Engineering and Thin Films IST and the Physikalisch-Technische Bundesanstalt Braunschweig (PTB). This collaboration of a transdisciplinary consortium in a joint lab is unique in the German research landscape.

As an active member of the BLB and the main institute responsible for formation, ageing and characterization, we at elenia are researching relevant issues and expanding our expertise. In cooperation with the PTB, we focus on research activities in the field of ageing tests on battery modules as well as electrical and thermal safety tests. The battery technology team deals with a wide range of research topics at cell and module level. The research results obtained are incorporated as current content in the co-design of teaching. The research fields can be categorized into four areas: Battery formation, battery diagnostics and safety, battery use and ageing, battery diagnostics and safety as well as second life and recycling.

Within the battery cell production chain, forming represents the bottleneck, as this step is time-consuming and therefore cost-intensive. Forming is the final production step and serves to electrically activate the battery cells. Current research work in the FormEL project is concerned with the model-based and experimental optimization of forming, the identification of sensitive influencing parameters and the determination of quality gates for evaluating cell quality.

Battery diagnostics and safety is a versatile and overarching field of research. In the battery laboratories, various metrological tests are carried out on battery modules and cells in order to evaluate the quality and condition based on parameters. For example, the electrical properties are determined by loading with different current and voltage profiles and the energy properties are determined by constant current loading. The electrical performance and battery condition can be determined using current, internal resistance and impedance measurements. In the PolySafe project, innovative current collectors with fuses are installed in the battery cells, which are triggered by internal cell short circuits to prevent thermal runaway.

After the formation and thus the BoL (Begin of Life) of the batteries, experimental long-term cycling is carried out in order to characterize the electrochemical performance of the cells during operation and to draw conclusions about ageing mechanisms. The aim of the FastChargeLongLife research project is to develop an ageing-adaptive fast-charging strategy that also ensures a long service life for the battery cells.

The research training group CircularLIB investigates scalable, economically efficient and ecologically sustainable process technologies along the material and production cycle of batteries. The aim is to develop methods for the recovery and reuse of materials along the entire material cycle, which should enable a closed loop.

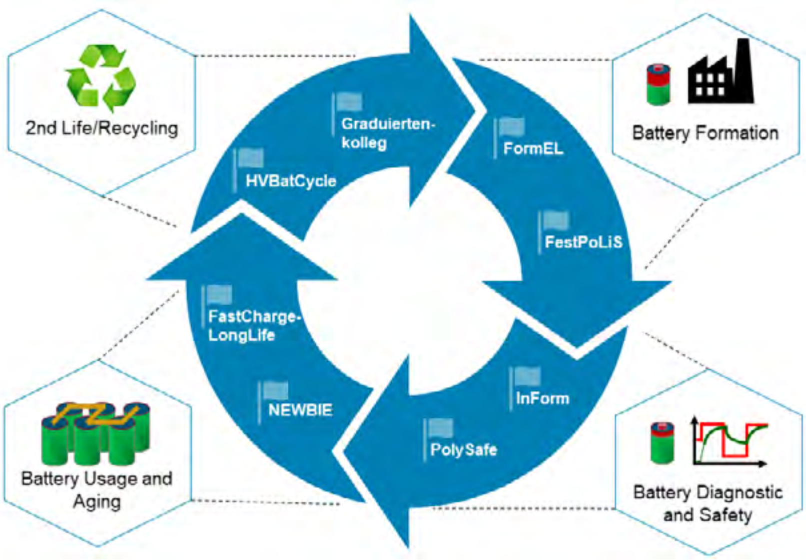


Figure 4: Classification of the elenias battery technology research projects in various research fields

RESEARCH NAME

Research Electric Mobility

RESEARCH MENTOR

Dr.-Ing. Frank Lienesch (PTB)
Frank.Lienesch@ptb.de
+49 531 - 592 9090

GRID AND SYSTEM INTEGRATION

Gian-Luca Di Modica, M.Sc.
g.di-modica@tu-braunschweig.de
+49 531 391 7704

BATTERY TECHNOLOGY

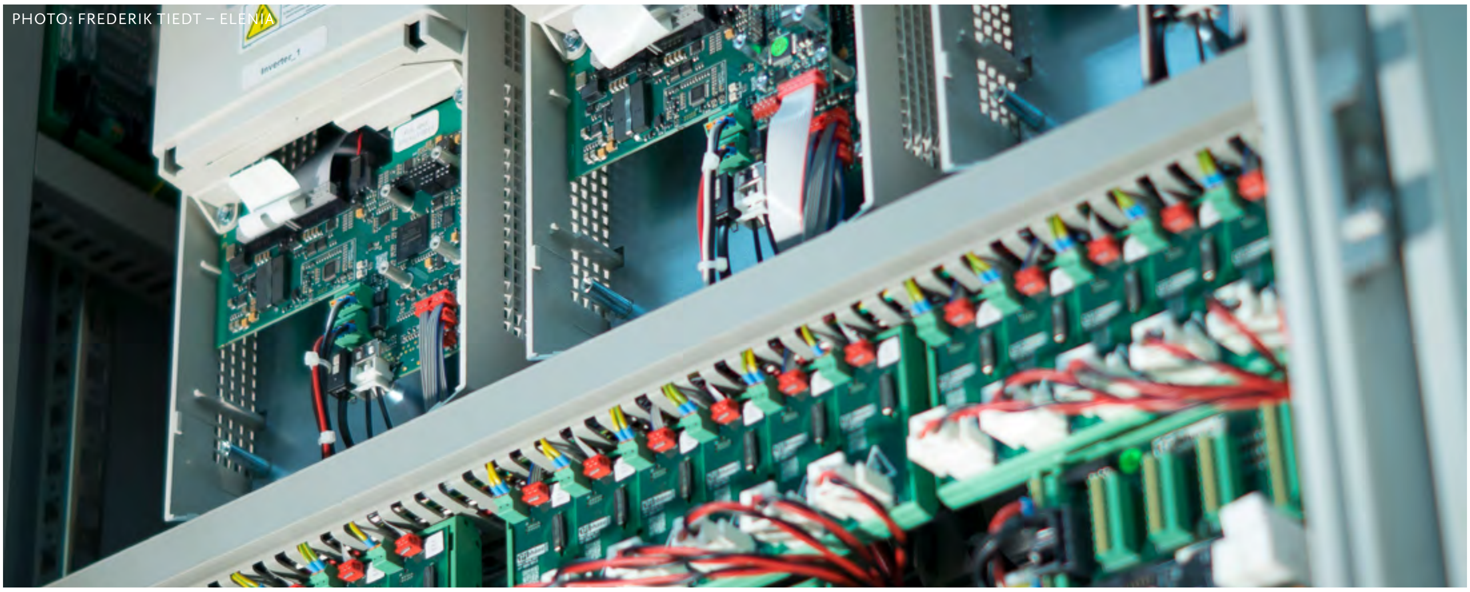
Oliver Landrath
o.landrath@tu-braunschweig.de
+49 531 391 7742

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/elektromobilitaet


PHOENIX
CONTACT

Research Reports



NetFlexum

New possibilities for the provision of ancillary services through grid-supporting prosumer systems

Motivation & objectives of the project

The energy grid is in transition due to the climate crisis and the associated energy system transformation. The shutdown of nuclear and coal-fired power plants means that their contribution to ancillary services is no longer available. In future, these will be covered by renewable energies. The elimination of the power plants' synchronous generators means that the inertia provided by these generators at the transmission grid level no longer exists. This so-called instantaneous reserve is a part of frequency stability and contributes to system stability. In order to continue to ensure stability, the rapidly increasing number of generators at the low-voltage level should be utilized. These can contribute to frequency stability through grid-forming inverters, among other things. In a future energy grid, grid-forming inverters will be used in combination with grid-following inverters, as shown in Figure 01.

The general objective of the project is to contribute to the secure and effective introduction of grid-forming inverters in prosumer households and thus to work on solutions for greater grid efficiency, flexibility and cost-effectiveness of prosumer households. The renewable energy sources and storage systems are to be connected to an in-house direct current grid. The project is being carried out in collaboration with the IMAB, PTB, Temes and SMA. The sub-projects of TU Braunschweig are

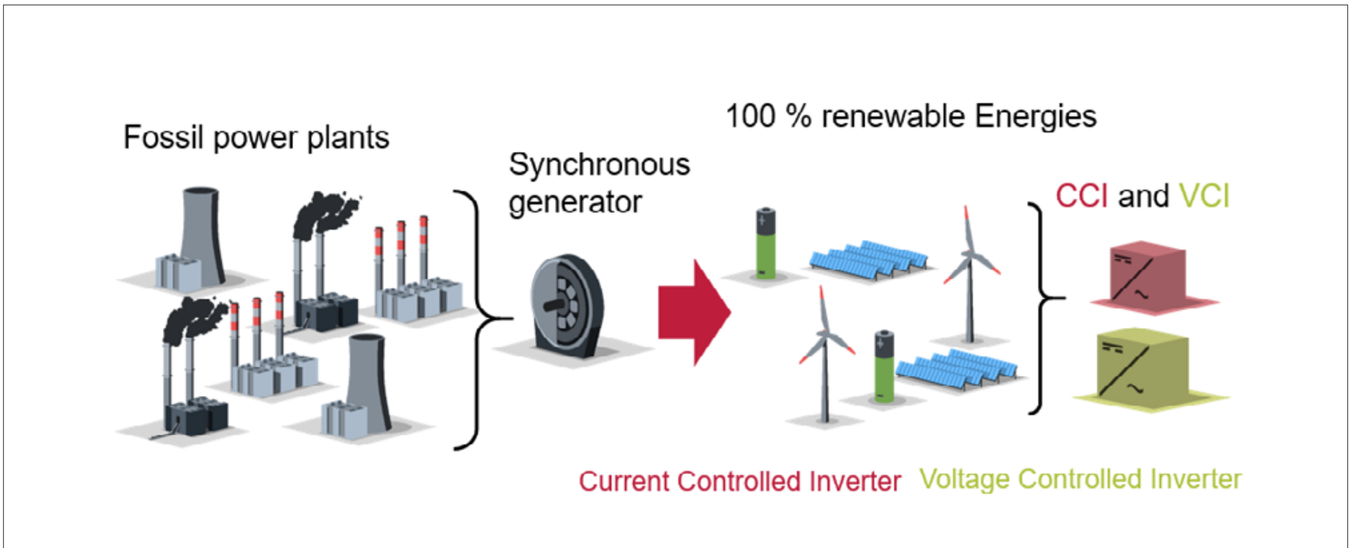


Figure 1: Development of the power grid

concerned with the provision of non-frequency-bound ancillary services (e.g. instantaneous reserve provision and dynamic reactive current feed-in) and with the protection of the direct current grid.

Prosumer households and EMS operating strategies

One of the first steps in the project is to develop operating strategies for an Energy Management System (EMS). The objective of these strategies is to contribute to the frequency stability. This involves, for example, prioritizing the order in which prosumer components are used to provide flexibility. Based on this, a range of type households are created. Typical system configurations for prosumers are identified and load time series are created for these households in order to subsequently estimate what contribution they can make to the provision of frequency stability. This will first be determined using simulations. In addition, the electric car is also considered as a component for providing flexibility. The electric car is not only charged unidirectionally, but also used bidirectionally as additional battery storage in order to increase the self-consumption rate in the household and increase the flexibility.

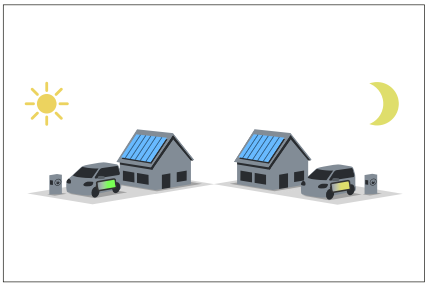


Figure 2: Bidirectional charging in prosumer households

Load spectrums for grid-forming inverters

Load spectra are created in order to investigate the loads on grid-forming inverters in the future energy grid when providing ancillary services. A MATLAB Simulink model is used for this analysis. A control for the grid-forming inverter is implemented, which is linked to a grid model. This is shown in Figure 03.

In particular, the impacts on the provision of non-frequency-related ancillary services, the instantaneous reserve provision and the dynamic reactive power feed-in are to be simulated. Different scenarios are tested for the simulations. For example, the frequency gradient, the voltage dip depth and different grid scenarios are varied. In addition, everyday impacts and worst-case scenarios such as a system split will be investigated. The simulative investigations will then be validated in the grid dynamics laboratory as part of a demonstrator construction. The objective is to show the feasibility of the interaction and interactions between grid-forming inverters and the EMS in the dynamic time range as an example for instantaneous reserve provision and dynamic reactive current feed-in. At the end, an economic evaluation of the provision of SDL from these prosumer households follows.

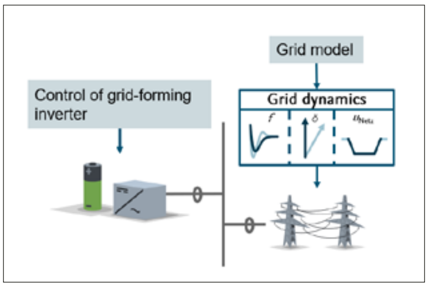


Figure 3: Approach for creating the load spectra of the grid-forming inverter

DC-Protection system

The use of direct current in residential buildings allows an increase in efficiency by eliminating DC/AC and AC/DC conversion losses, but also presents the protection system with new challenges. Fault currents increase faster due to the lower grid inductance and, unlike with alternating current, do not extinguish due to the lack of zero crossing.

To design a suitable DC protection system, a requirements analysis is essential, which can be carried out using grid simulations. Several DC-network-topologies consisting of active front-end inverter (AFE), electric car, second-life battery, photovoltaic generator, load inverter, DC bus with constant voltage and several DC/DC controllers were examined in MATLAB/Simulink. These models were used to simulate several operating points, the change between the operating points and various short-circuit fault cases (conductor-conductor and conductor-earth at different points in the grid) were analyzed and evaluated. Based on the network parameters used, a catalog for delimiting the permissible operating conditions from the fault case was created, on the basis of which a protection system can be developed.

The switchless protection concept shown in Figure 04 appears promising in the NetFlexum project and is characterized in particular by high speed and robustness. Modern power electronics have the intrinsic ability to limit fault currents to any maximum value (e.g. buck converter, full bridge MMC, back-to-back VSC). If the fault persists, the fault must be detected despite current limiting and the converter must be switched off. It is then electrically isolated with disconnectors. In terms of control technology, there are several options for current limiting, e.g. setpoint limiting

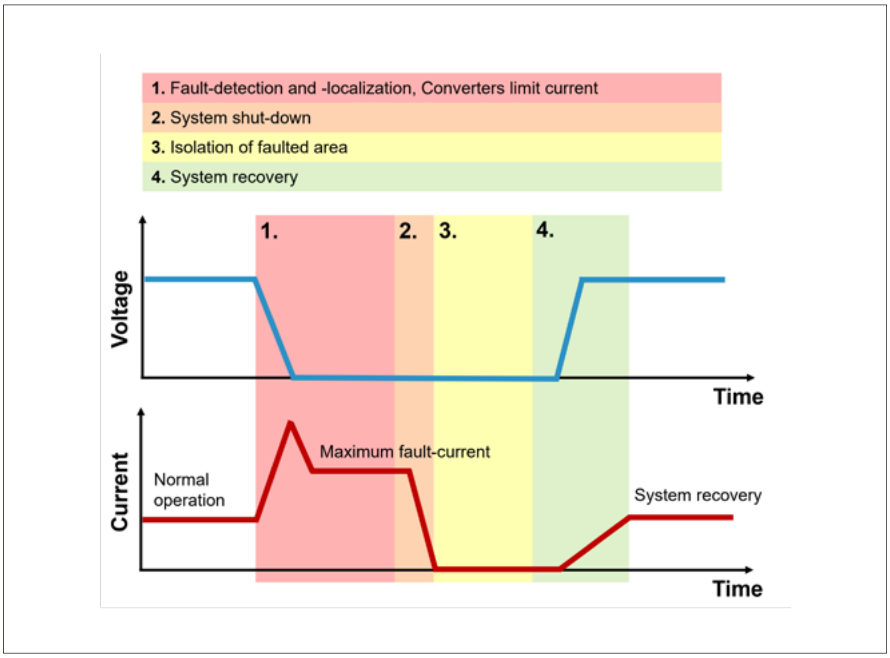


Figure 4: The switchless protection concept

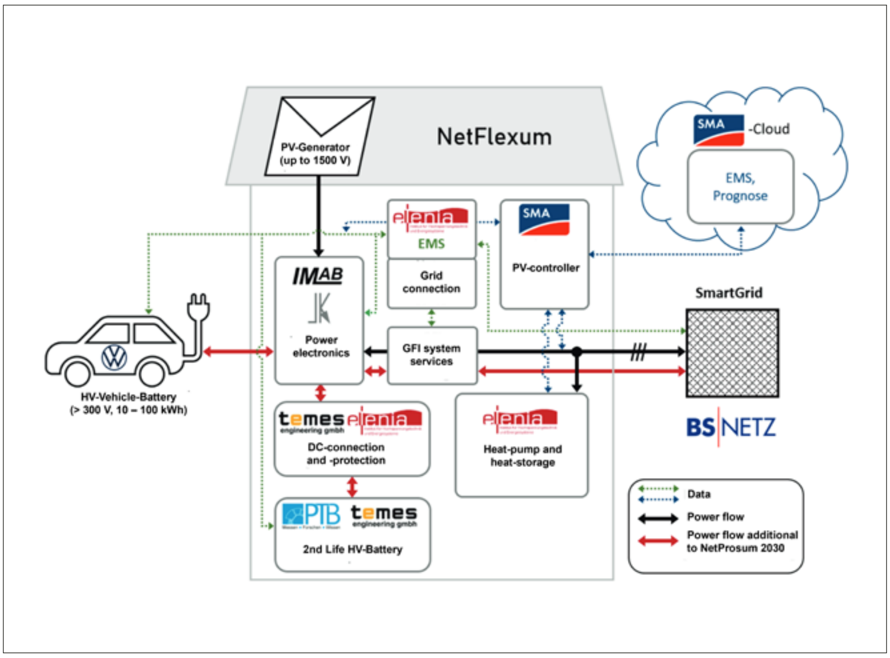


Figure 5: Project structure NetFlexum

in cascade control or increasing the droop resistor.

Cooperation of the working groups

The elenia work packages are closely connected. The load spectra created by the Energy Systems working group represent boundary conditions for the design of the protection system by the Energy Technologies working group. The provision of instantaneous reserve requires overload capability from the power electronics and a corresponding calibration of the protection system. Transient over currents must be permitted and distinguished from fault conditions. The Energy Systems working group provides the operating states that are used in the grid simulations of the Energy Technologies working group as part of the requirements analysis. In turn, the requirements of the new protection concepts can also result in extended conditions for the control of the grid-forming inverter.

Figure 05 shows the project structure and the cooperation between the project partners. Here it can be seen where elenia is involved and how the project parts are connected with each other. A solution for future prosumer systems that can contribute to system stability is being worked on together.

PROJECT TITLE

NETFLEXUM

NetFlexum - Next Generation Close-to-Consumption PV Combi-Systems for Households and Enterprises: Investigation, Realization and Qualification of Integral Concepts and Solutions for More Grid Supporting, Flexibility and Cost-Effectiveness

DURATION

September 2022 – August 2025

CONTACT PERSON

Johanna Grobler
j.grobler@tu-braunschweig.de
+49 531 391 7760

Fabian Benedikt Witt
fabian-benedikt.witt@tu-braunschweig.de
+49 531 391 7703

Lukas Ebbert
l.ebbert@tu-braunschweig.de
+49 531 391 9727

PROJECT PARTNERS

- IMAB: TU Braunschweig IMAB – Institute for Electrical Machines, Traction and Drives
- SMA: SMA Solar Technology AG
- temes engineering gmbh: Temes Engineering GmbH
- PTB: PTB – Physikalisch Technische Bundesanstalt

ASSOCIATED PARTNERS

VW, BS|NETZ

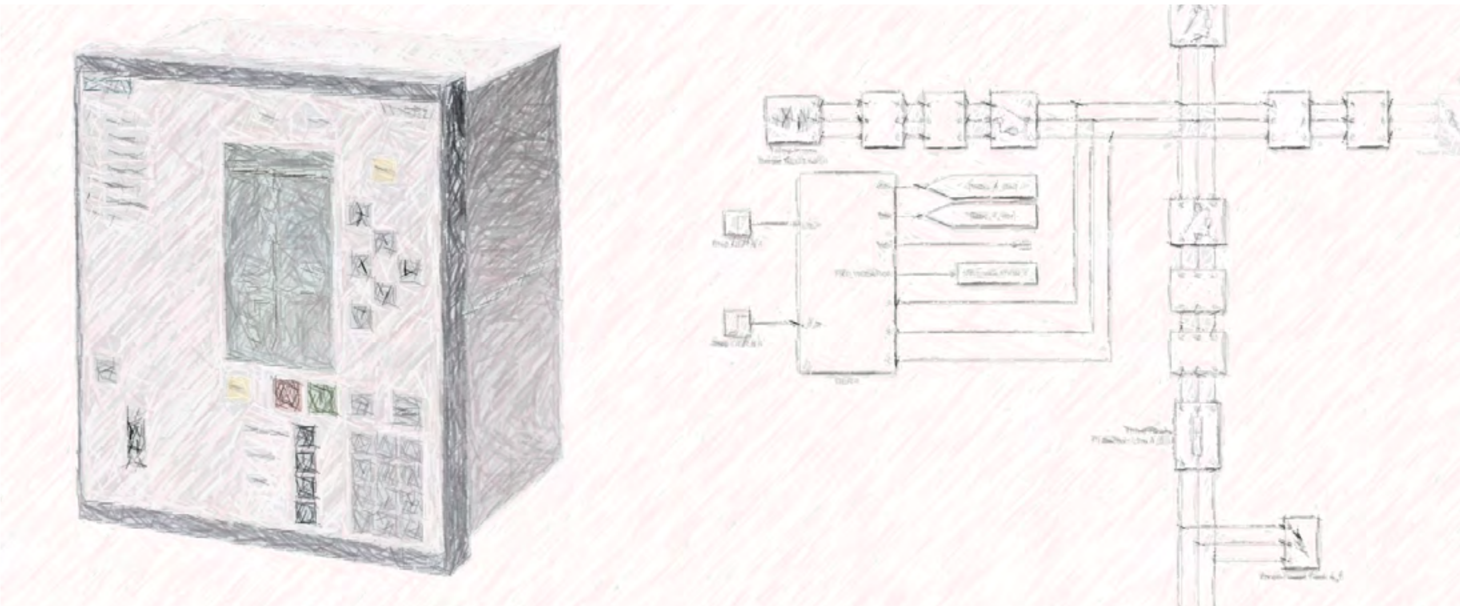
FUNDED BY

Federal Ministry for Economic Affairs and Climate Action
PtJ Projektträger Jülich

COORDINATED BY

TU Braunschweig IMAB – Institute for Electrical Machines, Traction and Drives

CAUTION
Risk of Electrical Shock
Inverter_2
Inverter_3



SiNED: Protection Systems in Distribution Grids

Ancillary Services for the Power System from Power-Engineering Devices of Modern Households in the Low-Voltage Grid

The socially and politically driven phase-out of large generation plants such as nuclear or coal-fired power plants has a significant impact on the provision of grid-supporting functions for the reliable operation of electricity grids. While the large generators of these power plants were largely responsible for the provision of ancillary services (AS) in recent decades, this task will now fall to the increasing number of converter-based systems in the distribution grid. The SiNED project is working on the further development of existing ancillary services for the power grids of the future. In particular, the possibilities and resulting changes in requirements based on the ongoing energy transition and increasing digitalisation are being taken into account.

Summary of the First Project Phase

In the first phase of the project, reference grids were defined in order to investigate the influence of increased inverter-based infeed on conventional protection systems using simulations. It was found that the configuration of intermediate infeed in particular negatively impacts the functionality of upstream distance protection systems. The reason for this is that the configuration appears as a parallel connection of converters and cables, leading to a measured impedance that is interpreted incorrectly by the conventional protection systems.

In order to reduce the negative influence on the protection systems, several concepts were developed and analyzed. First, the distance protection system algorithms were adapted in such a way that the so-called error impedance was eliminated. This allos the conventional protection system settings to be retained. Second, the inverter-based system was adapted to feed in defined currents in positive and negative sequence during faults which reduces the critical imaginary part of the error measurements. Then, conventional settings can also be retained.

Development of a Scaled Laboratory Environment

For validation of the developed protection algorithms, they are demonstrated in a laboratory environment. It represents a scaled medium voltage grid with 400 V instead of 20 kV. Faults can be performed with a fault current of up to 63 A. The cable sections are modelled as PI section equivalent circuits, scaled in such a manner that they behave similar to medium voltage cables regarding their dynamics.

Figure 1: Integrated laboratory components, Photo: TU Braunschweig, Marc René Lotz

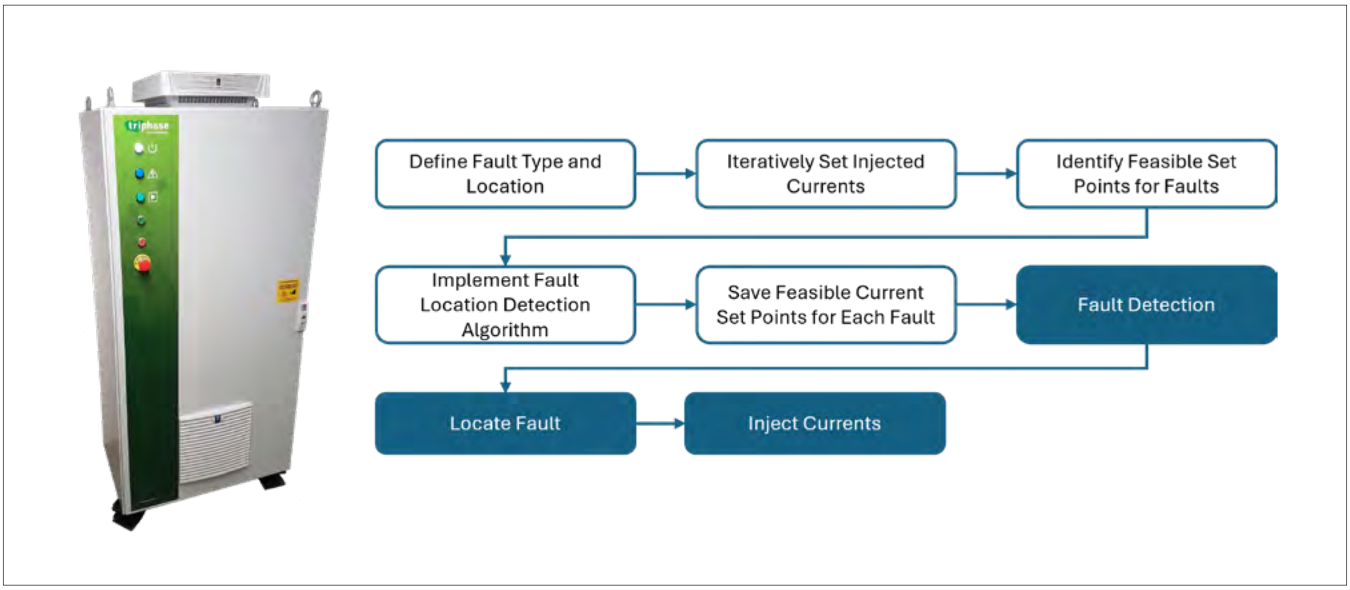


Figure 2: Power amplifier with implemented algorithms,
Photo: TU Braunschweig, Marc René Lotz

Other features of the laboratory environment includea control concept that can be used to generate different fault types (pole-to-pole, pole-to-ground), for user-definable durations and with varying fault impedances. This makes it possible to reproduce the previously simulated scenarios.

A real-time simulator (dSPACE SCALEXIO) serves as a platform for implementation of the protection systems, their adaptation, and control of the inverter-based system. Additionally, the faults are controlled and measurements can be recorded. The described components are integrated into a cabinet which is shown in Figure 01.

A power amplifier (Triphase PM15) is used to act as the inverter-based system, which also has a platform to deploy user-definable control algorithms. Furthermore, a communication interface with a real-time simulator makes it possible toexternally control the system and deploy additional algorithms.

Outlook

The laboratory environment has already been set up and tested, so that the results of the simulative tests can now also be analyzed experimentally as a first step. The newly developed protection principles are then implemented and validated. Figure 03 shows the flow chart of one of these algorithms.

During a fault, the inverter-based system should inject currents in such a way that the fault impedance measured by the upstream distance protection system is minimized with regard to its imaginary part. This signifiantly reduces the negative influence. Optimum current set points must be determined in advance. In addition to fault detection, an algorithm is also required to determine the fault location, which has been developed and is based on evaluating the trajectory of the grid impedance at the location of the inverter-based system.

Overall, in addition to new protection algorithms, this concept demonstrates therole that inverter-based systems can play in the event of faults and the configuration of protection systems in the future with increased integration.

PROJECT TITLE

SiNED
Ancillary Services for Reliable Power Grids in Times of Progressive German Energiewende and Digital Transformation

DURATION

2019–2024

CONTACT PERSON

Marc René Lotz
m.lotz@tu-braunschweig.de
+49 5331 939 4322 0

PROJECT PARTNERS

German Aerospace Center (DLR), OFFIS e.V., Carl von Ossietzky University of Oldenburg, Leibniz University Hannover, TU Clausthal

FUNDED BY

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COORDINATED BY

TU Braunschweig – elenia

SiNED: Grid-serving Prosumer Households

Ancillary Services for the Power System from Power-Engineering Devices of Modern Households in the Low-Voltage Grid

Das gesellschaftlich und politisch getriebene Wegfallen großer Erzeugungsanlagen wie Kern- oder Kohlekraftwerke hat einen wesentlichen Einfluss auf die Bereitstellung netzdienlicher Funktionen für einen reibungslosen Betrieb von Stromnetzen. Nachdem die großen Generatoren dieser Kraftwerke in den letzten Jahrzehnten größtenteils für die Bereitstellung von Systemdienstleistungen (SDL) zuständig waren, fällt diese Aufgabe in Zukunft den in der Anzahl steigenden Umrichter-basierten Anlagen im Verteilungsnetz zu. Im Rahmen des Projects SiNED wird an der Weiterentwicklung der bisherigen SDL für die Stromnetze der Zukunft gearbeitet. Dabei werden insbesondere die Möglichkeiten und resultierende veränderte Anforderungen berücksichtigt, die auf der fortschreitenden Energiewende sowie zunehmender Digitalisierung basieren.

Change of Households and Challenges in the Flexibility Provision

For decades, low-voltage grids were characterised by fixed consumption at household connections that could hardly be influenced. For a few decades now, however, households have increasingly been able to reduce their grid consumption through PV systems and in some cases produce so much power that it can be fed into the low-voltage grid. Other modern household devices include battery storage systems (BSS), heat pumps (HP) and electric vehicles (EV). In addition to performing their primary task - in the case of domestic BSSs, for example, this is the intermediate storage of PV electric-

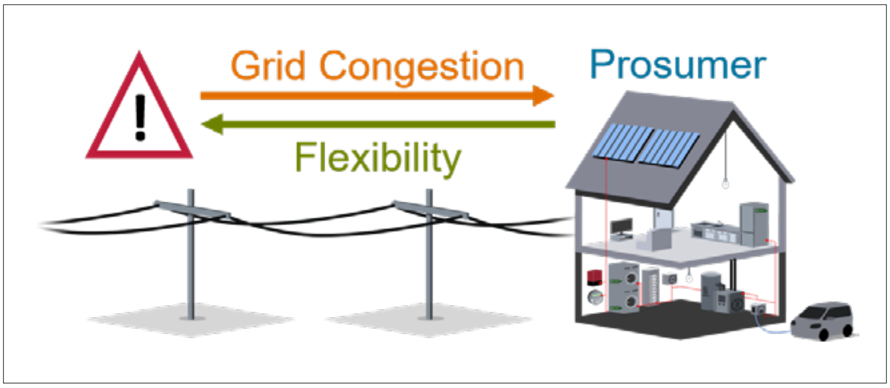


Figure 1: Schematic presentation of the provision of ancillary services by prosumer households, Graphic: Carsten Wegkamp

ity to maximise self-consumption - these prosumer devices are able to perform a grid-supporting function. This is because the devices have the flexibility to vary their power consumption or feed-in in terms of time and quantity and are connected to the power grid via converters, which is why their operating point can be controlled swiftly and easily. Identified potential for a contribution lies in the AS voltage control, local congestion management, frequency control and instantaneous reserve. This could, for example, reduce the need to expand the electricity grids with additional lines.

Goals of the Project

In addition to the general analysis of regulatory issues and economic feasibility, the investigations at elenia focus on the technical design.

The project will first analyse the potential for providing AS by estimating the penetration of prosumer devices for the years 2020 and 2030 and then examine the extent to which these components can contribute to local (voltage stability, congestion management) and global AS (frequency stability). One of the focal points is the comparison of voltage stability through prosumer devices via reactive power provision with alternative voltage stability concepts such as controllable local grid transformers. Overall, the influence of the provision of ASs by prosumers on the low-voltage grids and the integration potential of modern systems will be analysed with the aim of being able to integrate as many PV systems, EVs, HPs and BSSs as possible into the German low-voltage grids without causing critical grid situations.

The concepts for the provision of AS by modern prosumer devices are being successively integrated into the existing, proprietary simulation environment eSE - elenia Simulation Environment. eSE was already developed in the predecessor project *NEDS - Sustainable Energy Supply Lower Saxony* and is being expanded to include various models. These include various voltage stability concepts, components such as controllable local grid transformers and string regulators as well as the coordinated control of the provision of ancillary services.

Interim Results and Outlook

Some exciting and promising results have already been achieved in the course of the project. The characteristics and specifications of the individual AS and the associated conditions of provision were analysed. Various voltage control concepts were simulatively compared and contrasted with each other and with the current connection guidelines. This enabled a recommendation to be made for the various prosumer devices from a grid technology perspective. In addition, a model for the centrally coordinated, economically optimised retrieval of flexibility for local ASs in the low-voltage grid was developed and tested. The results, shown as an example in Figure 02, demonstrate the clear possibility of improving local grid stability through the efficient, coordinated utilisation of prosumer flexibility. This applies both to the current load on lines (congestion management) and to voltage problems at grid nodes. In addition, current studies show a potential for improving grid utilisation with grid-supportive operation of domestic BSS without significantly changing the economic efficiency for the storage owner. In addition, the potential for the contribution of prosumer devices to frequency control with their flexibility was simulatively analysed and a high, possible degree of coverage of the control power demand by households alone was determined, especially during the day and in summer, with the BSS contributing a high share to this.

Figure 2: Exemplary simulative results for the line loading with and without the utilization of flexibility from prosumer households, Source: Carsten Wegkamp

In the further course of the project, final simulative analyses are planned that will make it possible to assess the potential for AS provision by prosumer devices. In addition, a laboratory-based validation of a selection of the ideas and concepts developed and simulatively tested is planned. To this end, both the energy management laboratory and the grid dynamics laboratory will be used to identify the effects of prosumers on the electricity grid and to validate the grid-serving utilisation of flexibility by prosumers.

PROJECT TITLE

SiNED
Ancillary Services for Reliable Power Grids in Times of Progressive German Energiewende and Digital Transformation

DURATION

2019 – 2024

CONTACT PERSON

Carsten Wegkamp, M.Sc.
c.wegkamp@tu-braunschweig.de
+49 531 391 7756

PROJECT PARTNERS

Deutsches Zentrum für Luft- und Raumfahrt, OFFIS e.V., Carl von Ossietzky Universität Oldenburg, Leibniz Universität Hannover, TU Clausthal

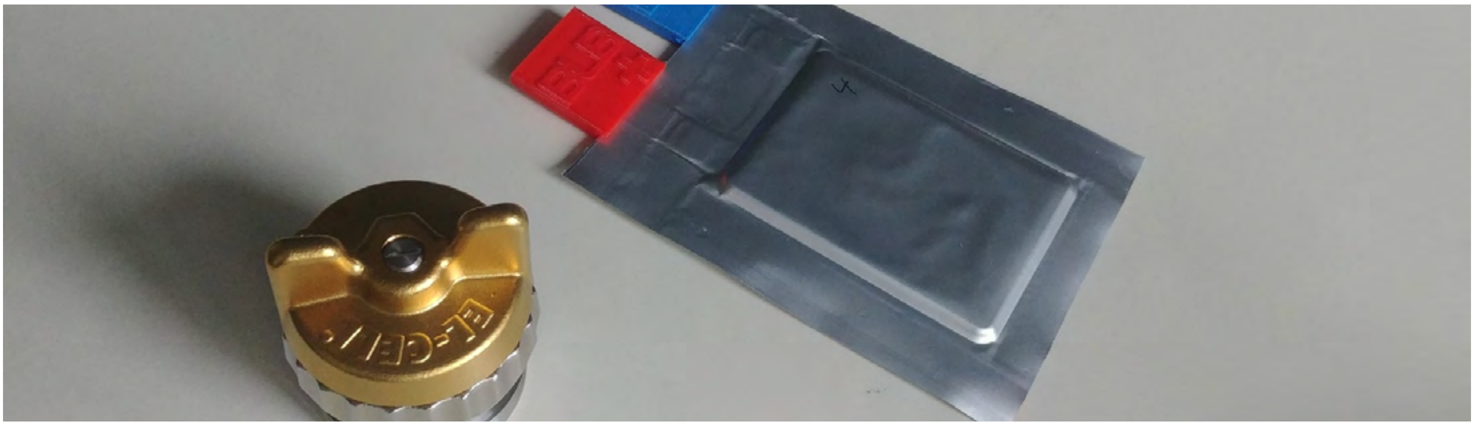
FUNDED BY

Niedersächsisches Ministerium für Wissenschaft und Kultur

Lower Saxony Ministry for Science and Culture – Additional funding for science and technology in research and teaching from the Niedersächsisches Vorab

COORDINATED BY

TU Braunschweig – elenia



Adaptive fast charging strategies

Model-based evaluation of the operating limits of different cell systems for the design of ageing-adaptive fast-charging strategies

A variety of factors influence consumer acceptance of electromobility. The terms cost, energy efficiency, safety, sustainability, range and performance come up again and again in this context. In addition, a long service life of lithium-ion battery cells and a short charging time during operation are crucial for the success of electric vehicles. The requirements for fast-charging capability come from the respective application, but are often limited by the material system and cell design. In addition, the cell properties deteriorate due to battery ageing. Fast charging processes in particular can lead to accelerated ageing. For this reason, the operating limits are often designed very pessimistically in order to avoid safety-critical processes and accelerated ageing processes such as lithium plating. A promising alternative is the determination of ageing-dependent operating limits to adapt the fast charging strategy accordingly. However, this approach is associated with challenges because an ageing-related adjustment of the operating limits depends on states of the material and cell system that cannot be measured directly.

Project goal

The FastChargeLongLife project addresses this challenge and develops a methodology for the model-based evaluation of different cell material systems with regard to the maximum charging operating limits as a function of the ageing condition. To this end, a coupled modeling approach is used, which combines real-time equivalent circuit models and detailed physicochemical degradation models (see Fig. 1). A model-based scalability of the material data is provided in order to transfer the model parameters from small cell formats in 3-electrode format to large-format pouch cells. Ageing-adaptive fast-charging strategies are derived on the basis of the model-based operating limits, which avoid safety-critical degradation effects. This is done for different cell material systems, which can then be compared with each other in terms of their ageing-dependent fast-charging capability. The optimized fast-charging strategies should improve the charging time and service life by at least 10% compared to state-of-the-art fast-charging strategies without age-dependent adaptation.

Design of the fast charging strategies

The design of the state-of-the-art reference fast-charging strategies for different cell material systems serves as the basis for subsequent age-dependent optimization of the fast-charging strategies. The basis for the reference fast-charging strategies is provided by an electrode equivalent circuit diagram model developed at the Institute, which considers the electrodes separately from each other and thus enables the anode voltage to be controlled. By setting a minimum anode voltage above 0 V during fast charging, lithium plating can be avoided and accelerated ageing reduced. Various characterization methods such as capacity tests, current interrupt tests at different states of charge (SOC) and C-rate tests on small-format cells in 3-electrode format are used to parameterize and validate the model. The cell type is a PAT-Cell from EL-Cell GmbH with approx. 8 mAh and a lithium reference electrode on the separator, which allows the electrode potentials to be determined. Depending on the specification of the maximum charging current, the minimum anode voltage and the SOC to be achieved after fast charging, the model specifies a corresponding charging strategy. A total of two reference fast charging strategies are defined for each cell material system. The first charging strategy (Ref A)

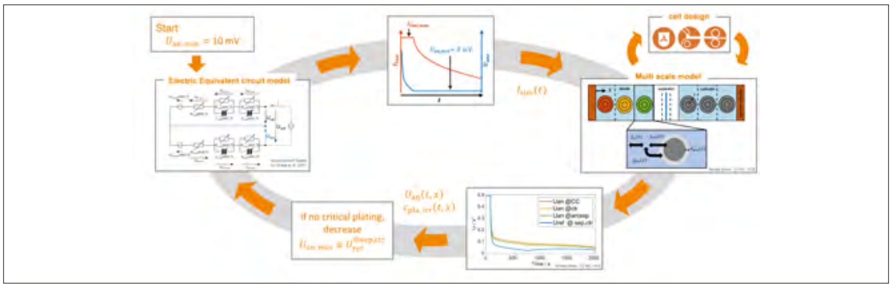


Figure 1: Model coupling between electrode equivalent circuit diagram model and physicochemical model

results for a charge of 0 - 80 % SOC, a minimum anode voltage of 10 mV and a maximum charging current of 3C. The second reference charging strategy (Ref B) is also based on these boundary conditions, but is dimensioned on the basis of a 50 % higher internal resistance of the cell.

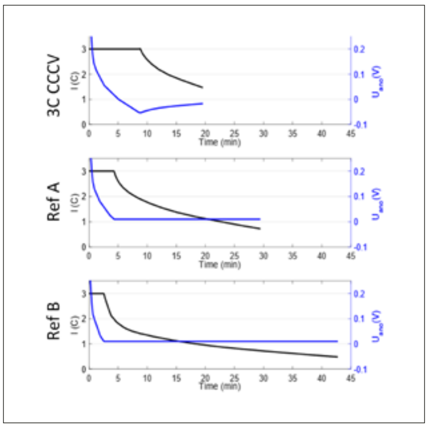


Figure 2: Reference charging strategies, C-rate in black, anode voltage in blue

The three line diagrams (see Fig. 2) show the cell and anode voltage curve for a measured fast charge with 3C CCCV (maximum cell voltage = 4.2 V) as well as for the simulated profiles Ref A and Ref B. The cell material system under consideration is based on the cell chemistry NMC622/G, the ambient temperature is 20 °C. With 3C CCCV fast charging, the charging time is 19 min for the first cycle, but the anode voltage drops to as low as - 50 mV, which causes lithium plating during the charging process and significantly accelerates cell ageing during cycling with this charging strategy. Ref A and Ref B have charging times of 29 min and 42 min respectively while simultaneously avoiding lithium plating and thus slower cell ageing.

Results

The 3-electrodes are cycled using the reference charging strategies (Figure 2). After a fixed number of fast charge cycles, electrochemical characterization tests and optical post-mortem analyses are performed. The cells that are cycled with 3C CCCV show a capacity loss (capacity test: 0.5 C CCCV) of between 12 - 21 % after 100 fast-charging cycles, whereas the cells with charging strategy Ref A show a capacity loss of 1–3 %. In the post-mortem examinations, clear lithium metal deposits can be identified in the cells with 3C CCCV cyclization in contrast to the cells with Ref A cyclization.

The charging strategies are scaled up to multi-layer pouch cells with a capacity of 1.35 Ah. For production reasons, a different separator is used for the pouch cells, which turns out to reduce the fast-charging capability.

PROJECT TITLE

FastChargeLongLife

DURATION

October 2020 – March 2024

CONTACT PERSON

Oliver Landrath
o.landrath@tu-braunschweig.de
+49 531 391 7742

PROJECT PARTNERS

InES (TU Braunschweig)
IPAT (TU Braunschweig)

FUNDED BY

Federal Ministry of Education and Research

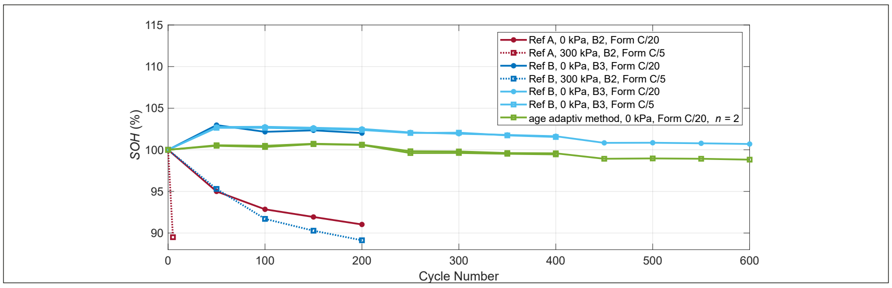


Figure 3: Fast-charging cycling of multilayer pouch cells with Ref A, Ref B and adaptive charging strategy

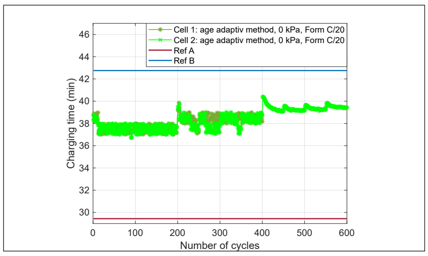
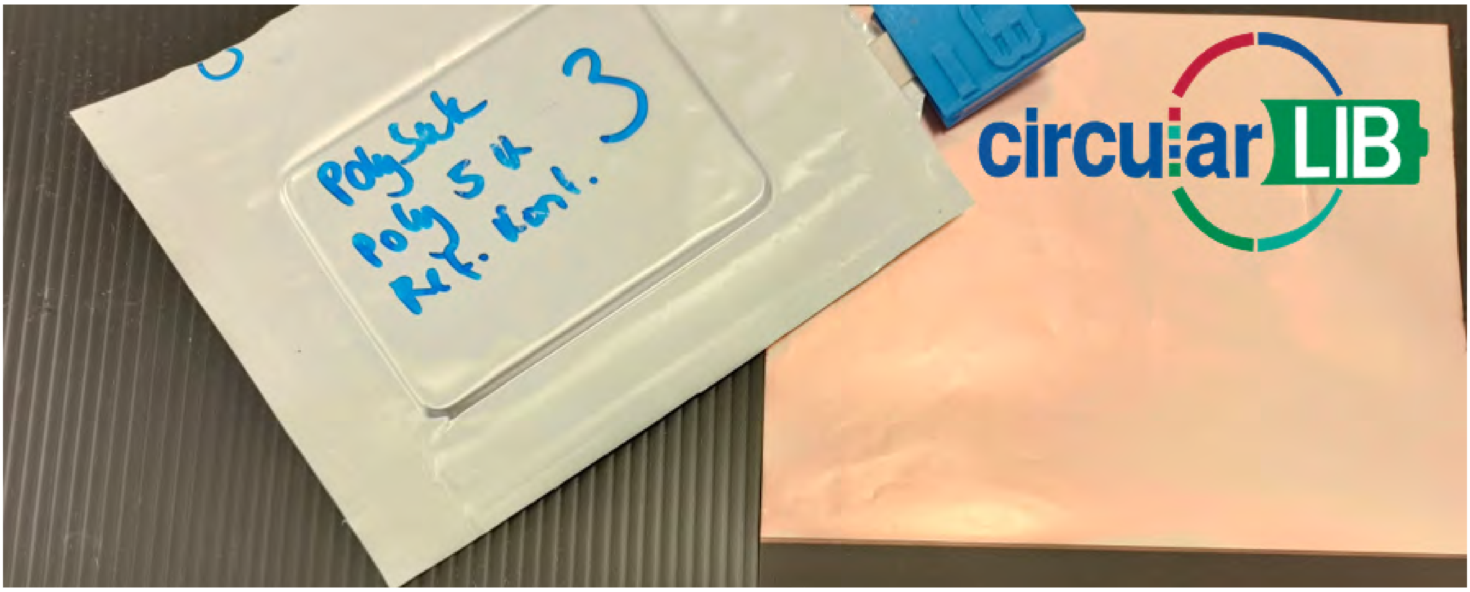


Figure 4: Charging time over cycles with Ref A, Ref B and adaptive charging strategy



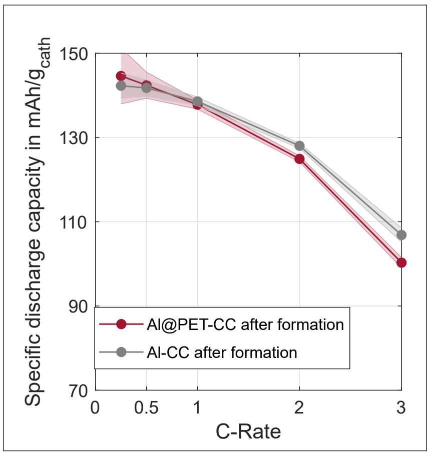
Latest developments in battery safety and recycling

Optimization of the economic integration of different materials into existing process chains

The growing demand for batteries in areas such as electric vehicles, renewable energy systems and portable electronics is driving the search for innovative solutions in the areas of battery safety and recycling. This article presents two projects at elenia that take different approaches but share the common goal of economically integrating battery materials into existing process chains.

The **PolySafe** project pursues an approach that increases intrinsic safety through innovative metal-polymer composite current collectors. The polymer contained in the current collectors softens or melts in the event of an internal short circuit so that the electronic conductive path is destroyed, which ultimately limits the event locally and prevents the thermal runaway of the entire cell. In addition, the combination of metal layer and polymer substrate allows a weight and thickness advantage and thus the economical use of material resources.

The research training group **CircularLIB** is dedicated to scalable, economically efficient and ecologically sustainable process technologies as well as the associated diagnostic and simulation methods along the material



Discharge capacities of the reference cells (Al-CC) and the cells based on the metal-polymer composite current collector (Al@PET-CC) during the C-rate test

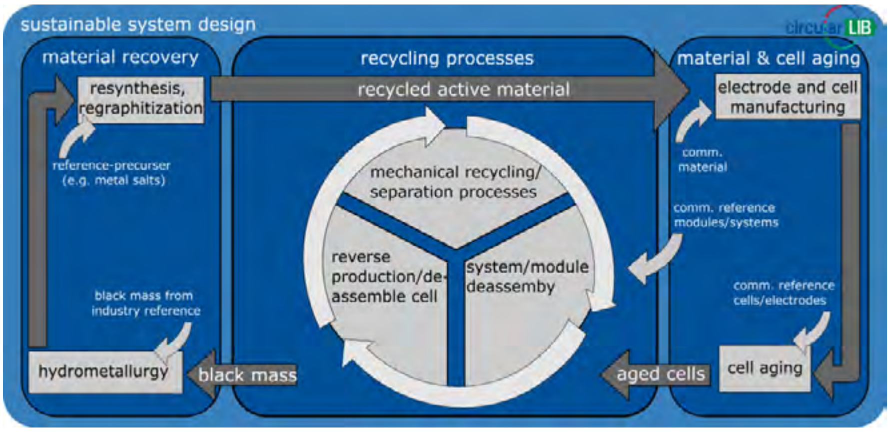
and production cycle of batteries. Along the entire material cycle from material (re)synthesis, material conditioning and formulation, electrode and cell production, battery use and recycling, methods for the recovery and reuse of materials are being investigated with the aim of creating a closed cycle.

To evaluate cell quality, parameters are recorded after formation, the first electrical activation of the cell and during ageing. This parameter-based method has been established at elenia in various research projects. These include capacitance, internal resistance and the decrease in state of health (SOH) over time.

A special form of the capacity test is the C-rate test. The aim of the C-rate test is to determine the current carrying capacity of the cells based on the capacity at varying current rates. This is initially carried out after formation to record the cell performance. Ageing effects are determined using the C-rate test by repeating it at defined intervals during cycling. Cyclization refers to the cyclical charging and discharging of a cell, which simulates the real operation of a battery cell.

PolySafe

In the PolySafe project, the quality and performance of cells produced on the basis of the metal-polymer composite current collector (Al@PET-CC) are analyzed in comparison with cells that have a metal current collector (Al-CC) as a reference. The investigation was carried out using the C-rate test,

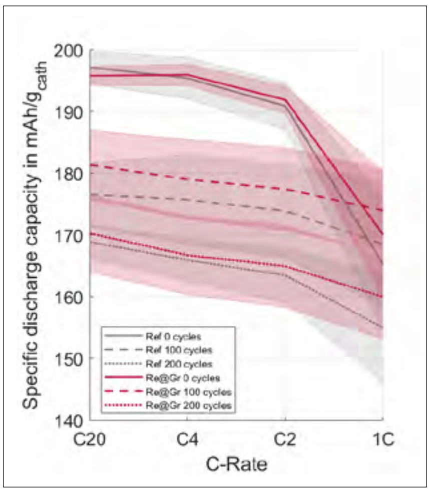


Project structure Graduiertenkolleg CircularLIB

among other things, which showed that the cell variations have a comparable discharge capacity at current rates of 0.2 C to 3 C. The cells manufactured on the basis of the Al@ PET current collector therefore have a comparable cell performance to the conventionally manufactured cells based on the metal current collector.

CircularLIB

In addition to increased safety, legal requirements must also be complied with, including those relating to recycling. In mid-2023, laws came into force that not only stipulate minimum quantities for materials recovered from used batteries from 2027, but also require a minimum recycled content in new batteries. This requires a carefully developed recycling process that includes the collection of used batteries and their complex processing using mechanical, thermal and chemical methods. This allows various valuable materials to be recovered to battery quality standards and reintroduced into the production cycle.
However, the shredding of the batteries in particular contributes to a significant proportion of impurities being contained in the recovered black mass. At elenia, the influence of these impurities is assessed and recovered material is analyzed. Using a C-rate test - as in the PolySafe project - it was possible to show that re-synthesized graphite behaves similarly to the reference after ageing.



Discharge capacity of different resynthesised battery cells at different C-rates

PROJECT TITLE

Polysafe

DURATION

June 2021 – May 2024

CONTACT PERSON

Merit Holdorf
m.holdorf@tu-braunschweig.de
+49 531 391 7763

PROJECT PARTNERS

iPAT, ifs, IWF, Frauenhofer IST, Frauenhofer FEP, von Ardenne, Varta, Brückner Maschinenbau

ASSOCIATED PROJECT PARTNERS

BMW, Rena

PROJECT TITLE

Graduiertenkolleg CircularLIB

DURATION

March 2021 – February 2025

CONTACT PERSON

Anna Rollin
anna.rollin@tu-braunschweig.de
+49 531 391 9734

PROJECT PARTNERS

Ifs, ITC, IWF, iPAT, InES, IÖNC, KI, AIP, IAP, IFAD (TU Clausthal), IOC (TU Clausthal), ICVT (TU Clausthal), ISSE (TU Clausthal), FKP (Leibnitz Uni Hannover), Fraunhofer IST

FUNDED BY

Niedersächsisches Ministerium für Wissenschaft und Kultur

VolkswagenStiftung

InForm (Cluster InZePro)

Development of intelligent forming systems for the optimization and diagnosis of cell properties

Tailor-made batteries with automated quality assessment are the key to intelligent and highly productive forming for competitive battery production of the highest quality in Germany as an Industry 4.0 location. Forming is the last crucial production step, which is decisive for subsequent performance, safety and longevity. The aim of this project is to accelerate and optimize the quality of the forming process using two intelligent optimization cycles. AI and physico-chemical models are used to actively intervene in the formation process in order to ensure a safe process (e.g. preventing the temperature from exceeding/falling below the limit) and to achieve positive cell properties. The aim is to show that it is possible to form tailor-made batteries with shorter process times, e.g. with regard to improved electrical properties or service life, and to accelerate the development of needs-based forming procedures. This project therefore addresses the cluster goal of AI in production by establishing an innovative system technology based on digitalization. The physicochemical basis for this is the generation of the so-called solid electrolyte interphase (SEI) during the first charging and discharging cycles. The SEI is a complex corrosion interphase consisting of electrolyte and electrode material, which prevents further corrosion of the electrolyte through passivation. If the SEI is inhomogeneous, damaged or of poor quality, the service life of a battery is shortened to the point of dendrite formation and explosion. By actively controlling the process using AI and physicochemical battery models, the aim is to achieve a homogeneous and high-quality SEI layer, which leads to improved electrical properties and a longer service life with a shorter process time. The physicochemical models are coupled with AI methods, such as “explainable” sequential machine learning, in order to specifically improve individual battery properties

The AI provides optimal experimentation plans that improve both function and model. The models will also be used for automated quality assessment in order to increase productivity and output and reduce rejects. In addition, cooperative human-machine offline analytics will make it possible to link basic and production research. The overall goal of this project is the design of intelligent battery formation systems to accelerate, reduce process costs and increase the quality of lithium-ion batteries based on AI and digitalization in production. This significantly supports the key objectives of improving “production costs”, “product quality” and “productivity” of the competence cluster. The methods and concepts developed can be integrated in particular for battery cell research production (FFB) and in the research platform for the industrial production of large lithium-ion cells (FPL).

The first charging of a lithium-ion battery - the formation

The first charging and discharging cycles of a lithium-ion battery during formation have a decisive influence on performance, ageing and safety. Due to the low potential of the negative electrode, the electrolyte is decomposed and forms the passivating solid-electrolyte interphase (SEI). The SEI has been examined in several reviews with regard to its structure and material interactions, properties and characterization methods as well as electrochemical relationships. The structural and morphological properties of the SEI are to be adjusted in a controlled manner with the formation process parameters in order to positively influence the cell properties and process duration. There are only isolated studies on the influence of process parameters such as temperature, current density, voltage profiles and various materials. A systematic investigation and discussion of the influence of process parameters during formation is lacking.

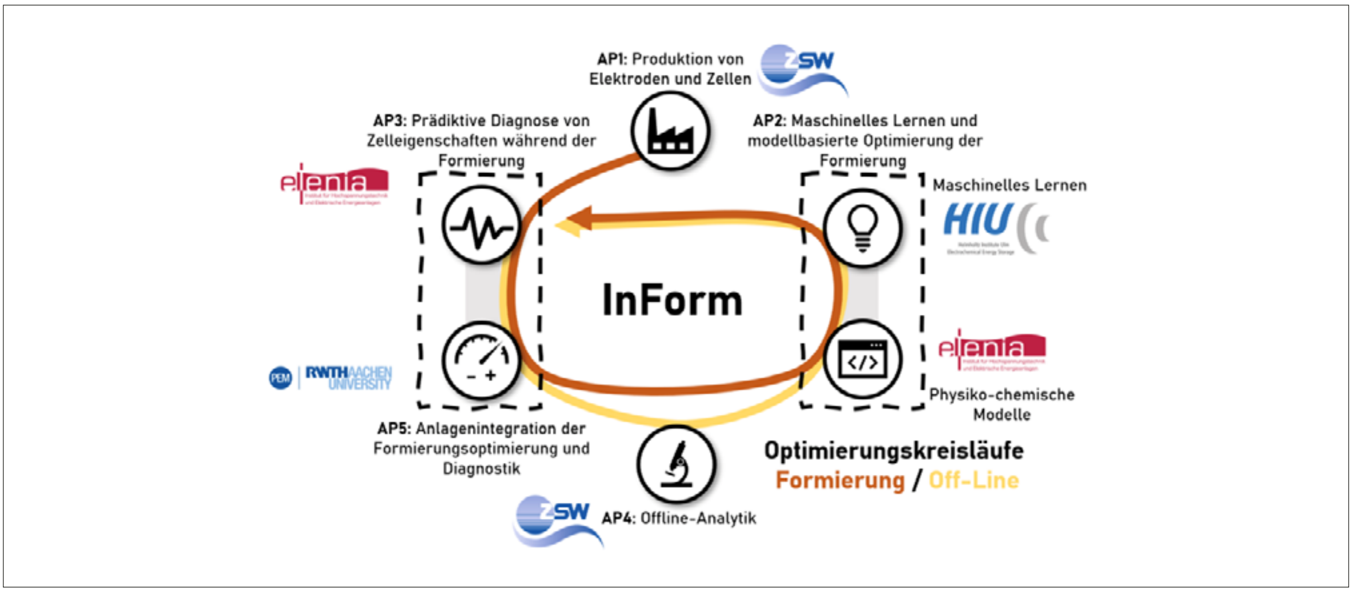


Figure 1: Work packages of the InForm project partners

The choice of forming strategy has a decisive influence on the SEI layer morphology and thus on cell properties, such as ageing properties. The SEI layer consists of several phases, which together determine the properties.

There are already initial modeling approaches for considering the SEI layer as a homogeneous layer or as multiscale modeling based on the Monte Carlo method for simulating the layer structure. However, the disadvantage of such models is the complex and time-consuming model parameterization and often results that cannot be validated directly. Conventional molecular-dynamic models are limited to very short time scales and therefore cannot be used for simulations of technically relevant process times. In contrast, physical equivalent circuit models with intrinsic state information enable the simulation and prediction of internal cell properties. In addition, such models can also be used to determine the maximum operating limits during formation that do not cause harmful degradation effects.

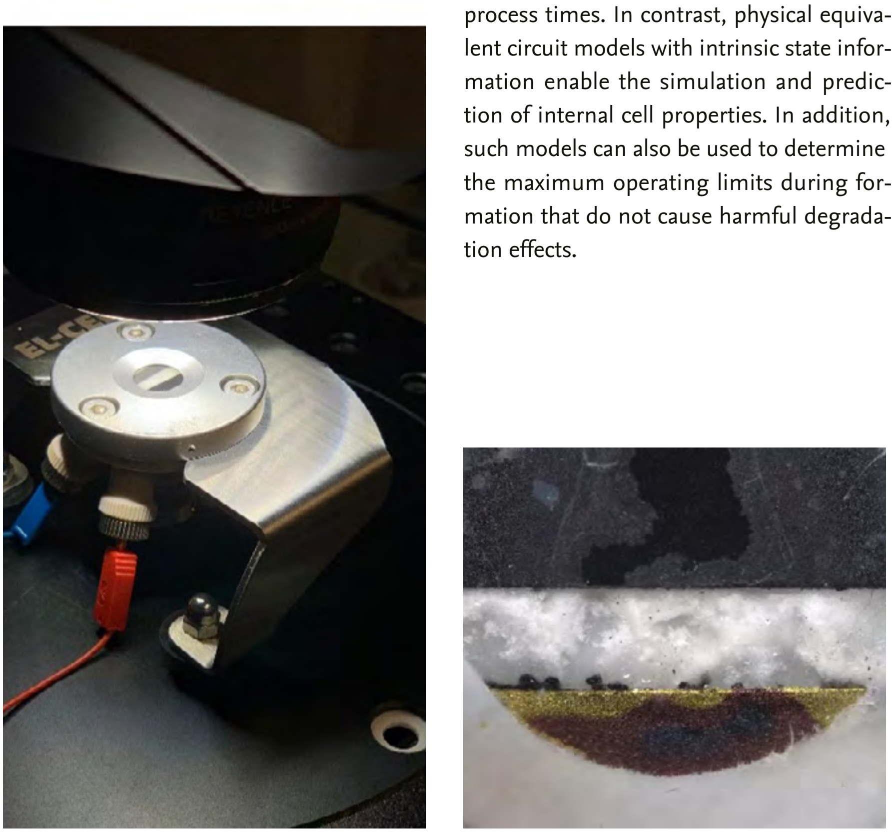


Figure 2: Optical battery cell for in-operando diagnosis of electrodes during formation

PROJECT TITLE

InForm

DURATION

2021–2024

CONTACT PERSON

Torben Jennert, M.Sc.
torben.jennert@tu-braunschweig.de
+49 531 391 9732

PROJECT PARTNERS

HIU, Ulm
RWTH, Aachen
ZSW, Ulm

FUNDED BY

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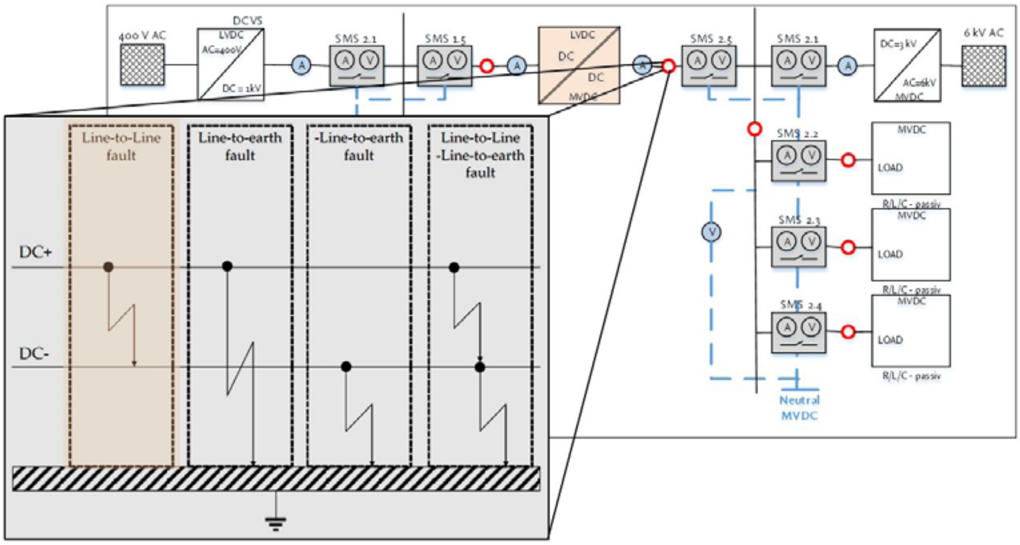
COORDINATED BY

Helmholtz-Institut Ulm
Elektrochemische Energiespeicherung
(JunProf. Dr.-Ing. Helge S. Stein)



Smart Modular Switchgear II

Modular protection system for selective fault disconnection in medium-voltage DC grid configurations

In addition to DC transmission (HVDC), there are other current and future applications for DC technology. These include, in particular, server farms, industrial networks, transmission networks and building networks. In the Smart Modular Switchgear II (SMS II) research project, the topics of protection technology, switching devices and grid behavior are being addressed. A demonstration grid with several voltage levels is being set up to investigate future DC grid structures. This can be used to simulate various grid topologies. The protection technology developed and the switching devices are tested on this setup. The effects of the grid dynamics on the switching behavior and fault detection are determined in the course of this. The demonstration network is to be understood as a bidirectional transfer function between the protection technology and the switching device. In the future, a scaled PHiL laboratory will be set up for the investigation of extended DC grid structures. The SMS-II project will be completed in 2024. completed. In the first half of the project (2019 - 2020), various issues and developments in the area of 1 kV processed. The following milestones and research results have been achieved:

1.) Testing of 1 kV hybrid switches
2.) Design, verification and validation of a simulation for a DC-DC converter with dual active bridge
3.) Selection and qualification of a suitable measuring device for investigating the emitted EMC interference of a DC network
4.) Design, calibration and implementation of 1 kV voltage sensors
5.) Construction, commissioning, electrical measurement and characterization of various operating cases of the 1 kV DC demonstration network
6.) Connection of the 380 V SMS-I DC network
7.) Construction of a system test bench to verify the protection system
8.) Validation of the protection system for two voltage levels in the demonstration grid (380 V, 1 kV)

In the second project phase (2021 - 2023), the focus was on expanding the demonstration network and upgrading all peripherals for the 3 kV level. The following goals were achieved:

1.) Definition of switchgear topologies for MVDC networks
2.) Definition of an MVDC network topology using simulation-based preliminary investigations
3.) Design, construction, and investigation of a 3 kV hybrid switchgear
4.) Recommissioning and upgrading of the 6 kV medium voltage outlet at elenia for supplying the MVDC network level
5.) Planning, design, and implementation of a control center for controlling the laboratory components
6.) Construction of MVDC AFE for +/- 1.5 kV and associated cooling

The construction of the 3 kV network, as well as the adaptation of the measurement technology, will be completed by the end of the year. Subsequently, the protection system in the demonstration network association (1 kV, 3 kV) will be validated. The findings of the completed work packages will be explained in the following sub-sections.

Protection technology

In the course of the project so far, a modular protection concept for the identification, localization, classification, and selective shutdown of current faults in DC networks at nominal voltages up to 1 kV has been examined and continuously developed. Various network topologies were considered, which are characterized, for example, by different voltage levels and their coupling via DC-DC converters. The concept of the protection system is based on the permanent monitoring of the system state using voltage and current sensors, which are installed on the switching devices used in the network. The data from the sensors are merged in a central protection unit before further derived quantities are calculated from the measured values via an FPGA controller. The measured and calculated quantities serve the decision-making of the protection algorithm. Depending on the dynamic change of state of the demonstration network, different assessments of the current status are made by the protection unit and, if necessary, instructions for action in the form of switching commands are forwarded to the switching devices in order to carry out a fault clearance as selectively as possible. The decentralized application of the protection algorithm on distributed controllers was a major milestone in the first half of the project. The system was also developed for the 3 kV level and validated in this at the end of the project.

Demonstration network

The multi-voltage level DC demonstrator is modular and bidirectional according to Table 1 and Figure 2. A variable plug-in system allows network structures to be freely interconnected at the LVDC level. For the qualification of the aforementioned protection system for the MVDC level, a requirement analysis was carried out. Subsequently, selected system states were examined in order to carry out an efficient (Design of Experiments) parameterization of the protection system. The characteristic curve of the error sizes determined in this way allows the protection system to be efficiently adjusted to various network topologies.

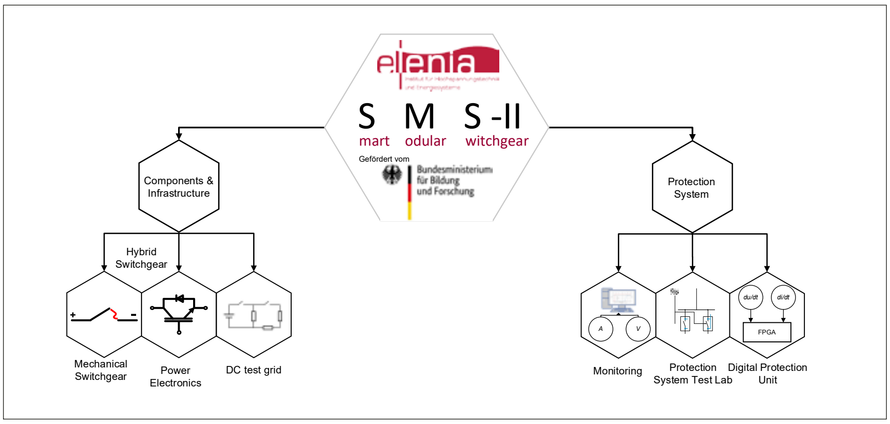
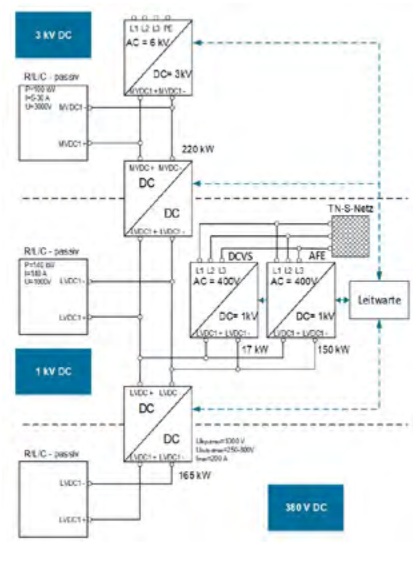


Figure 1: Project focus Smart Modular Switchgear II



Parameters	Value
Voltage levels	380 V, 1000 V, 3000 V
Power	220 kW
Network topology	Variable replica of: Industrial networks, server farms, building supply systems
switchgear	Hybrid
Load flow	bidirectional
loads	Ohmic, inductive, capacitive, electric
Connection to other network units	Bidirectional coupling tot he AC grid

Figure 2: Block diagram and characteristics of the demonstration grid and Parameters of the demonstration grid

PROJECT TITLE

Smart Modular Switchgear II

DURATION

2019–2024

CONTACT PERSON

Lars Claaßen
l.claassen@tu-braunschweig.de
+49 531 391 9715

PROJECT PARTNERS

E-T-A Elektrotechnische Apparate GmbH, Physikalisch Technische Bundesanstalt PTB, Siemens Energy AG, Phoenix Contact GmbH & Co. KG, IEMV, IMAB

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COORDINATED BY

TU Braunschweig – elenia (F. Witt)

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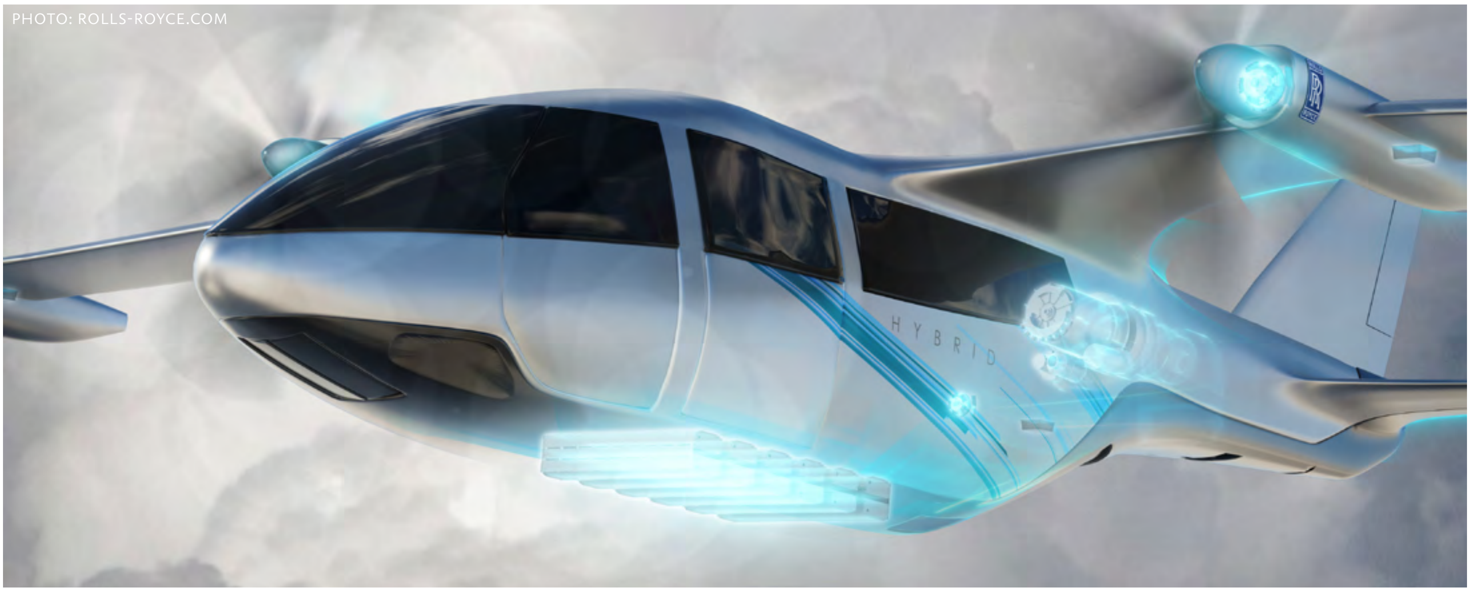


Electric Aircraft

Safe and reliable electrical and thermal networks for hybrid-electric propulsion systems

In response to climate change, many countries, including those of the European Union, have developed and signed the Paris Agreement. As part of this agreement, the EU has committed to reducing greenhouse gas emissions by at least 55% from 1990 levels by 2030 and achieving climate neutrality by 2050. Switching to sustainable and environmentally friendly aviation is an important part of achieving this goal.

ETHAN Project

Different types of electric aircraft have been investigated in many projects, such as ETHAN, SE2A and MOBILISE. The ETHAN project focuses on electrical and thermal networks of hybrid-electric propulsion systems. In this project, the Technical University of Braunschweig (TU Braunschweig), Rolls-Royce, BTU, KIT, LUH, TU Darmstadt and TUM are working together to develop environmentally friendly and reliable aeronautical systems. Three institutes of the Technical University of Braunschweig are involved in the project. These are the Institute for Motors, Drives and Trains (IMAB), Institute for High Voltage Technology and Power Systems (elenia) and the Institute for Electromagnetic Compatibility (EMV). Elenia's main tasks are:

1.) development of an electrical network model
2.) development of a protection system or protection algorithm
3.) validation of the protection concept

The focus is on hybrid-electric aircraft based on CS23 (Certification Specification 23, issued by EASA). This is a commuter aircraft with a maximum passenger capacity of nine. This hybrid-electric aircraft combines multiple gas turbines with electric propulsion to reduce CO_2 emissions and improve flight comfort and overall efficiency.

In this project, the electrical network is first simulated. Model-based systems engineering (MBSE) is used in the further development of protection concepts. The development steps are well illustrated by the V model (see Fig. 01).

The simulation of the on-board electrical network is now completed. Based on this, fault scenarios are analyzed and requirements for the protection system are identified. Requirements in terms of cost, weight,

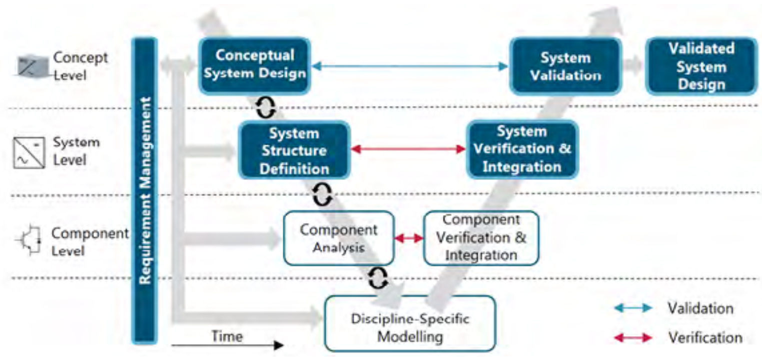


Figure 1: V-Model, Photo: TU Braunschweig, Melanie Hoffmann

volume, reliability, availability, maintainability and safety are discussed and analyzed. The corresponding protection systems are then developed at the conceptual, system and component levels. Various protection system strategies are compared and the most appropriate one is selected. The topology of the protection system is determined at the system level based on this strategy. Components such as measurement, protection and control devices are then selected or developed accordingly. The entire electrical system consisting of simulations and hardware devices (e.g. hybrid switches) is then tested using the HIL systems, which verifies if the system design meets the requirements.

Due to the absence of current zero-crossing points, fault arc that occurs during the switch-off process of a DC switch cannot be extinguished automatically. This is a challenge for the DC protection system. Therefore, the study of arcing is also a priority in the development of DC protection systems. When testing the performance of protection components such as switches, a low-pressure chamber is used to simulate the air pressure of the flight environment (see Fig. 02).

The air pressure in the low-pressure chamber is controlled by a vacuum pump. There is a viewing window on one side of the chamber. A high-speed camera is pointed at the switch through the viewing window to record the arc movement during the switch-off process (see Fig. 03).

Software

PSCAD, Simulink and Enterprise Architect are three frequently used tools in this project. The electrical network model is simulated in MATLAB/Simulink and PSCAD. Enterprise Architect is used as a modeling tool for the development of protection systems.

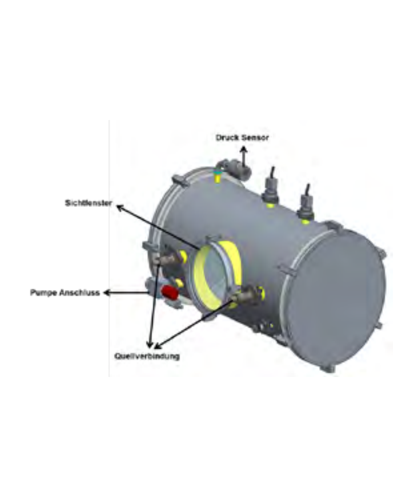


Figure 2: Low pressure chamber, source: Tobias Kopp

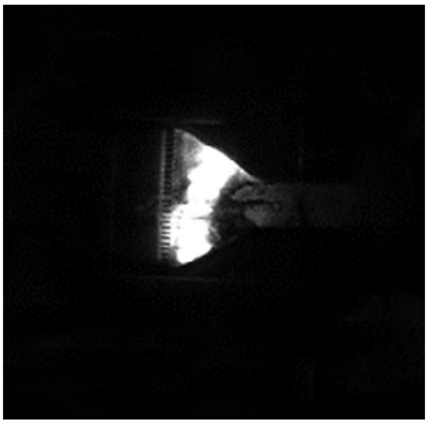


Figure 3: Arc during switch-off process (recorded with high-speed camera)

MathWorks
PSCAD
ENTERPRISE ARCHITECT

Figure 4: Tools, Quelle: mathworks.com, pscad.com, sparxsystems.de

PROJECT TITLE

ETHAN

DURATION

2022–2024

CONTACT PERSON

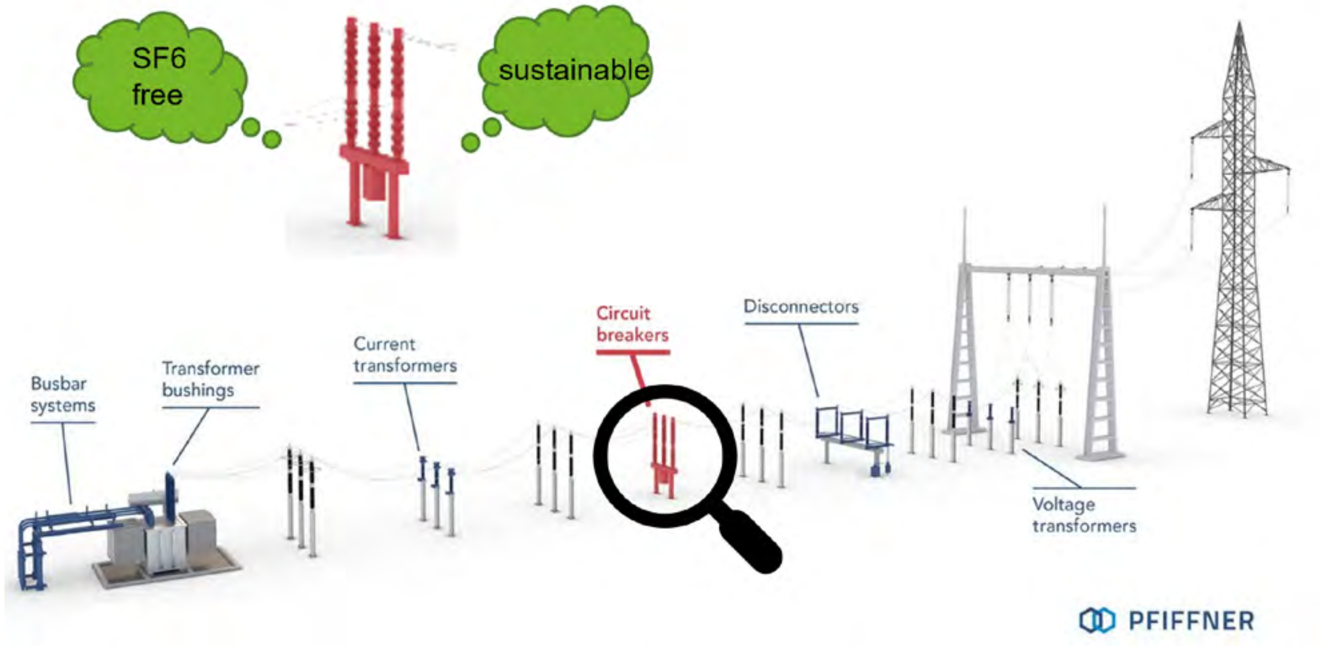
Fanke Zeng
f.zeng@tu-braunschweig.de
+49 531 391 9736

PROJECT PARTNERS

Brandenburgische Technische Universität Cottbus - Senftenberg
KIT Karlsruher Institut für Technologie
Rolls-Royce
Technische Universität Darmstadt
Technische Universität München
Leibniz Universität Hannover

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action



High-voltage circuit breakers of the future

Why a flourine gas-free circuit braker makes sense in high-voltage technology

SF_6 offers outstanding electrical properties in energy technology, but is extremely harmful to the climate with a CO_2 equivalent of 25.184. In view of increasing demand, especially due to the expansion of the grid for renewable energies, the elenia Institute for High Voltage Technology and Energy Systems at the TU Braunschweig is developing fluorine gas-free circuit breakers for the high-voltage range with the PFIFFNER Group. These are intended to replace SF_6 and offer more environmentally friendly solutions in order to minimise the negative effects on the climate. This will make an important contribution to sustainability in energy technology.

Thermal and dielectric investigations of the extinguishing gas are an essential part of the project, and this report is organised accordingly.

Thermal analysis of the test gas

As part of the investigations, the thermal extinguishing capacity of the gases to be investigated is to be characterised. For this purpose, the test setup from Dirk Bösche's dissertation (see page 99) will be used in a modified form. The setup enables the investigation of the resolidification of the gas or the switching distance with variable adjustment of the contact distance, the load duration and the load on the switching distance. The tests can be carried out independently of the properties of the actuator. A corresponding test circuit can then be used to compare solidification speeds under different conditions. This makes it possible to qualitatively characterise the behaviour of different gases and pressures on the thermal hardening of the switching section. It is to be investigated how the pressures of different test gases influence the thermal solidification. The setup must be extended accordingly to include a test vessel in which the switching device can be installed. In collaboration with an external manufacturer, a vessel was configured in accordance with the requirements specified in the project (see figure 1).

A sight glass enables the use of a high-speed camera to examine the (residual) plasma during the test. The test setup can be contacted internally via various electrical feed-throughs. The container can be evacuated via the gas feed-throughs to remove

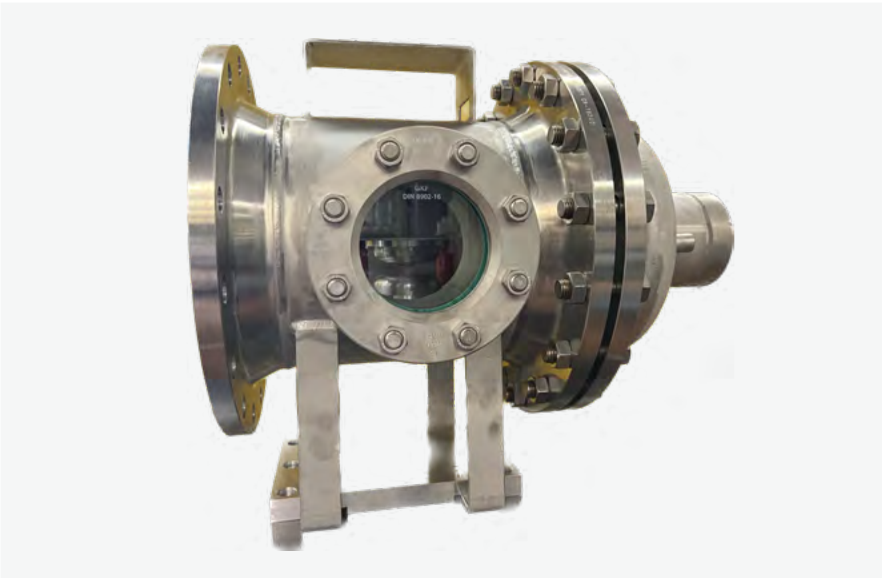


Figure 1: Test setup WP2, Photo: TU Braunschweig, Patrick Vieth

←
Cover picture: Area of application of HVCB, Pfiffner Group/Tiedemann/Vieth

the ambient air. Subsequently, the test gas can be injected at pressures of up to 11 bar via a gas cylinder and tests can be carried out. A safety valve and pressure gauge allow the pressure to be set without exceeding the operating limits.

Dielectric analysis of the test gas

In a further part of the project, the dielectric properties of the test gases are to be analysed in more detail. In particular, the dielectric strength of the different gases at different pressures, electrode distances and electrode surfaces will be determined. The aim is to determine which of the test gases to be analysed represents the best alternative for a fluorine gas-free circuit breaker. In order to investigate the dielectric strength of the gases at different pressures, a pressure vessel is used into which a variable bolted electrode arrangement can be inserted (see Figure 2). Different electrode distances can be set by adjusting the screw connection of the electrodes. The pressure vessel is largely transparent so that it is visually possible to distinguish a breakdown between the electrodes from a flashover on the vessel. After installation or a change in the distance between the electrodes, a residual amount of ambient air remains in the vessel. In order to minimise the influence of this residual air or of previously filled gas mixtures on the measurements, the vessel can be evacuated via a gas connection. The test gas is then fed into the test vessel via the same connection. The pressure in the vessel can be checked using a pressure gauge. A pressure relief valve at the bottom of the vessel prevents the pressure limits from being exceeded. At the end of a test, the test gas can be channelled outside via a gas hose. A system with measuring satellites is used for both the thermal and dielectric measurements, which transmit the measurement results to the measuring console via fibre optic cables. This results in galvanic isolation from the measurement setup.

In the first step of the dielectric tests, the test gases are subjected to a lightning impulse voltage. A two-stage Marx circuit is used to generate the lightning impulse voltage in the high-voltage hall of the elenia. In the next step, the various test gases will be exposed to other forms of voltage.

Figure 2: Test setup WP2, Photo: TU Braunschweig, Laura Tiedemann

PROJECT TITLE

PEEL

DURATION

2023–2025

CONTACT PERSON

Patrick Vieth
p.vieth@tu-braunschweig.de
+49 531 391 9725

Laura Tiedemann
laura.tiedemann@tu-braunschweig.de
+49 531 391 7736

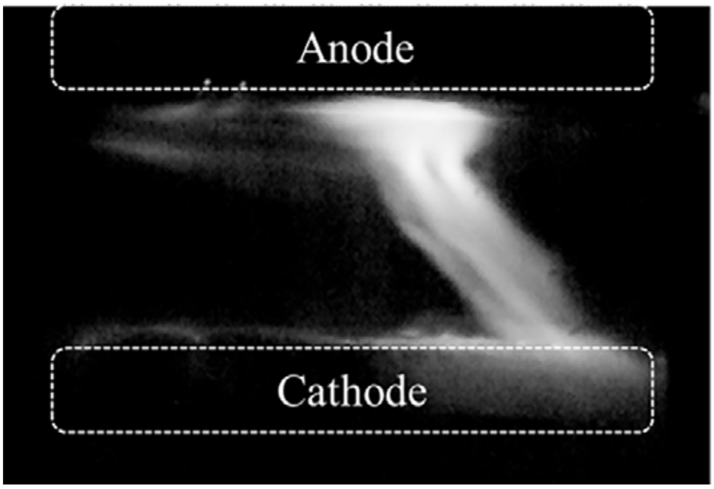
PROJECT PARTNERS

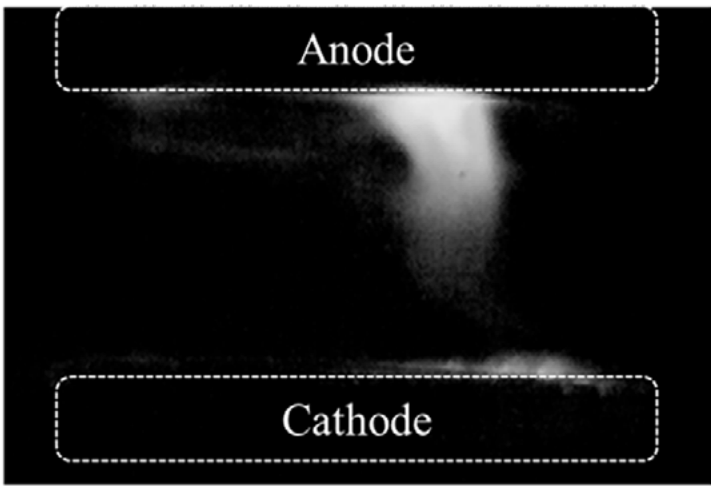
PFIFFNER
Current and voltage – our passion

Pfiffner Messwandler AG

FUNDED BY

IndustrieProject (Pfiffner)





Basic research into vacuum circuit breakers for future systems

As an SF_6-free circuit breaker, the vacuum circuit breaker has potential for use in high-voltage applications - we are contributing to this!

As the widely used insulating and switching gas sulphur hexafluoride (SF_6) has a global warming potential of 23,500 times CO_2, energy technology is endeavoring to replace it. In addition to alternative gases and technical air, vacuum can also be considered as a replacement insulating and switching medium. The main advantages of vacuum are that vacuum switching devices are climate-neutral and maintenance-free. Due to these advantages, the proportion of vacuum switchgear in medium voltage has been increasing for years. Our research contributes to the development of high-voltage vacuum circuit-breakers through a better understanding of individual aspects.

Dielectric

The degressive characteristic of the electrical strength of the vacuum over the distance makes it difficult to utilize the advantages of vacuum switching technology in the high-voltage range. The electrical strength of vacuum circuit breakers is therefore an important area of research. In addition to the excessive increase of the distance, the series connection of several vacuum circuit-breakers is used as a possibility for high voltages. Special attention must be paid to the voltage distribution, as the voltage distribution across the series connection shifts due to parasitic capacitances. As a result, the voltage across the top vacuum interrupter is higher than that across the others. Control capacitors are used to keep the voltage distribution in balance despite the parasitic capacitances. At elenia, the use of field controls made of metal shields that control the electric field capacitively is being investigated.

Plasma parameters

In addition to the dielectric stresses in the open state of the vacuum interrupter, the control of increasing short-circuit currents and transient voltages during disconnection must also be ensured. The breaking of a switching path is realized by a stationary and movable contact. When a fault occurs, the moving contact is removed from the fixed contact. Due to the high thermal stresses caused by the short-circuit current, the contact surfaces melt and metal vapor is distributed inside the vacuum interrupter. The conductive metallic particles cause the formation of a plasma column, the so-called vacuum arc (see cover picture). The geometric contact design of the switching contact pieces causes this arc to rotate due to magnetic forces and the contact pieces are worn evenly. TMF contacts (transverse magnetic fields), which are widely used in the medium voltage range, are being investigated at elenia. There are various research and development approaches to make them suitable for use in higher voltage ranges. We are investigating high contact strokes of up to 45 mm and the switching off of two vacuum interrupters in series. The arc behavior is observed with a high-speed camera (see Figure 1) during the entire switch-off and compared with measured electrical parameters in order to obtain as detailed a statement as possible about the plasma behavior. The formation and subsequent extinction of the plasma is being researched in order to enable good switch performance even for higher voltage levels.

Arc analysis

The vacuum arc can be observed in two different ways during the switch-off tests. At elenia, observation of the arc is made possible by a high-speed camera and simula-

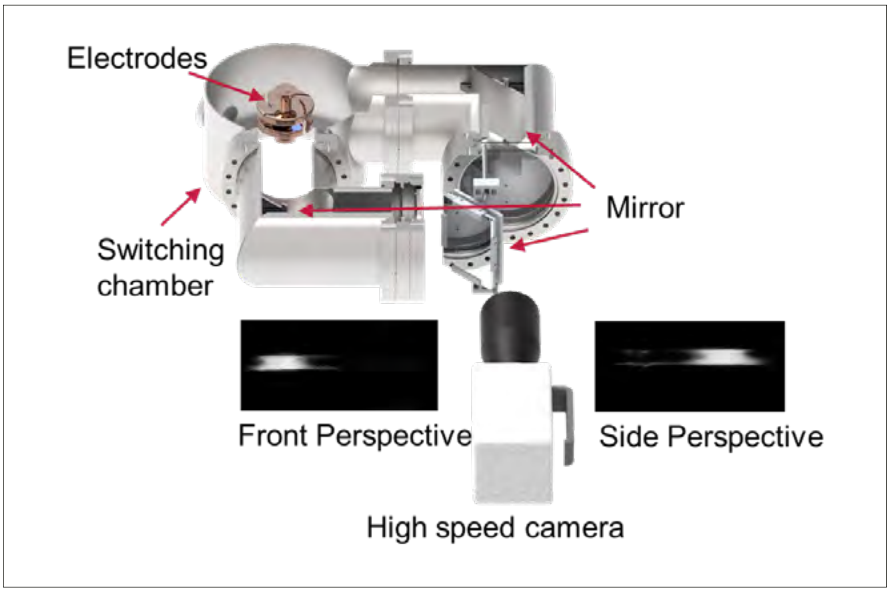


Figure 1: Schematic diagram of the optical vacuum arc observation with the high-speed camera

ted in a 3D representation with a corresponding mirror arrangement (see Figure 1). Our project partner, the Department of High-Voltage Equipment and Systems at TU Darmstadt, uses Hall sensors distributed around the chamber (see Figure 2). The deflections on the Hall sensors indicate the location of the vacuum arc. These two methods are being compared and verified in a DFG-funded project. For example, parameters such as arc speed and the number of arc rotations are being investigated, as shown in Figure 3. The movement of the arc can be seen when the contact pieces are pulled apart.

As part of the project, a model switch was developed that enables simultaneous optical and magnetic investigations. This initially confirmed the magnetic measurement method. Subsequently, fundamental experiments contribute to a better understanding of the arc behavior. This understanding is then used for the further development of commercial vacuum circuit-breakers. Due to the successful work and results, the project was extended

PROJECT TITLE

MoLiboA

DURATION

September 2023 – February 2026

PROJECT PARTNERS

HST TU Darmstadt

FUNDED BY

Deutsche Forschungsgemeinschaft

PROJECT TITLE

EUDo, EUlaS & Dielektrik

DURATION

EUDo II & EUlaS:
January 2021 – December 2022
EUDo III & Dielektrik:
January 2023 – December 2025

CONTACT PERSON

Timo Meyer
timo.meyer@tu-braunschweig.de
+49 531 391 9739

Karen Flügel
k.fluegel@tu-braunschweig.de
+49 531 391 7785

PROJECT PARTNERS

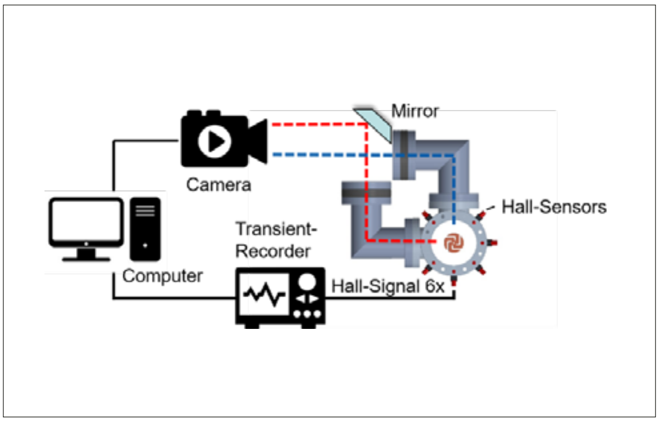


Figure 2: Schematic diagram of the simultaneous optical and magnetic localization of the vacuum arc

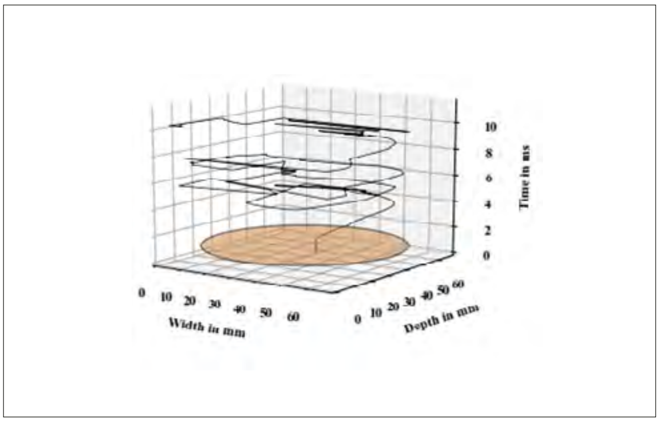


Figure 3: Movement of the vacuum arc when opening the contact pieces under high current load

Insulation Material Technology

Entering Energy Technology with 3D Printing

Rapid prototyping is a method in modern product development. Using additive manufacturing processes such as Fused Filament Fabrication (FFF), test specimens are printed layer by layer from a thermoplastic material. Improvements to the test specimens can be directly implemented, printed, and retested. To qualify these processes, various dielectric tests are conducted on these materials at elenia.

Electromobility is currently heavily involved in the development and research of optimized electric drives and corresponding technologies for future mobility concepts. In particular, rapid voltage rises and fast-switching wide-bandgap semiconductors pose significant requirements for insulation systems in electric cars. These requirements lead to overloading of the insulation system. To investigate these influences and effects, quickly manufacturable and easily adaptable test specimens with constant quality are needed. Fused Filament Fabrication (FFF) could be a suitable method for this purpose. FFF is an additive manufacturing process where a thermoplastic polymer is cured layer by layer to form components.

The manufacturing process is tool-less and moldless, directly based on CAD data. The infill density, printing temperature, pattern filling, and many other printing parameters can be varied, influencing the resulting dielectric properties. This enables resource-efficient production and optimal component design. While the dielectric properties of various materials produced using FFF (Fused Filament Fabrication) do not yet reach those of conventionally manufactured dielectrics, they offer an alternative when dielectric properties are of secondary importance. Especially for specially fabricated components that can only be produced conventionally with great effort, they can be important. Another additive manufacturing process, Stereolithography Printing (SLA), has the advantage of not creating process-related voids, leading to significantly better print quality. However, these standard resins are not designed for dielectric properties and may have, for example, poorer electrical breakdown strength or a high loss factor.

Keeping an Overview with CT Scanning

In collaboration with the Institute of Applied Mechanics (IAM), a series of test specimens were scanned using a micro-CT. The CT scan clearly shows the regularly occurring voids in the insulation, which arise during the printing process. These voids can take on considerable dimensions and are attributed to the printing settings. The printed layer starts and ends at these positions, leading to the formation of these sources of errors. These errors, in turn, have significant impacts on the dielectric properties of the test specimens. The quality of the 3D print exhibits strong fluctuations. The CT scans provide interesting insights into the structure of the test objects and contribute to better understanding and further improving the printing process.

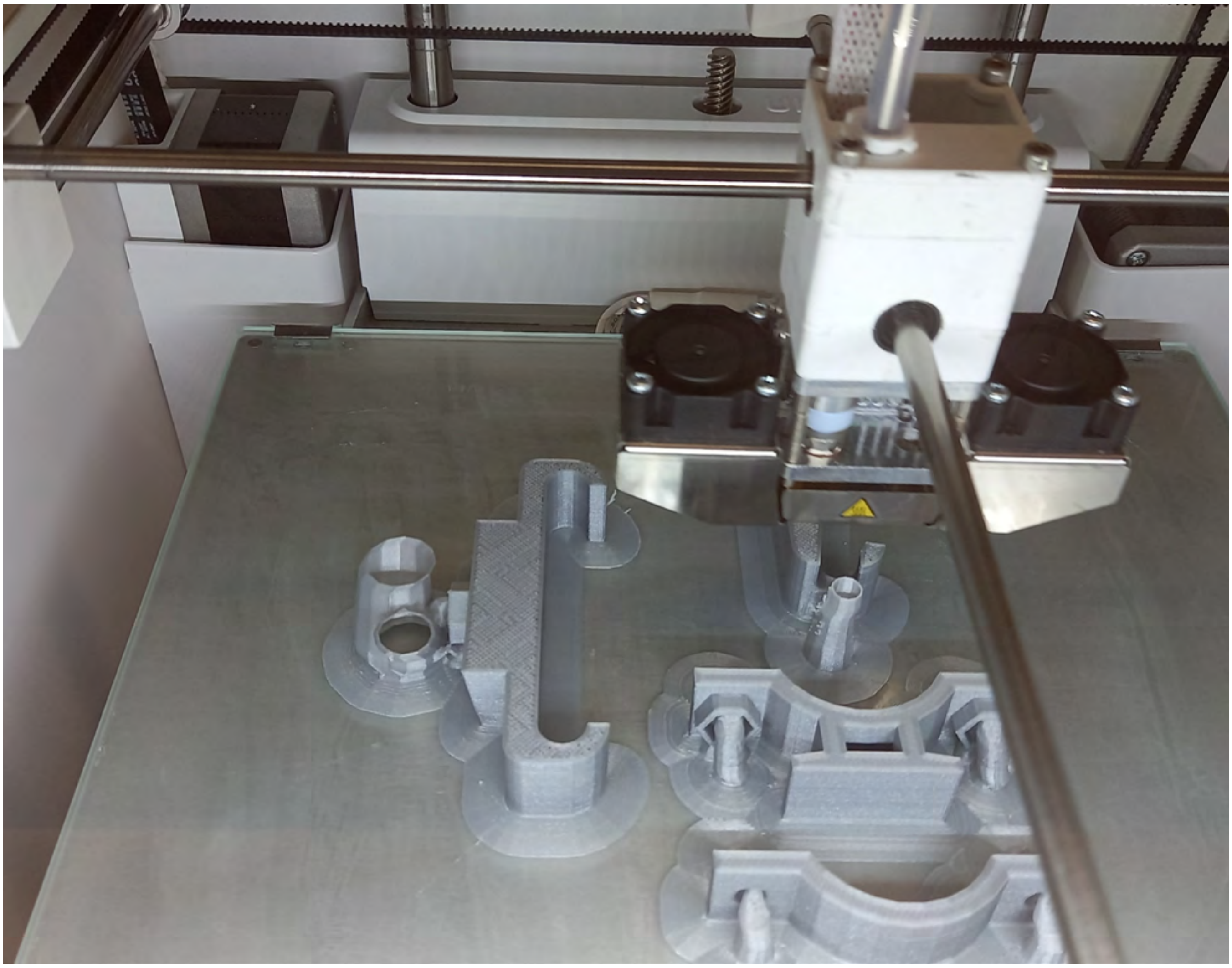


Figure 1: 3D-printed sample

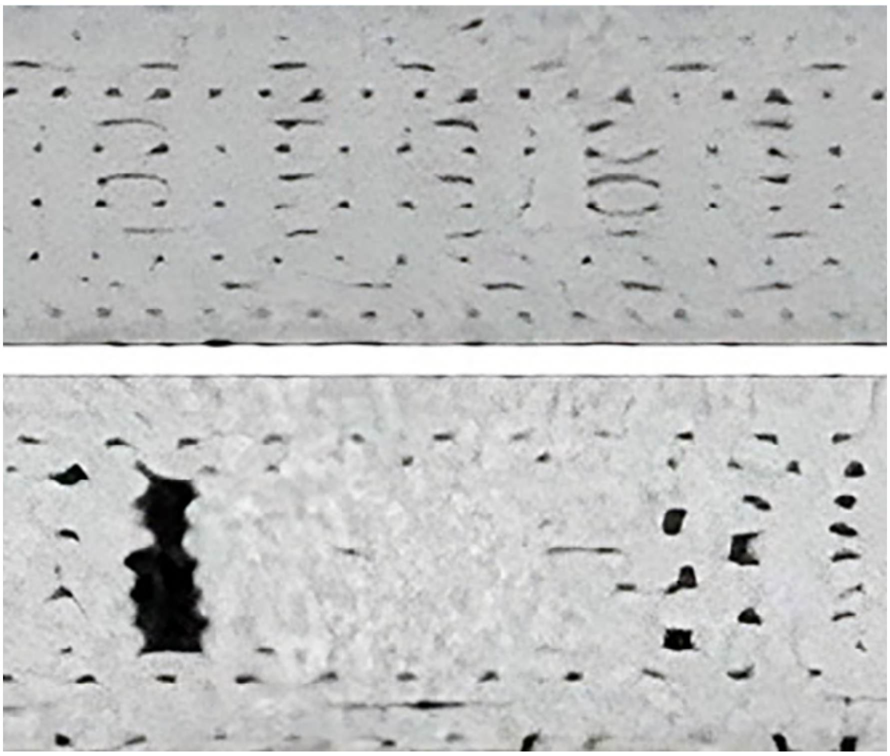


Figure 2: CT-CT-scan of a 3D-printed sample, photo: TU Braunschweig, Maik Kahn

PROJECT TITLE

Robuste Isoliersysteme

DURATION

November 2019 – ongoing

CONTACT PERSON

Maik Kahn
m.kahn@tu-braunschweig.de
+49 531 391 7741

PROJECT PARTNERS

Volkswagen AG – Group Innovation

flexess – Flexibilisation of the energy system

Development of strategies and solutions to leverage future flexibility potential

The energy transition and the associated integration of renewable energies into the electricity system are bringing significant changes to all sectors of the energy system. A crucial element for the success of the electricity, heating and mobility transition is the effective use of flexibility, in other words, the change in feed-in or withdrawal of active power in response to an external signal.

Providing flexibility across all sectors

For the provision of flexibility, the four case studies of full-electric households, commerce, trade and services, industrial processes and electromobility are being analysed. In addition to potential providers of flexibility, the research project also analyses potential flexibility users. In contrast to most related research projects, both the grid- and the market-orientated use of flexibility are considered. All subsystems are examined via a co-simulation in the overall system called „flexCity".

Schedule-based flexibility

In flexess, a schedule-based instrument was developed to utilise cross-sector flexibility from the above-mentioned case studies. Based on the predicted cost-optimised residual power curves (reference schedule) for the forecast horizon, alternative operating modes (alternative schedules) of the controllable plants are determined, taking into account the technical, regulatory and individual-specific boundary conditions.

The resulting costs due to increased grid power consumption or ageing effects, e.g. due to an increased number of full cycles of the battery storage system, are recognised as schedule costs and serve as the cost basis for the remuneration of flexibility. All uncertainties resulting from the boundary conditions of the power flow forecasts can be considered via a probabilistic safety factor.

The discretisation of the power shift potential in the form of schedules enables external flexibility users to improve planning and consider catch-up effects (power shifts as a result of the original power change). In addition, the standardised product design offers advantages in the aggregation of flexibility, which is particularly relevant for lower-performance classes to exploit economies of scale. Furthermore, all sensitive consumer data (e.g. presence profiles, device specifications) is abstracted and the decision on the amount of flexibility available to third parties remains with the owner of the controllable system.

Analysing the potential of flexibility

To illustrate the relevance of flexibility, the current and future theoretical potential for flexibilisation was determined at the beginning of the research project on a case study-specific basis. However, this potential calculated based on the power ranges of the controllable systems does not reflect the actual flexibility for the different forms of utilisation, as technological parameters are not taken into account. To determine the practical, i.e. usable potential, models and schedule-based flexibilisation algorithms were developed in flexess for various equipment levels and technology types.

The practical potential was visualised as a heat map, thus enabling outsiders to understand the topic. Consecutively, the presentation as a bar plot offers the possibility of not only a qualitative, but also a quantitative, time-correlated categorisation of the potential as a result of contracting. On the provider side, it is thus possible to immediately analyse how the flexibility currently offered can be optimally matched with past demand on the user side, for example.

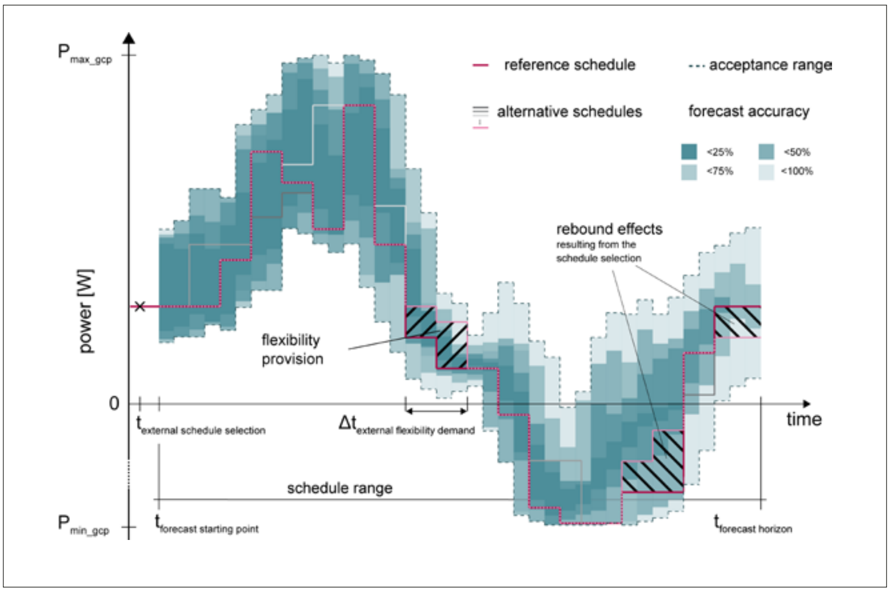


Figure 1: Schematic illustration of schedule-based flexibilities, own illustration

PROJECT TITLE

flexess

flexess

DURATION

2019–2023

CONTACT PERSON

Mattias Hadlak
m.hadlak@tu-braunschweig.de
+49 531 391 9713

PROJECT PARTNERS

IWF, SMA, Carano, BVG, TLK, BS|NETZ, BS|ENERGY, REWE, GEWI, TransnetBW

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action

COORDINATED BY

TU Braunschweig – elenia

Validation in field and laboratory tests

As a functional validation for the practical applicability of the scheduling approach, a demonstrator was designed and implemented for the household case study in the elenia energy management laboratory. This allows the electrical-thermal behavior of households to be simulated. Using a Simulink realtime-based computing system, the previously linear optimisation-based residual load schedules were disaggregated on the system side and converted into power curves. In addition, the elenia accompanied the field test at the Berlin transport company in cooperation with the developer of fleet management software carano. Using real booking data from a fleet management system, it was possible to generate schedules based on various charging strategies, convert them into charging processes in response to an external schedule selection and subsequently monitor their fulfilment.

Optimised use of flexibility

The generated schedules allow third parties to compare the flexibility of different providers and to contract for their own utilisation purposes. The research project focussed on grid and market-oriented applications. The flexControl communication structure was developed for clear coordination between the grid operators and electricity suppliers/flexibility marketers. This provides a clear framework for contracting schedules, monitoring their fulfilment and billing mechanisms.

In co-simulations, it was possible to show that flexControl supports selective operational planning and prevents conflicting signals from different external users. Power-related grid congestions, which could occur in the future due to further electrification, particularly at the low-voltage level, could be resolved. For market-oriented use, it could be shown that the aggregated contracting of flexibility can optimise procurement and thus reduce costs.

Results on schedule generation, possible revenues and costs as well as the concepts for monitoring delivery and billing concepts are summarised in a final report and can be viewed on the institute's website.

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Cover picture: Field test object in Bielefeld, photo: TU Braunschweig, Michel Meinert

Smart solutions for multi-family houses with energy storage systems

Generate, store & share solar energy on site: with a shared PV system, storage and energy management system

Energy storage systems are crucial to the success of the energy transition, as they allow locally generated green electricity to be used flexibly. The use of energy storage systems is already increasing in private homes. In multi-family houses (MFH), however, the basic measurement technology and regulatory principles for sharing stored, locally generated energy are still lacking. Concepts for the integration of PV storage systems in apartment buildings are therefore absolutely essential.

Obstacles to implementation include, for example, the Metering Point Operation Act and the technical guidelines of the BSI, which need to be overcome through innovations in metering technology. This is because when several residential parties access one and the same electricity storage system, it must always be possible to determine and bill exactly which quantities of electricity were drawn by which residential party from the domestic electricity generation system, the storage system or from the public grid. This data must be collected in accordance with calibration law and made available to the relevant market partners in the electricity market.

The MELANI project consortium is developing concepts for integrating apartment users into the energy and transport transition so that cheaper, self-generated green electricity is not only possible in homes in the future. The project aims to clarify questions such as how the joint use of decentralized energy systems by several players in apartment buildings can be implemented technically and energy-efficiently or which business models and operating concepts contribute to practical feasibility and acceptance by potential users (apartment users, energy suppliers, third parties).

Key elements of the project

Technical innovations such as the development and validation of metering and billing solutions and associated energy management functions, ICT solutions and data services in apartment buildings are at the heart of the multi-year research project. The main task of the elenia Institute is to develop a data and control platform which, in addition to networking all components, serves to offer users a means of interaction. To this end, the users of the apartments are made aware of their consumption behaviour through visualization. In addition, the management of their virtual system shares is made possible, which can provide incentives to change consumption behavior.

Development of an innovative energy management system

The above-mentioned central element of the research project is the implementation of a central data and control platform, which has already been completed. It contains the energy management system (EMS) for controlling components and therefore also power flows.

A Python-based energy management system was developed to meet the special requirements of the MELANI concept. Requirements include the division of physical storage and generation systems into virtual components and the possibility for apartment users to trade with these. Dynamic load management was also integrated into the EMS to avoid overloading the grid connection. At the same time, a conventional EMS has been programmed, which will serve as a reference object during the test period and will run in the identical reference building.

Intensive, successful tests in the laboratory

In order to validate the specially programmed system, a demonstrator was set up in the elenia Institute's energy management laboratory. Tests of the overall concept were carried out there together with the PTB and the computing unit was integrated. The focus was on error-free communication between the various interfaces. This includes an API (programming interface) developed by Naturstrom, in which various values can be written for visualization for apartment users. In addition, extensive communication was established with the calculation unit in order to be able to generate the billing values correctly

Calculated power setpoints are transmitted from the EMS to the calculation unit.

The control of individual components such as the charging station or the battery storage system (consisting of battery storage & inverter) and the logics and triggers of individual parts of the operating strategies were also successfully tested in the elenia Institute's laboratory. The illustration shows various flexible, electronic loads that act as replicas of household loads during the tests.

In addition, safety measures were developed for the EMS to ensure automatic start-up after a power failure and to enable automatic backup of the collected data. Final tests to ensure the accuracy of the billing values and rule out errors in continuous operation have been carried out in recent weeks and months, so that everything is now ready for the upcoming field test in the Grünewald district of Bielefeld.

Figure 1: Electronic loads, photo: TU Braunschweig, Nils Hartau

Figure 2: Part of the experimental setup in the energy management laboratory, photo: TU Braunschweig, Nils Hartau

Starting point for the field test in the apartment building

At the time of reporting, the start of the field test is imminent. From October 2023, the energy management system previous-ly tested in the laboratory will be running in the MELANI building (see cover photo) with all the associated compo-nents. The PV system on the roof of the apartment building has been installed, the storage units are ready for use and the 12 wallboxes for charging the apartment users' electric cars have been installed in the garage. To make all this possible, there were regular exchanges in advance between the consor-tium, the system operator, the property developer and the local contractor. In addition to technical aspects, the coordi-nation meetings also dealt with contractual matters, for exa-mple. Furthermore, the second, identical part of the building, the reference property, was almost completed at the time of reporting, meaning that the apartment users will be able to move in soon.

And then?

During the entire field test period, relevant data is to be coll-ected and analyzed at 1-second measurement resolution. Research data of this quality has hardly been publicly available to date, which is why it is of particular importance to the elenia Institute. At the end of the project, this data will be used for further research projects.

The project can open up multi-storey residential buildings for storage use in conjunction with renewable energy generation and new consumers from the sector coupling of mobility and heat, thus providing a further part of the population with economically attractive access to locally generated, innova-tively managed and affordable electricity and electromobility. In this way, the intelligent processes and operating methods developed make a positive contribution to the energy, mobili-ty and heating transition in the residential sector, which can also increase the capacity of the distribution grids in urban areas.

PROJECT TITLE

MELANI

DURATION

November 2020–April 2025

CONTACT PERSON

Marcel Lüdecke
m.luedecke@tu-braunschweig.de
+49 531 391-9726

Michel Meinert
m.meinert@tu-braunschweig.de
+49 531 391-9728

Tamara Beck
t.beck@tu-braunschweig.de
+49 531 391-7702

PROJECT PARTNERS

Naturstrom AG, SMA Solar Technology AG, PTB Braunschweig

WEBSITE

www.projekt-melani.de

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action

COORDINATED BY

Naturstrom AG

Future Laboratory Energy (Zukunftslabor Energie)

Co-Simulation-Based Energy System Analysis of Energy Communities and Development of a Collaborative R&D Platform

Digitalization is a global megatrend which enables new functions and processes in various industries as well as interconnecting them. Digitalized energy systems open up the opportunity to make a significant contribution to the successful implementation of the energy transition by enabling more efficient and sustainable operation. However, digitalization in the safety-critical energy system leads at the same time to new interactions and sensitive dependencies. In order to systematically minimize the interactions between the functionally coupled areas and technologies in digitalized energy systems, a more efficient integration of energy system research is required. It is essential to better integrate different disciplines and make it easier to put the results of research into practice. The Future Laboratory Energy ("Zukunftslabor Energie – ZLE") formulates two central research objectives based on these problems: the research and development of digitalized energy systems and the digitalization of energy system research and development.

Figure 1: The ZLE at the Hannover Messe 2023, Source: elenia Institut, Henrik Wagner

Research objectives of the Future Laboratory Energy

The first central research objective is addressed via five different scenarios that consider several technical components of the energy system. The scenarios examine the following key areas and issues: Use of *flexibility* in energy systems to compensate for grid-critical imbalances in generation and consumption; influence of disruptions *in information and communication technology*; grid capacity of energy communities and residential districts for *electromobility*, energy supply for *buildings* and *grid operation* in digitalized energy systems. For the second central research objective, the ZLE researchers are developing a collaborative research platform to pool research and development interests in the energy sector and make research activities transparent. Six different elements were designed for this purpose: *Competence* to present technical expertise; *Methods* in the form of best practices of successful methods and models; *Core* as an area of basic functions and technical processes, *Repository* as a digital archive of usable simulation and data models, *Simulation* to visualize and analysis of digitized energy systems and *Transparency* for the publication of research results.

Investigation of the Grid Capacity for Electromobility

Within the scenario *electromobility*, the grid capacity for electric vehicles was investigated for the "Am Ölper Berge" district in Braunschweig, Lower Saxony, considering the EN 50160 standard for voltage quality. An open-source co-simulation was developed for the investigation using the mosaik framework. This co-simulation enables the modeling and linking of various key components of the district's energy system, including component models, control models, grid calculations and data storage. A simu-

Figure 2: Prototype of the ZLE R&D platform, Source: elenia Institut, Henrik Wagner

lation study was carried out to investigate the increase in grid capacity by user-sided measures in form of systems for the cooperative generation and storage of renewable energies as well as coordination and control algorithms. In accordance with the ZLE's Open Science Declaration, all models and associated data developed within this framework are freely accessible. The simulation results show that the integration of renewable energy components in the grid without active controlling them does not achieve any significant synergy effects for the grid integration of electric vehicles. However, the combination of these components with an intelligent grid control algorithm that utilizes the flexibility potential of the district and/or charging strategies leads to a significant increase in grid capacity for electromobility.

Development of the Competence Element for the Collaborative R&D Platform

Competence is part of the five basic elements of the ZLE research platform to be developed, see cover figure. The objective of the platform element is to present the multi-layered competencies in the ZLE energy research network. The presentation of expertise on the research platform is based on four different sub-elements: Profiles, Research Networks, Research Clusters and Research Map as shown in figure 2.

The sub-element *Profil* presents the research competencies and interests of the members of the ZLE energy *Research Network*. Various information is used for this purpose, including a brief description, associated research projects and scientific publications. The sub-element Research Network provides an overview of possible localized research networks. Potential users can thus find a direct link to the ZLE energy research community via their membership in such a network. In the sub-element *Research Cluster*, competencies are grouped according to freely selectable research clusters, e.g. co-simulation. The fourth sub-element *Research Map* depicts a possible geographical proximity of current and potential future research partners and thus the strength of the network.

Figure 3: ZLE employee Henrik Wagner at the Meet-the-Scientist event at phaeno Wolfsburg, Photo: Hochschule Ostfalia Braunschweig, Tobias Lege

PROJECT TITLE

Zukunftslabor Energie

DURATION

October 2019 – March 2025

CONTACT PERSON

Henrik Wagner
henrik.wagner@tu-braunschweig.de
+49 531 391 9718

PROJECT PARTNERS

OFFIS e.V., DLR Institut für Vernetzte Energiesysteme, Leibniz Universität Hannover, Carl von Ossietzky Universität Oldenburg, Hochschule Emden-Leer, Hochschule Ostfalia Braunschweig

FUNDED BY

Lower Saxony Ministry of Science and Culture within Lower Saxony's "zukunft.niedersachsen" program of the Volkswagen Foundation

COORDINATED BY

Center for Digital Innovations Lower-Saxony (ZDIN)

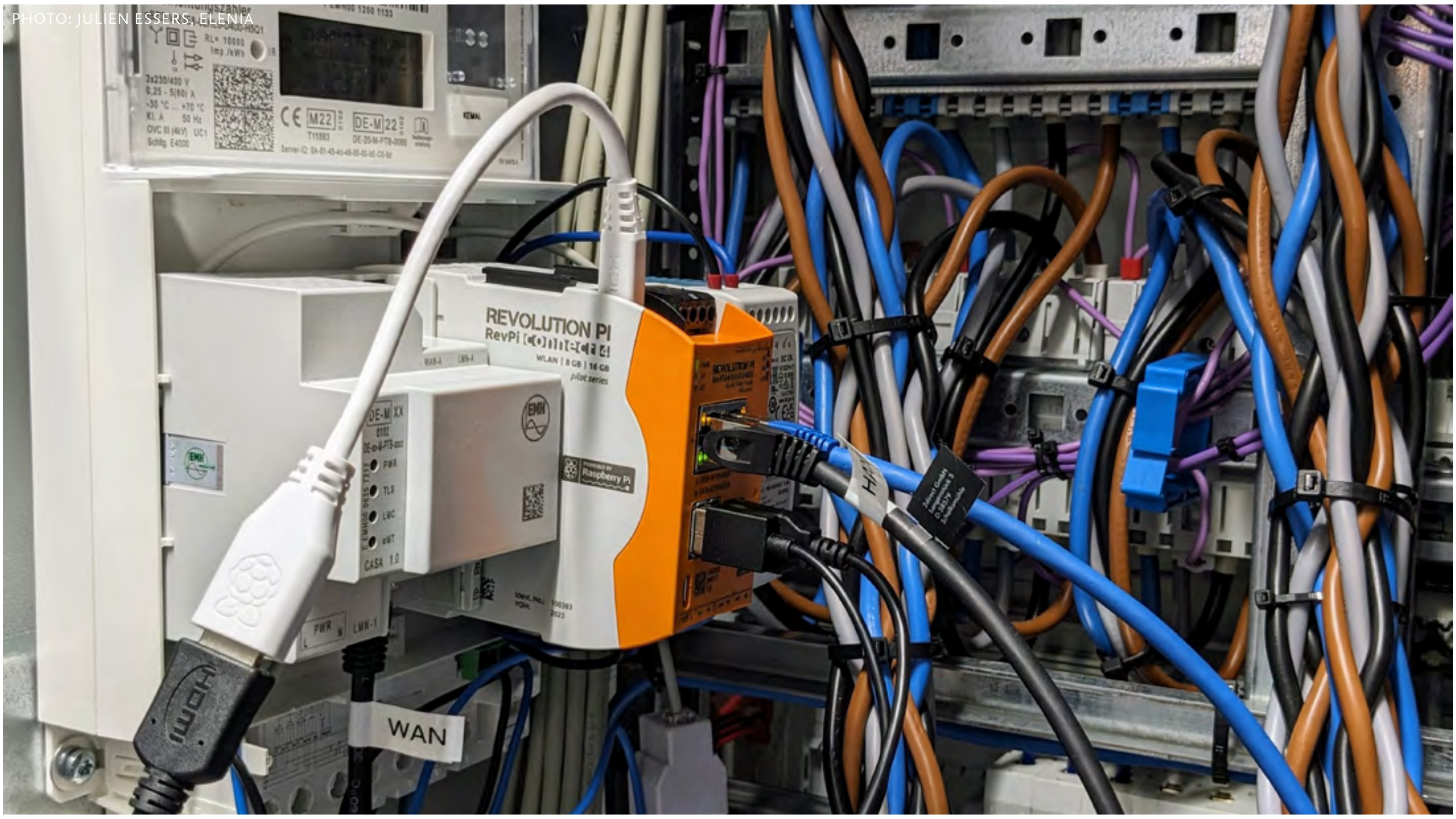

PHOTO: JULIEN ESSERS, ELENIA

KEMAL

KEMAL – Kundenorientiertes Energiemanagement mit autonomer Lastregelung (Customer-oriented energy management with autonomous load control)

The smart meter rollout and the associated digitalization of the low-voltage grid are opening up exciting new application possibilities in the field of energy management. Innovative supply tariffs with attractive price models enable the efficient use of volatile renewable energies. Here, energy management not only optimizes the customer's own electricity consumption, but also automatically shifts loads to low-price time windows, thus ensuring the most cost-effective operation for the customer.

As part of the KEMAL joint project, which is being carried out in cooperation with the partners EMH metering GmbH & Co. KG and Biberach University of Applied Sciences, these innovative possibilities are being further researched and developed in an ap-

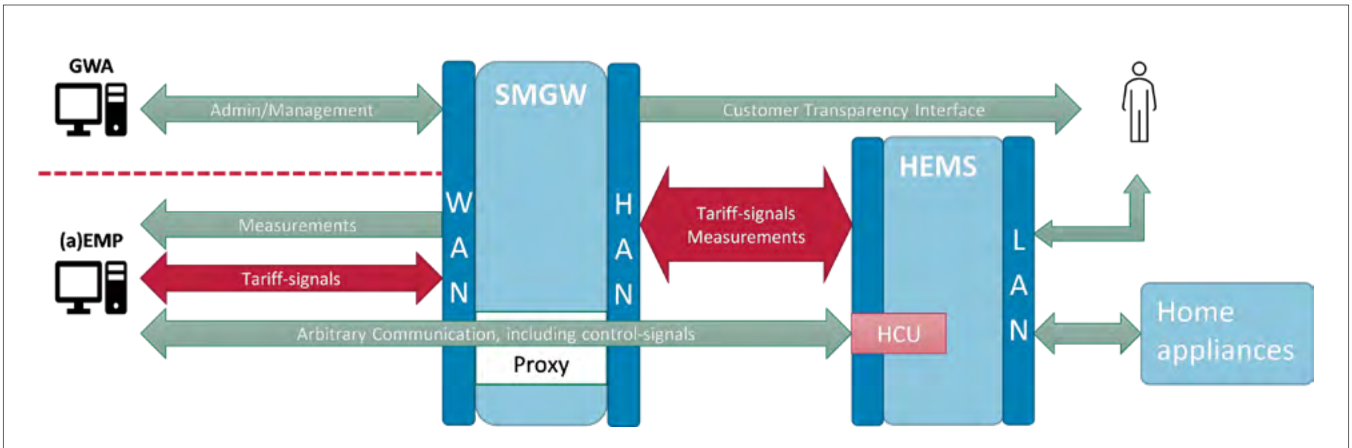

Figure 1: SMGW and HEMS interfaces. Functional extensions are marked in red.

Figure: Eike Niehs, elenia.

plication-oriented manner. In order to realize efficient load control that is protected against external interference, the focus is also on the integration of smart meter technology. This will enable innovative tariff models that allow customers to actively participate in the energy transition.

Energy management with the smart metering system

The implementation of smart metering systems forms the basis for the digitalization of the energy transition and is therefore essential for achieving our climate targets. With smart meters, consumers and companies have the opportunity to record their electricity consumption and the feed-in of self-generated electricity, for example from photovoltaic systems, transparently and synchronously and to control net consumption and grid load effectively and conveniently. This opens up new opportunities for smart metering systems to efficiently integrate renewable energy systems and controllable consumption devices, such as electric cars or heat pumps, into the electricity grid.

The intelligent metering system consists locally of a digital base meter and a smart meter gateway (SMGW), which is integrated into a highly secure, wide-ranging communication network. In KEMAL, the smart meter is used as a measuring point to carry out energy management. The relevant energy and performance data for energy management can be tapped via the gateway's transparency and data interface and made available to the Home Energy Management System (HEMS). Communication is certified in accordance with the IT security requirements of Technical Guideline 03109 of the German Federal Office for Information Security (BSI).

Research objectives

As part of KEMAL, the solution approach is being investigated with regard to various aspects of energy management. A primary objective is to determine the extent to which a smart metering system can be used as a measuring point for energy management. The aim is to analyze whether the potentially higher latencies that can occur due to encryption have an impact on prosumers' energy management.

Furthermore, it is planned to implement tariff use case 5 for mapping event-variable tariffs in the SMGW. Other potential solutions are also to be identified. These solutions will be integrated and presented as part of a demonstrator. In addition, the solutions found will be validated in the energy management laboratory to test their effectiveness and applicability.

The KEMAL research project thus aims to gain a deeper insight into the possibilities of energy management using smart metering systems and, in particular, to investigate the potential impact of encryption processes on the prosumer sector. In addition, the aim is to develop and validate new approaches for the implementation of tariff models.

Scenarios, requirements and gap analysis

In order to ensure the effectiveness and functionality of the developed demonstrator, detailed technical system use cases were summarized at the beginning of this research project. These use cases describe requirements and scenarios in real operation and form the basis for further development and implementation work. A comprehensive deficit analysis of the legal and technical framework conditions defined the KEMAL framework for action and solutions at this stage.

A key step in the development of the demonstrator is the description of the interface signals and functions required to implement the market and grid scenarios and use cases. This includes in particular the communication and interaction between the various components and systems, including the control box function, the HEMS and the SMGW. To map the new TAF 5 tariff use case, the existing HEMS and SMGW interfaces will be used and expanded to include new functionalities.

Testing under real conditions in the laboratory

A decisive step is the construction of the demonstrator in the elenia energy management laboratory. Specific scenarios are created that enable the use cases to be simulated realistically. Among other things, this includes the integration of prosumers with varying degrees of flexibility.

The focus is on validating the interactions of all components. This includes test runs, simulations and practical applications to ensure that the developed systems work together smoothly and achieve the set goals. The laboratory development is therefore a key milestone in the research project, as it enables the theoretical concepts and models to be put into practice and their functionality to be tested in a controlled environment. This forms the basis for further findings and optimizations in the course of the project.

PROJECT TITLE

KEMAL

DURATION

2021–2024

CONTACT PERSON

Eike Niehs
e.niehs@tu-braunschweig.de
+49 531 391 7787

Julien Essers
j.essers@tu-braunschweig.de
+49 531 391 9716

PROJECT PARTNERS

EMH metering GmbH & Co. KG, Hochschule Biberach

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action

COORDINATED BY

EMH metering GmbH & Co. KG
(Dr. Rainer Frank)

Energy-4-Agri

Integrated concept and modelling of agricultural systems with regenerative energy supply

Both energy generation and the supply of energy customers are facing major challenges due to the implementation of climate policy goals. Fluctuations in power generation, e.g. from weather-dependent wind or solar energy, as well as in energy demand (electromobilisation in private and freight transport) require new holistic concepts for their calculation. In this context, the use of so-called „smart grids" is being pursued as the basis for efficient and reliable system operation. Due to a future transition to an electrical supply for energy-intensive field cultivation, agriculture is a key factor influencing this system.

The project Energy-4-Agri

The Energy-4-Agri research project „Integrated concept and modelling of agricultural systems with regenerative energy supply" deals with the investigation and modelling ofconcepts for agricultural systems with renewable energy supply for the decarbonisation of agriculture in the context of the energy transition. Together with the Institute for Mobile Machines and Commercial Vehicles (IMN), the Institute for Geoecology (IGÖ), the Department of Work, Organisational and Social Psychology (AOS) at the Institute of Psychology at the Technische Universität Braunschweig and the Institute for Design Research (IDF) at the Braunschweig Hochschule für Bildende Künste, a holistic concept and multi-criteria evaluation of the energy supply for sustainable agricultural systems is being carried out as a contribution to the decarbonisation of agricultural production.

Measurement campaign on reference farms

As part of a measurement campaign, measurements of electricity consumption and generation were carried out on various farms in Lower Saxony. Individual consumption groups (e.g. barn facilities or cold storages) were measured and their electricity consumption validated on the basis of animal numbers and harvest quantities. Together with the energy requirements of the electrical agricultural machinery, this allows overall conclusions to be drawn about electrical energy systems in agriculture.

Potential for rooftop photovoltaic systems

In agriculture, large roof areas of stables, warehouses, machine halls and administrative buildings are particularly suitable for the installation of rooftop photovoltaic systems. In 2021, the installed rooftop PV capacity in agriculture amounted to approx. 11 GWp and thus accounted for 18.8% of the total installed capacity in Germany. The majority of the systems are operated as full feed-in systems; self-consumption has only played a minor role in agriculture to date. A study on the status quo and potential for rooftop photovoltaic systems in agriculture was published in order to determine the further expansion potential for rooftop photovoltaic systems in agriculture and thus make a contribution to the climate-friendly transformation of the German energy system. Using data from the core energy market data register, data from the agricultural structure survey and typical building models, the theoretical potential was analysed for each district in Germany. As a result, a theoretical potential of 91.5 GWp was determined for Germany.

Potential for agrivoltaic systems

Parallel to the development of the methodology for estimating the potential for rooftop photovoltaic systems, a GIS-based method for estimating the potential for agrivoltaic systems was developed and published. By taking into account typical geographical obstacles (e.g. wind turbines or electricity grid pylons), estimates of the technical potential can be made for each field in Lower Saxony. The crop rotation on the field and possible field inclinations are

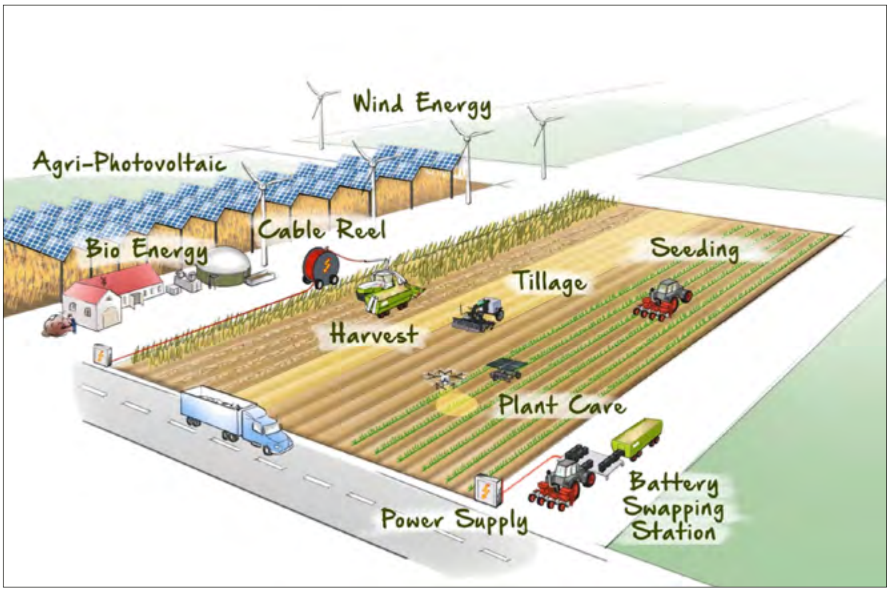

Figure 1: Concept image of electric field cultivation with regenerative energy supply, Illustration: Johanna Frerichs, TU Braunschweig

not taken into account. The agrivoltaic systems are installed on a flower strip placed in the field, which enables simultaneous energy and crop production as well as an increase in biodiversity. As a result, a technical potential of 78 GWp was determined for Lower Saxony.

Energy supply for electrically powered agricultural machinery

From an energy supply perspective, a high load coverage ratio, low mains connection power combined with low load peaks and even power consumption are advantageous. Innovative machine concepts such as the cable-operated gantry system with a working width of 12 m can be disadvantageous from this point of view compared to the conventional tractor with a working width of 6 m, as the simulation has shown higher load peaks and a lower self-supply with an agrivoltaic system. Options for improving the self-sufficiency of the gantry system include the use of a battery storage system or shifting the working time in the field towards midday.

Other energy supply options exist in the alternating concept of battery storage systems. Here, smaller battery storage units are replaced periodically, thus enabling longer operating times for battery-powered agricultural machinery in the field. Compared to a cable-connected energy supply, the energy demand is better distributed throughout the day with the alternating concept due to the coordinated recharging of the batteries that are not required, which means that a higher load coverage can be achieved with renewable energies. However, the investigations show that battery-powered agricultural machinery, both with permanently installed and exchangeable battery storage systems, is not suitable for all field work. Hydrogen-powered agricultural machinery, for example, could be an alternative, particularly for energy-intensive processes such as tillage or harvesting

PROJECT TITLE

ENERGY 4 AGRI

Energy-4-Agri

DURATION

2019–2023

CONTACT PERSON

Felix Klabunde
f.klabunde@tu-braunschweig.de
+49 531 391 9720

PROJECT PARTNERS

Hochschule für Bildende Künste Braunschweig, Institut für mobile Maschinen und Nutzfahrzeuge, Institut für Psychologie, Institut für Geoökologie, Institut für Designforschung

WEBSITE

www.tu-braunschweig.de/energy-4-agri

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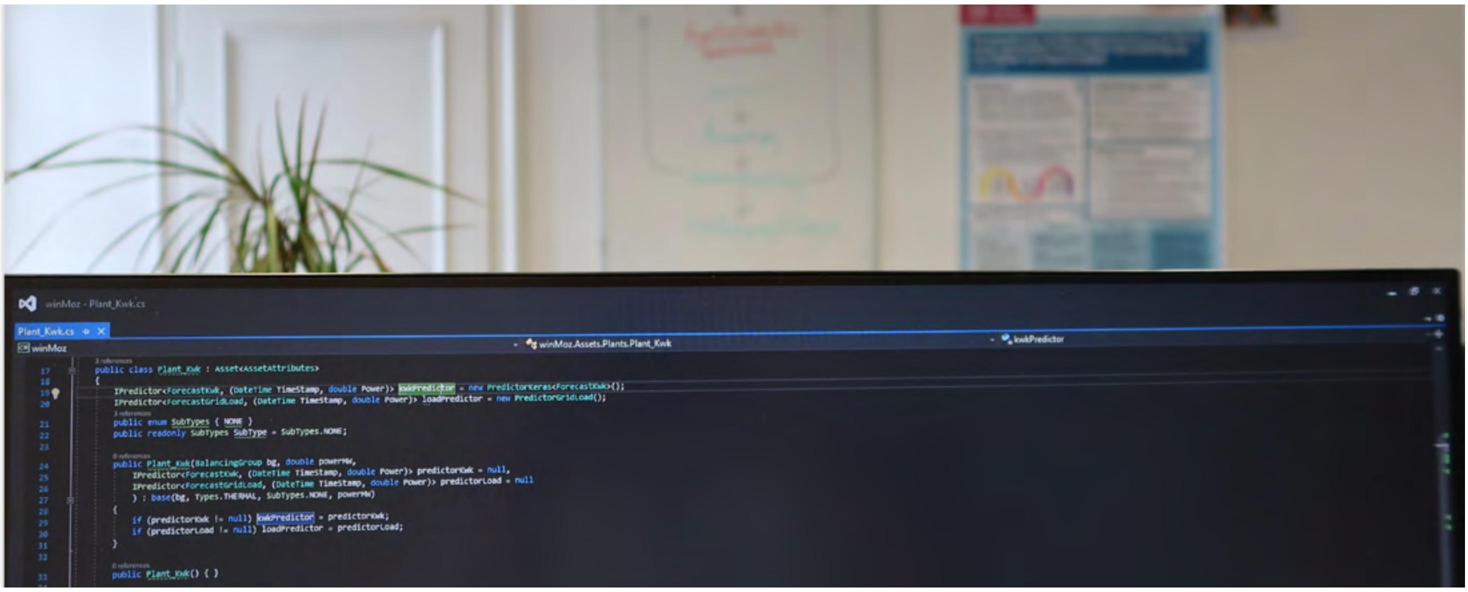
Federal Ministry for Economic Affairs and Climate Action



MozuBi

Modelling of future balancing group management considering renewable energies

The energy transition and the associated constant increase in (almost) marginal-cost-free, supply-dependent renewable energies and the ongoing intelligent connection of controllable consumers is having an impact on the entire electricity supply chain. The tightening of climate targets and recent political decisions against Russia due to the act of war against Ukraine are accelerating this change and increasing the pressure on all stakeholders to adapt.

Balancing group-based energy economy

The most important tasks for a secure electricity supply are covered by grid operators, generators and suppliers. Due to the physical properties of electricity, the proper functioning of the energy system requires a constant balance between generation and consumption. To reduce deviations in the energy system, the active players manage balancing groups. Within the MozuBi research project, this balancing group system was scientifically modelled and investigated as a key instrument in the energy system.

However, the objectives of the players are fundamentally different. While grid operators, as regulated operators holding a natural monopoly on the electricity grid, are responsible for ensuring secure operation as efficiently as possible, producers and suppliers generally aim to pursue commercial interests. These different objectives can lead to conflicts, for example if the costs for the actual balancing of differences between generation and consumption, which is conducted by the grid operator, are lower than a market-based balancing in the management of the balancing groups by suppliers and generators.

Agent-based modelling of the energy system

In order to be able to comprehensively analyse and evaluate these complex issues, detailed market, stakeholder and asset models are required that can map the balancing group system in the electricity supply in Germany.

The market models include futures contracts, day-ahead trading, intraday trading and the control reserve market with control power and control energy. In addition, the

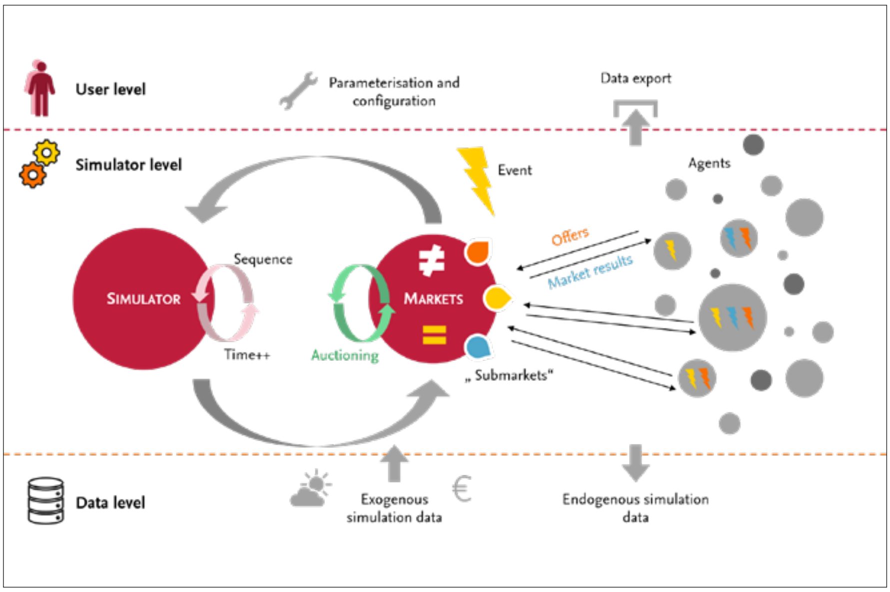


Figure 1: Basic structure of the simulation model

control reserve demand and the balancing energy price are calculated endogenously in the model using the control area balances. The model therefore has all the necessary functions to calculate the costs of balancing group management in addition to market revenues. The stakeholder models (agents) can be used to map the basic structure of the balancing group management chain from the transmission system operator to the distribution system operator to the balancing group manager. The main assets of the energy system were also modelled. Time-series-based bottom-up models were developed, which enable the determination of quarter-hourly schedules for the marketing of generation and consumption services using various forecasting and optimisation algorithms. In order to enable the consideration of electrically and thermally operated power plants, both the demand for electricity and heat are considered in the simulation model. Both plant-specific and aggregated analyses are possible for each asset. This means that the calculation speed of the simulation remains high, particularly for portfolios with a high penetration of renewable energy plants.

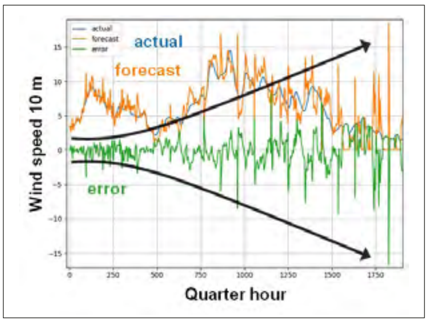


Figure 2: Simulated wind forecast, Henrik Herr

To ensure that trading works across three market levels, forecast uncertainties are simulated, e.g. for wind and PV power plants. These are simulated in such a way that they decrease as the time between the tendering and determination periods decreases in order to take account of the increasing quality. All forecast errors after intraday trading form the basis for the control area balance. Various options such as bids on the control reserve market and day-ahead trading are taken into account by opportunities in the power plants‘ trading strategies. There are strategies adapted to the different circumstances of the power plants and loads, ranging from arbitrage strategies for storage facilities to make-or-buy strategies for thermal power plants.

Publication of project results

The development of the model followed an open source approach using freely available software and software libraries. In addition, freely available data sources were used, which ensures that the model can be used in a connected manner. The division into modules, which are combined in a class library (dll), also makes it possible to use sub-functions, such as those of the wind power plant or the price forecasting methods, independently of the complete model simulation for other projects or issues such as a wind yield forecast or a price forecast for day-ahead trading.

To facilitate access to the individual models for new users, a user interface has been programmed in addition to the simulator level, which enables the creation of scenarios over flexible observation periods and the user-specific parameterisation of individual submarkets of the energy industry and asset classes. The user can also use the interface to configure the data records to be saved and their format in order to use the simulation results for further analyses. There is also a decapsulated data level that separates exogenous simulation data, such as weather data as input data for the price forecasts, from the simulator level and thus enables the connection of alternative data sources.

The MozuBi model library has been freely available via GitLab since last year and we invite all interested parties to take a look at the project results for themselves.

PROJECT TITLE

MozuBi

DURATION

2018–2021

CONTACT PERSON

Mattias Hadlak
mattias.hadlak@tu-braunschweig.de
+49 531 391 9713

PROJECT PARTNERS

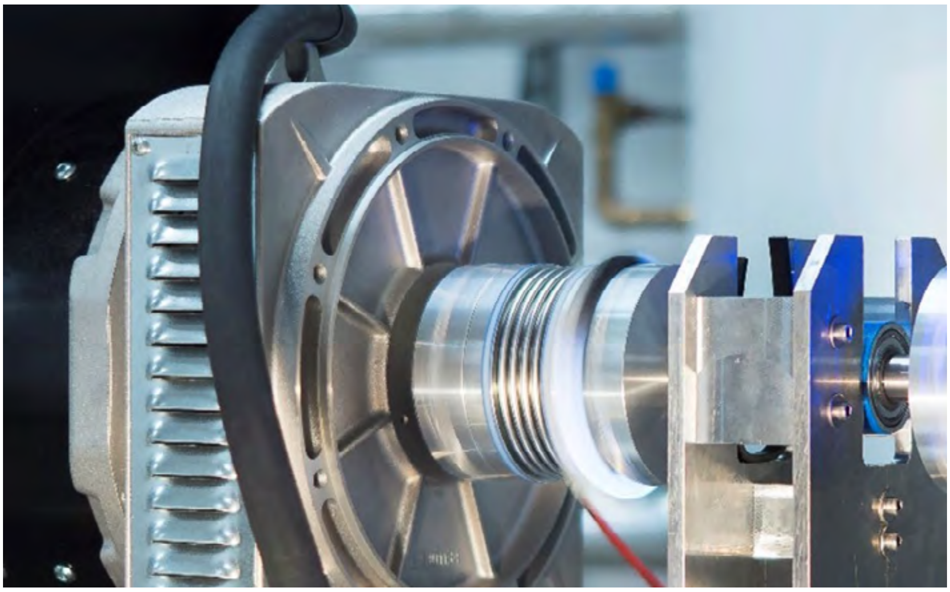
IZES gGmbH – Institut für ZukunftsEnergieSysteme

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action

COORDINATED BY

TU Braunschweig – elenia



Market-based Procurement of Instantaneous reserve

Participation in a study discussing the need for and development of market-based instantaneous reserve procurement.

The transformation of our power system with the aim of achieving climate neutrality is characterised by many technical challenges. With the nuclear and coal power phase-out, large generation capacities that have contributed to grid stability by providing important ancillary services will be disconnected from the grid. The demand for these ancillary services will therefore have to be covered by other facilities and systems in the future, which may require market-based procurement. In the case of the ancillary services, instantaneous reserve ("inertia of local grid stability"), the efficiency review of market-based procurement from 2020 by the Federal Network Agency has shown that there is no additional demand in the short-term future. On the other hand, the analyses conducted as part of the current grid development plan clearly show that significantly higher power imbalances occur in the event of a grid separation (system split) and that there is less instantaneous reserve provision in Germany due to the shutdown of conventional power plants. The demand for instantaneous reserve can therefore be very high and also vary greatly from region to region. For this reason, Amprion, as one of the four transmission system operators in Germany, commissioned a study to examine the requirements and develop a concept for market-based procurement for quick implementation. elenia was responsible for supporting the study and contributed to the fruitful discussion on the topic with its technical expertise.

The primary report shows an increase in demand and came to the conclusion that it makes sense to introduce market-based procurement for instantaneous reserves, specifically to accelerate technology development. The secondary opinion from elenia agrees with this statement, but finds, however, that due to the maturity and characteristics of the various technologies, differentiation should be made in market-based procurement in order to achieve a timely introduction in particular. Based on experience from other countries, a tender for the secured provision of instantaneous reserve (24h / 365d / 10a) by the transmission system operators is recommended. This appears to be possible from as early as 2024 using large-scale batteries in the extra-high and high-voltage grid, which, in addition to energy trading or primary control power, can add the instantaneous reserve as a further grid-supporting application ("service stacking") in accordance with Figure 1. For other technologies, technology development - increasing the "technology readiness level" and "system readiness level" - must first take place, for which a bonus system is also a reasonable option according to the primary report.

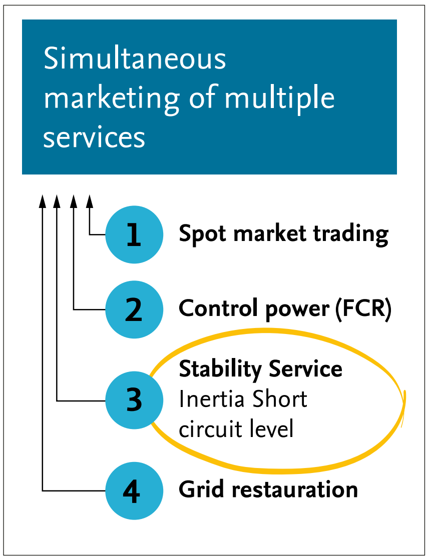


Figure 1: Example of „Service Stacking" (multiple applications) with battery energy storage systems, for which the provision of instantaneous reserve can be added to the already present applications

PROJECT TITLE

Secondary report: Development of a market-based procurement concept for instantaneous reserve

DURATION

2022–2023

CONTACT PERSON

Carsten Wegkamp
c.wegkamp@tu-braunschweig.de
+49 531 391 7756

PROJECT PARTNERS

Amprion GmbH
Primary report: Consentec GmbH, Technische Universität Stuttgart (IFK)

Battery storage system compatibility test

Technical evaluation of the operation of battery storage systems with inverters from a leading German manufacturer.

The expansion of photovoltaic and wind power plants is leading to an increasing need to store electrical energy for integration into a future sustainable energy system. Battery storage systems are an important solution. These systems consist of an electrochemical storage unit and an inverter, which forms the interface between the battery and the power grid.

In households, commercial enterprises and industry, battery storage systems are often used in combination with photovoltaic systems to maximise self-consumption of self-generated sustainable electrical energy. These systems often offer an emergency power function that ensures a reliable power supply, especially in regions with unstable power grids. In addition, battery storage systems can be used in remote areas without a grid connection to set up local stand-alone grids and utilise the solar energy generated during the day at night. These different operating scenarios place high demands on a reliable battery storage system, especially on the battery itself. In off-grid operation, i.e. when operating in a stand-alone grid or when decoupled from the grid, smooth co-operation between the inverter and the battery is of crucial importance, as a system failure in this case is equivalent to a complete grid failure.

As part of a service project, lithium-ion batteries from various manufacturers are being tested for compatibility with the inverters of a leading German manufacturer at the elenia Institute for High Voltage Technology and Energy Systems in order to ensure safe and stable operation of the battery and inverter. The compatibility tests include a commissioning test, safety checks and operation in on-grid and off-grid mode. The commissioning test ensures that the batteries can be installed correctly using the operating instructions and the installation material supplied in accordance with the current state of the art. The safety test shows that the entire system communicates safely and is switched off even in the event of incorrect installation or defects. Both the battery and the inverter must be intrinsically safe. During the operational test, different load and generation scenarios in on-grid and off-grid operation of battery storage systems are run through to ensure that the battery can easily cope with these requirements without any impairments or shutdowns occurring. If the test result is positive, the tested batteries are declared compatible by the inverter manufacturer and placed on the whitelist.

Compatibility tests are essential to ensure the safe and reliable functioning of battery storage systems in combination with battery inverters.

PROJECT TITLE

Compatibility test for the technical evaluation of the operation of battery storage systems with inverters

DURATION

2023–ongoing

CONTACT PERSON

Frank Soyck
✉ f.soyck@tu-braunschweig.de

Stefan Klöpping
✉ s.kloepping@tu-braunschweig.de

Kevin Preißner
✉ k.preissner@tu-braunschweig.de

PHOTO: INTIS GMBH

Research Project LISA4CL

Development of a Standard-Compatible, High Power, Inductive Charging System and its Intelligent Grid Integration

Short charging times and the associated shortest possible downtimes are particularly important for frequently used vehicles or even fleets. Inductive charging systems have been under development for several years, promising a massive increase in customer acceptance of electric and hybrid vehicles. The first standards and norms have emerged, which form the basis for today's systems with charging capacities of up to 11 kW. However, charging times with these charging capacities are very long, as this power class was primarily developed for home use with a view to overnight charging. High power systems are needed especially for public areas and fleet operation in non-public areas. Accordingly, the further development of standards and norms for fast-charging-capable inductive charging has begun.

In addition, intelligent grid integration of charging systems is important because the penetration of electric vehicles and consequently the load on the grid is increasing. The focus is on ensuring safe grid operation. Grid-oriented charging approaches play an important role in terms of relieving grid congestion and minimizing grid expansion. In addition, from an economic and ecological point of view, generation-oriented charging approaches to increase the proportion of renewable energies used are of particular importance.

Project Contents

Figure 1 shows the content of the LISA4CL research project. The project is divided into three parts. In the first part, a standard-compliant, fast-charging-capable,

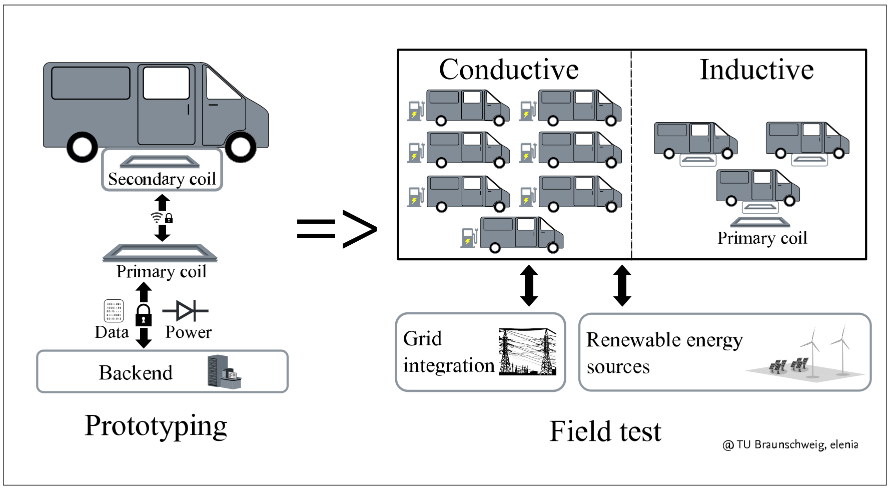


Figure 1: Overview of the contents of the LISA4CL research project

inductive charging system for use in light commercial vehicles is being developed and constructed, which will provide higher outputs of up to 22 kW compared to current standards. The charging system consists of the stationary charging station (primary unit) and the secondary unit, which will be integrated into test vehicles. The development is based on the results of the previous project InduktivLaden or emilia, in which an inductive charging system for an e-Golf was implemented. The second part of the project comprises the grid and system integration of the charging infrastructure. Here, grid-oriented and generation-oriented concepts for charging are developed, which are tested with simulations and in the laboratory. In the last part, the inductive charging system and the charging concepts for grid and system integration are used in field tests at a city logistics company in real operation. This part is divided into a field test with conductive charging infrastructure and a field test with the inductive charging system in order to compare the charging technologies with regard to demand-oriented charging infrastructure.

Due to the cooperation of the project partners in various standardization committees, the project results are directly incorporated into future standards and guidelines. The involvement of industry partner INTIS ensures a high level of practical relevance. On the scientific side, the research results are also incorporated into doctoral projects at the institutes. They will also be incorporated into relevant courses, such as lectures, laboratory practicals and student theses, and presented and discussed at national and international conferences and meetings. The project and its methodology were presented at the NEIS 2021 - Conference on Sustainable Energy Supply and Energy Storage Systems. Results of the grid- oriented and generation-oriented charging concepts were published at the 6th E-Mobility Power System Integration Symposium and ETG Congress 2023. The inductive charging system concept was presented at the HEV 2022 - Hybrid and Electric Vehicles Conference. In addition, a press release on the successfully launched conductive field test and an article on inductive charging were published in the Electrosuisse trade journal.

Current Status

The inductive charging system was developed and set up. This includes both the components of the power path and the communication and control infrastructure. Figure 02 shows the schematic structure of the inductive charging system. The grid interface of the system is realized with an Active Front End, which offers the possibility to provide reactive power for voltage maintenance. Q(U) control is implemented with the Active Front End. The functionality of the overall system was tested extensively on the INTIS GmbH test bench. This included carrying out charging tests and fault tests. In the next step, the inductive charging system will be installed at Fairsenden GmbH in Berlin in order to test it in real operation. Various investigations were carried out with regard to grid and system integration. A potential analysis for local renewable energies was carried out at the Fairsenden GmbH charging site. In addition, characteristic curve-based controls to reduce voltage unbalance were investigated in simulations and laboratory tests. Furthermore, an energy management concept was developed, which is currently being tested in the elenia-energy-labs.

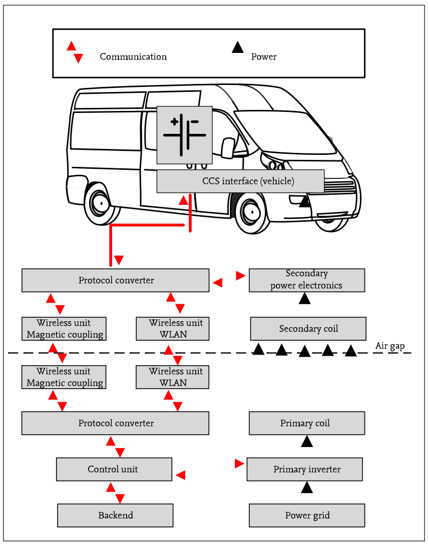


Figure 2: Concept of the power and communication path of the inductive charging system

PROJECT TITLE

LISA4CL

LISA4CL
Laden – induktiv, schnell, autonom für City Logistik

DURATION

2020 – 2024

CONTACT PERSON

Gian-Luca Di Modica, M.Sc.
g.di-modica@tu-braunschweig.de
+49 531 391 7704

Lukas Ebbert, M.Sc.
l.ebbert@tu-braunschweig.de
+49 531 391 9727

Robin Herman, M.Sc.
r.herman@tu-braunschweig.de
+49 531 391 7702

PROJECT PARTNERS

TU Braunschweig IMAB – Institute for Electrical Machines, Traction and Drives

INTIS – Integrated Infrastructure Solutions

ASSOCIATED PARTNERS

Fairsenden GmbH, Berliner Agentur für Elektromobilität eMO, Volkswagen Nutzfahrzeuge

FUNDED BY

Federal Ministry for Digital and Transport

COORDINATED BY

TU Braunschweig – elenia

Research Project U-Quality

Power quality problems and their control in modern low-voltage grids

The research project U-Quality investigated the effects of future low-voltage grid use cases - photovoltaics, photovoltaic battery storage systems, electromobility and power-to-heat applications and their mode of operation - on voltage quality. Voltage quality was examined in terms of flicker, harmonics, unbalance and rapid voltage changes.

Field measurements

The project began with a comprehensive meta-study that analyzed the current state of research with regard to future penetration scenarios. A wide range of results were then obtained in field and laboratory measurements. The components measured in the laboratory (household appliances, heat pumps, PV systems, battery storage systems, EV charging infrastructure) always showed stable behavior during normative operation or operation with only slightly disturbed supply voltage and, for their part, only generated standard-compliant voltage quality disturbance inputs. However, non-standard operating modes of the tested components sometimes led to limit violations with regard to power quality aspects. The field measurements also provided new insights into various power quality disturbances in different grid types. In more

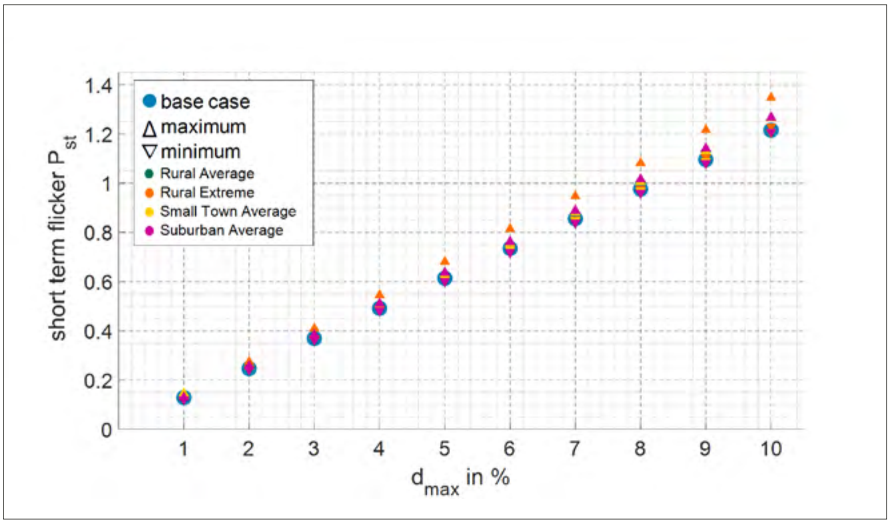


Figure 1: Simulation results of the flicker tests: Influence of positive dmax values on the short-term flicker value with active Q(V) control

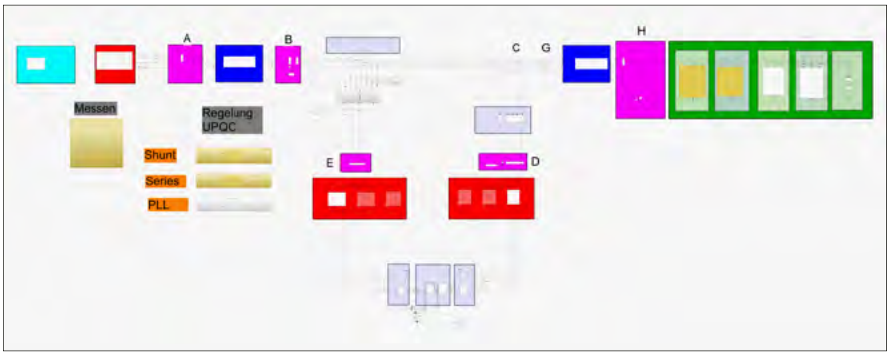


Figure 2: MATLAB model of an UPQC controller,
Screenshot: github.com/U-Quality-Regler/UPQC-Model

modern grids, only very minor and rare power quality disturbances were detected.

Simulations

As the project progressed, realistic penetration levels and models as well as partial simulations (load profile models, sample grids, models of future operation) were created and evaluated for further grid simulations. Based on this, extensive grid simulations were carried out for the various power quality characteristics. The grid simulations showed that the future grid usage cases will lead to a significantly higher load on the individual voltage quality characteristics in the low voltage. Despite this increase, however, the power quality limits were largely adhered to in the simulations (1 or 5% calculation quantile). Based on the simulations, the grid usage cases investigated are therefore not expected to result in widespread voltage quality violations in the low voltage during regular operation and with sufficiently expanded grids. In certain grid usage cases, however, limit values for individual voltage quality characteristics may be exceeded. The spectrum of grid simulations was broadly diversified so that, among other things, statements on the summation of power quality disturbances, for example flicker caused by electric vehicles, were also explained. The grid simulations were also used to analyze the optimal location for the regulation of various power quality characteristics.

Hardware implementation

In further work packages, a power quality controller prototype and a corresponding simulation model were developed. A large number of concepts were developed for this and a comprehensive simulation platform was set up to determine suitable synchronization, supply and control methods. The control methods developed in the process lead to the reducing of all voltage quality characteristics when applied. The simulation platform was published for scientific purposes and the power quality controller prototype was tested in laboratory tests. Further testing and further development of the prototype is currently in the broader implementation phase.

The simulation model can be found here:
https://github.com/U-Quality-Regler/UPQC-Model

The knowledge gained across all work packages in grid-related, component-related and normative sub-areas was finally summarized in recommendations for further use. The recommendations for action were shared with network operators and industrial companies during the final workshop and presented to a wide range of interested parties in publications.

We would like to thank our sponsored and associated partners for the very good exchange and excellent cooperation!

PROJECT TITLE

U-Quality

DURATION

2019–2023

CONTACT PERSON

Cornelius Biedermann, M.Sc.
cornelius.biedermann@tu-braunschweig.de
+49 531 391 7788

Gian-Luca Di Modica, M.Sc.
g.di-modica@tu-braunschweig.de
+49 531 391 7704

Till Garn, M.Sc.
t.garn@tu-braunschweig.de
+49 531 391 7714

GEFÖRDERTE PROJECT PARTNERS

RWTH Aachen University -IAEW

TU München

FGH e. V.

Ruhstrat Power Technology GmbH

ASSOCIATED PARTNERS

Netze BW, Bayernwerk, BS|Netz, avacon, Phoenix Contact, Stromnetze Hamburg, SMA

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action

COORDINATED BY

TU Braunschweig – elenia

Reactive Power Management

Application of innovative concepts and reactive power sources at the interface of distribution and transmission networks

With the energy transition, the electrical energy system in Germany is undergoing a profound transformation process. This has a fundamental influence on the existing concepts for maintaining grid and system security. This also affects voltage stability and the closely related reactive power management (RPM) in transmission systems (TS) and distribution systems (DS).

The reactive power requirement is continuously increasing due to longer transmission paths and higher grid utilization and is also becoming more dynamic overall. This is aggravated by the fact that the transmission of reactive power over long distances is not economically feasible, meaning that demand must be balanced locally. A large proportion of the required reactive power is currently provided at the TS level by synchronous generators, which, in the course of the Energiewende are gradually being switched off.

Due to the increasing expansion of renewable energy systems (RES), new reactive power sources are installed in the grids - especially at the DS level. This potential is predominantly utilized in the defined working areas of the technical connection rules, which is why the technical potential is not fully utilized. An extension of the working area and a cross-interface utilization of the potential is taking place in isolated cases, but is not common practice among transmission system operator (TSO) and distribution system operator (DSO).

Completed research work at elenia

The resulting research questions have been continuously addressed at elenia since 2015 in various research projects and studies. In the PV-Wind-Symbiosis research project (2015 - 2019), key questions on the efficiency of reactive power provision from RES were answered. In addition, an optimization-driven RPM approach was developed and the technical and economic effects of the approach were investigated using a real high-voltage grid. In the follow-up project Q-Integral (2019 - 2023), the focus was expanded and placed on the interface between the DSO and TSO. In cooperation with the transmission system operator 50Hertz and in part with the subordinate DSOs E.DIS, TEN and WEMAG, a comprehensive grid model was created across voltage levels and grid operators, see Figure 1, which was used to investigate integral approaches for the RPM in grid operation and grid planning.

The grid model was used to validate and analyse an optimization-driven and cross-grid operator RPM approach developed by elenia for the DSO and TSO interface. In addition, the flexibility potential of the subordinate DSOs and the technical and economic effects of the RPM for different demand cases and scenarios were examined.

It was shown that the grid has high flexibility potential, but that this is limited by the applicable guidelines and is therefore rarely used at present. By expanding the use of the technical potential, an almost 24/7 availability of reactive power sources can be achieved. It has also been shown

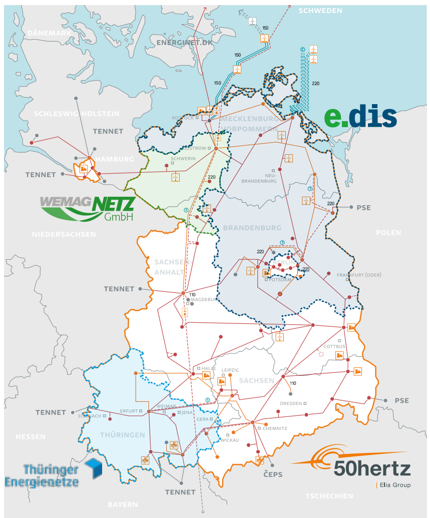


Figure 1: Representation of the grid region (as of 2017) of the cross-voltage level grid model based on 50Hertz Transmission GmbH 2017

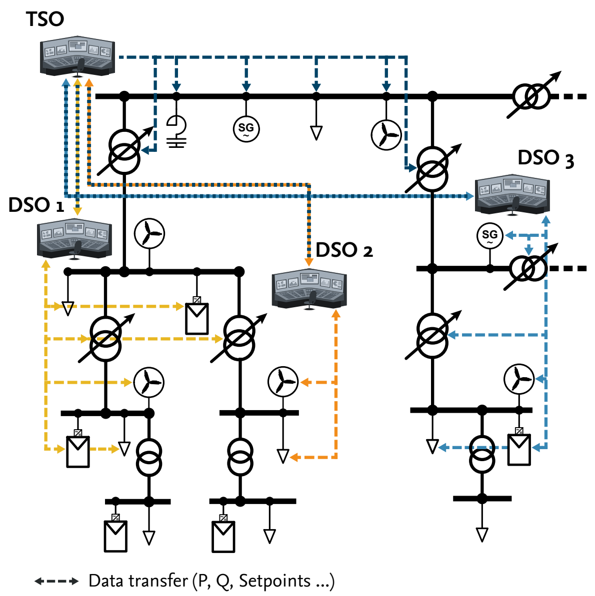


Figure 2: Integral reactive power management

that the flexible and efficient use of reactive power through the integral RPM can be equally beneficial for grid operators and system operators. The system operator has more options for self-optimization and can save losses and costs through the optimized use of reactive power. In addition to quickly controllable and reliable reactive power sources, the grid operator also has the opportunity to optimize the grid and save on investments in fully integrated grid components.

To implement the active and integral RPM, a short-term reactive power forecast for operational grid planning was also developed. In addition to mapping future grid states, the forecast enables a quantitative statement to be made on the reactive power requirements of individual substations, grids and TSO interfaces. The reactive power is forecast using a deep-learning approach for 12 to 24 hours of the following day. The approach has shown that more complex reactive power characteristics and patterns of individual grid areas can be learned. However, it also shows that granular, consistent and adjusted historical data sets are required for this. Based on the forecast results and with the help of optimization, reactive power values can then be created in the form of schedules for an active setpoint specification. With the help of these, an optimized reactive power provision

Follow-up project Q-REAL

The successful collaboration between the research institutions and the participating companies is being continued in the Q-REAL project. At elenia, the focus is on the development of new and adaptive reactive power control methods for RES and the expansion of the data-driven reactive power forecasting method. In addition, work is being carried out on a method that can be used to estimate the reactive power-specific losses of any given RES more accurately, thereby improving the quality of economic analyses. The in-depth investigation of the designed reactive power methods and the analysis of the losses will also be tested and validated in the context of a real pilot park. The project is expected to run until 2025.

PROJECT TITLE

Q-REAL:
Reactive Power Management in Real Applications: Network planning, network operation and reactive power sources for transmission and distribution networks

DURATION

2023 – 2025

CONTACT PERSON

Merten Schuster, M.Sc.
m.schuster@tu-braunschweig.de
+49 531 391 9719

Hartmudt Köppe, M.Sc.
h.koeppe@tu-braunschweig.de
+49 531 391 9717

PROJECT PARTNERS

Ostbayerische Technische Hochschule Regensburg

Fraunhofer-Institut für Solare Energiesysteme ISE

KBR Kompensationsanlagenbau GmbH

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action

FKZ Q-REAL: 03EI4063B

COORDINATED BY

Ostbayerische Technische Hochschule Regensburg

Remuneration of reactive power in the transmission grid

Development of a pricing model for the extended provision of reactive power from STATCOM-capable PV systems

As part of the short study "Pricing Model for the Extended Provision of Reactive Power by Power Converters", the provision of reactive of reactive power (Q) outside the technical connection rules (TCR) of a real PV park in the transmission grid was investigated. The aim was to calculate relevant losses and costs associated with the extended Q provision and the derivation of a corresponding remuneration. In cooperation with Fraunhofer ISE, elenia has developed the design of a simulation and pricing model. The focus of Fraunhofer ISE's was on the hardware analysis of the extended Q provision of the inverters.

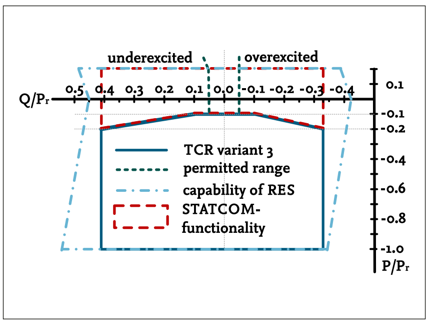


Figure 1 Representation of the reactive power ranges within and outside the TAR in the transmission grid

Key findings of the study

The results of the study show that modern PV parks are able to feed in Q outside the existing TCR without additional investment. In the grid under consideration, the systems thus represent a concrete added value for voltage stability. In the study, a methodology was developed with which the losses resulting from the extended Q provision and the wear and tear can be evaluated in monetary terms. The study thus provides a basic framework for understanding the resulting cost factors and their effects. In future market-based tenders for Q, this framework can be used as an assessment approach to evaluate costs and prices for Q deployment.

Cost components

The costs can basically be divided into three components: Investment in Q capacity, costs of Q provision and costs of Q deployment outside the TCR. For the PV park, only the costs of Q deployment outside the TCR were considered. The focus here was on the additional active energy losses in Q-carrying equipment and inverters. The costs of additional wear and the associated reduction in the service life of the inverters were also included in the analysis. In addition, Fraunhofer ISE, in cooperation with the inverter manufacturer Delta Electronics, determined a wear factor for the inverter installed in the park.

An average of € 0.34/Mvarh must be spent on an inverter with an acquisition cost of € 7,000 to compensate for the additional wear and tear in the extended Q provision. When determining the monetary compensation for the additional active energy losses, an average spot market price of €33.51/MWh was used, assuming no procurement strategy. This price is based on historical price trends on the planned days of operation (weekends and public holidays).

Simulation model and operating scenarios

For the simulation, three operating scenarios were derived from historical grid operating cases and then implemented in a model of the PV park and then simulated. The focus was on the "QbyNight" use case, in which Q is only called up between 22:00 and 06:00. The scenarios - basic, dynamic and extreme - vary in duration between 1.5 and 3 days. The basic scenario considers regular voltage band deviations over three days, typically for weekends and public holidays. The dynamic scenario includes rapid voltage dips over 1.5 days, often caused by parking activities. The extreme scenario refers to a three-day shutdown of a large Q-source, as can occur during maintenance work in power plants, for example.

Simulation results

Based on the simulation model, the relevant results of the reactive energy provided, the associated active energy losses and the loss factor - as a quotient of the two variables (MWh/Mvarh) - are shown in Figure 2.

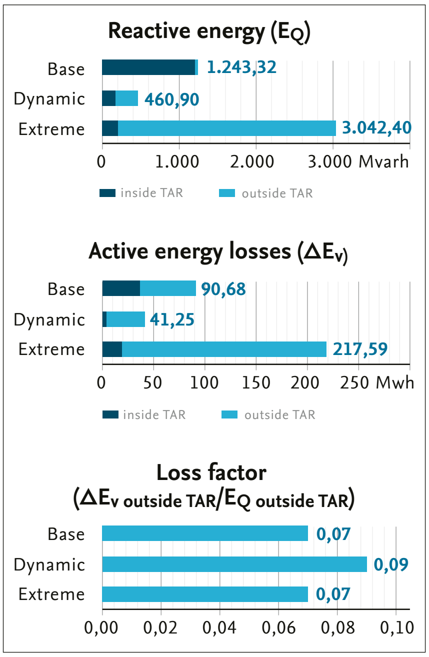


Figure 2: Simulation results according to operating scenarios

The data shows that the active energy losses for the dynamic scenario in relation to the reactive energy fed in are approx. 25% higher than for the classic or extreme scenario. This is due to the fact that operating ranges with higher losses are called up more frequently in the dynamic operating case. Accordingly, the specific costs of the simulated Q deployment vary depending on the operating scenario. While the costs in the basic and extreme scenarios are between €0.93 and €0.95/Mvarh, they rise to €1.07/Mvarh in the dynamic scenario due to the more loss-intensive operating points.

In the study, a flat-rate incentive of €0.05/Mvarh was added to the Q input costs. This makes it possible to compensate for unforeseen costs and creates an additional incentive. The operating scenarios thus result in a cost-weighted average price of €1.04/Mvarh for the extended Q provision. Table 1 below shows the annual income and expenditure of the system and grid operator at the aforementioned average price for 113 call-off days in the base scenario and for five days in each of the other scenarios.

The simulation results show that when pricing Q, both the above-mentioned plant-specific cost factors and external cost factors must be considered. In this case, external cost factors are, for example, price developments of the lost energy to be procured. Depending on the plant operator's procurement strategy, this can have a negative impact on the economic provision of Q.

The study thus provides a basic framework for understanding the existing cost factors and their effects within the extended Q provision of a PV system. It is shown that a compensatory and appropriate remuneration of Q can represent a balanced cost-benefit ratio for system and grid operators. Future studies should therefore focus on real-life testing in order to quantify the actual risks and utilize the existing Q potential of inverter-coupled systems in the extra-high and high-voltage grid.

Operating scenario	Call-off days [#d]	$P_{Q\ year\ net\ price}$ 1,04 [€]*	Wear and tear
Base	113	48.705,12	0,120
Dynamic	5	1.554,60	0,004
Extreme	5	5.291,87	0,013
Total	123	55.551,60	0,137

Table 01: Annual income, costs and wear and tear due to Q provision

* excluding levies and duties

PROJECT TITLE

Pricing model for the extended provision of reactive power by inverters

DURATION

November 2022–February 2023

CONTACT PERSON

Merten Schuster
m.schuster@tu-braunschweig.de
+49 531 391 9719

Hartmudt Köppe
h.koeppe@tu-braunschweig.de
+49 531 391 9717

PROJECT PARTNERS

Fraunhofer ISE

50Hertz Transmission GmbH

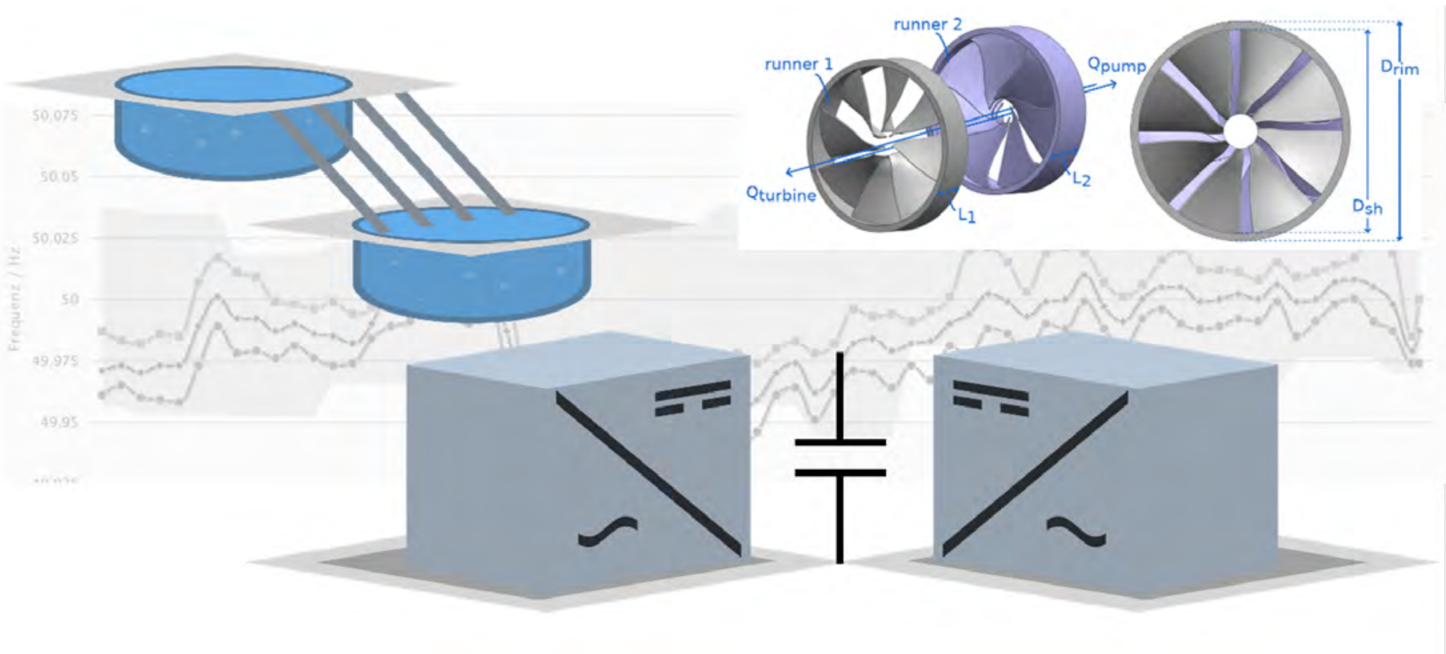
Delta Electronics

IM AUFTRAG VON

50Hertz Transmission GmbH

COORDINATED BY

Fraunhofer ISE



ALPHEUS – Innovative Pumped Hydro Storage System

Augmenting Grid Stability Through Low Head Pumped Hydro Energy Utilization and Storage

The EU-funded ALPHEUS research project is investigating and testing a new and innovative pumped storage power plant concept in an interdisciplinary and international consortium. The consortium consists of 11 partners from different countries in the European Union. The consortium includes partners from industrial turbine design as well as numerous institutes from university research facilities specialising in fluid dynamics, civil engineering and mechanical engineering as well as electrical engineering.

The ALPHEUS concept design differs from conventional pumped storage technologies, as these usually have average heads of over 100 metres to address the operating ranges of typical turbine technologies. This restricts locations for the installation of pumped storage in countries with low terrain topographies such as the Netherlands and Belgium. This is where the ALPHEUS research project comes in and evaluates the technical feasibility of pumped storage with low heads, which require a rethink of conventional technologies. Conventional pumped storage power plants are usually rigidly connected to the grid via synchronous generators operated with their synchronous frequency. Partial load ranges

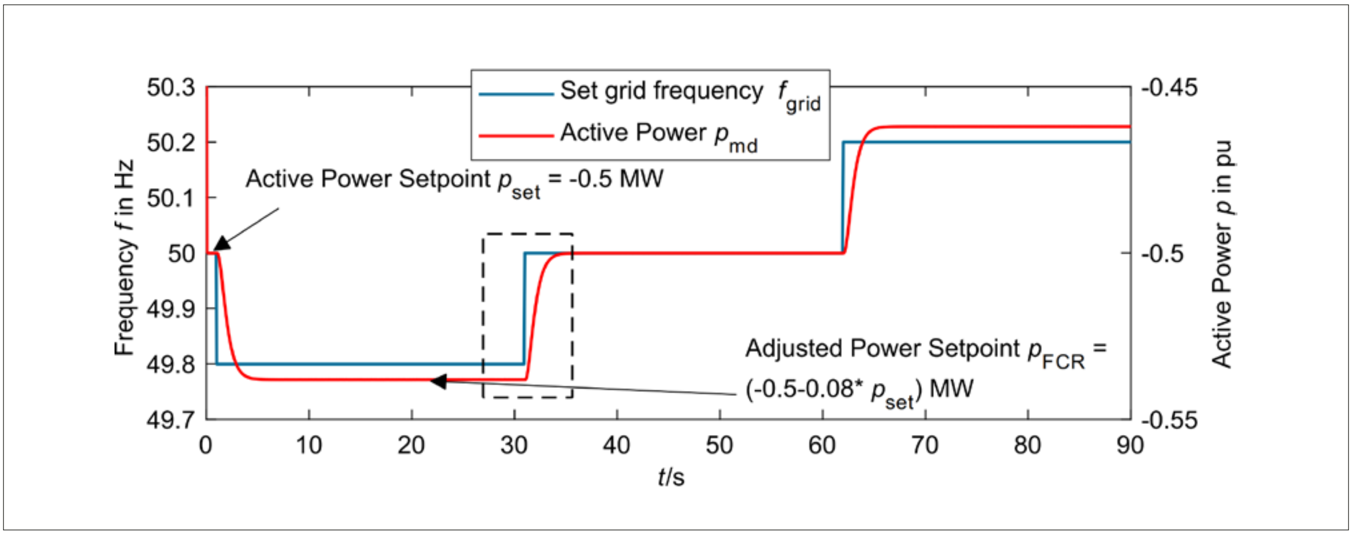


Figure 1: Frequency based active power reaction of the simulated ALPHEUS pumped hydro storage system in compliance with the requirements for provision of balancing energy like Frequency Containment Reserve Figure: Frederik Tiedt / elenia

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Cover picture: Axial Flux PMSM Power Take-Off for a Rim-Driven Contra-Rotating Pump-Turbine

can either not be approached at all or only with low efficiency, so that variable pump or turbine operation mode is not possible.

The ALPHEUS system concept is therefore based on the basic system architecture of a full-scale inverter-coupled machine set. This in turn consists of two turbines rotating in opposite directions, which are connected to the full inverter via highly efficient axial flux machines. The project is identifying the extent to which this innovative turbine and generator technology can be used to operate the ALPHEUS power plant efficiently with conceptual heads of between 10–15 metres.

Modelling of the electrical behaviour

In this context, the elenia Institute is addressing the challenge of integrating the ALPHEUS pumped storage plant into the electrical grid. The most important issues arising for elenia are investigations into the electrical characteristics of the pumped storage power plant with regard to grid-compliant and grid-stabilising behaviour. As the system architecture is based on a full-scale inverter coupling of the machine set, there are also numerous fields of application for the provision of ancillary services in the short and long-term range. To demonstrate the provision of these system services, a suitable converter control concept was designed for the ALPHEUS storage power plant in this context, which fulfils all requirements for operation on the European interconnected grid. For validation purposes, a simulation model of the grid-side inverter and its control principle was designed with a particular focus on stable grid-supporting power control.

Economic Potentials of Low Head Pumped Hydro Storage Systems

In the currently ongoing final project phase of the research project, elenia is evaluating the economic potential of the innovative pumped storage power plant. Typically, potential plant operators of storage plants have several operating strategies for efficient commercialisation. For example, conventional pumped storage power plants are suitable for skimming off arbitrage earnings due to their storage size. However, there is also potential to participate in the various balancing power markets: Primary, secondary and tertiary control. Participation in the balancing markets can also be considered for the ALPHEUS storage power plant using the technical proof of primary control power already validated in the project. The primary objective of the elenia work package is the identification of revenue potentials in the sense of analysing possible contribution margins in the ongoing operation of the pumped storage power plant.

PROJECT TITLE

ALPHEUS

ALPHEUS:
Augmenting Grid Stability Through Low Head Pumped Hydro Energy Utilization and Storage

DURATION

February 2020 – March 2024

CONTACT PERSON

Frederik Tiedt
f.tiedt@tu-braunschweig.de
+49 531 391-7787

PROJECT PARTNERS

Advanced Design Technology Ltd., TU Braunschweig, Technische Hochschule Chalmers, Technische Universität Delft, IHE Delft Institute for Water Education, Universität Gent, Technisch-Naturwissenschaftliche Universität Norwegens, Universität Pau, Universität Stuttgart, Universität Tuscia, Universität Uppsala

FUNDED BY

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H_2 Terminal Braunschweig

Establishment of a hydrogen competency centre on the campus of Technischen Universität Braunschweig

The energy transition and the associated integration of renewable energies into the electricity system entails a comprehensive change in all areas. In addition to the volatile feed-in of renewable energies into the electricity grid, other major challenges lie in storage and in the development and operation of the infrastructure for distributing the energy to the respective consumers. One of the key elements for the success of the electricity, heating and mobility transition is the targeted use of hydrogen at all levels of the energy system. This also requires grid-friendly integration and sector coupling of the hydrogen economy into the European interconnected grid.

Overall structure and objectives of the H2 Terminal Braunschweig

On March 23, 2023, a significant milestone in the energy transition was reached with the start of construction of the Hydrogen Terminal Braunschweig (H_2 Terminal) not far from Braunschweig Airport. The research project is being funded by the Federal Ministry of Education and Research (BMBF) with more than 20 million euros. The research project is being implemented as a joint project involving the Steinbeis-Innovationszentrum (siz) energieplus and the Technische Universität Braunschweig. The latter is participating with seven research institutes and the Facility Management division.

A research laboratory is being built on an area of around 4,700 square meters in Gerhard-Borchers-Straße in Braunschweig. This laboratory is being designed as a demonstration plant for a future megawatt energy centre that covers the entire value chain from renewable energies to the production of green hydrogen. For this purpose, a 1 MW anion exchange membrane (AEM) electrolyzer, a 1.1 MWh battery storage system with grid-forming power converter, a 150 kWp photovoltaic system, a hydrogen filling station, a coupling with the local heating network, hydrogen pipelines to neighbouring research facilities and various test benches will be installed. The objectives of this cooperative project include the bundling of research synergies along the hydrogen value chain and the implementation of research activities in the field

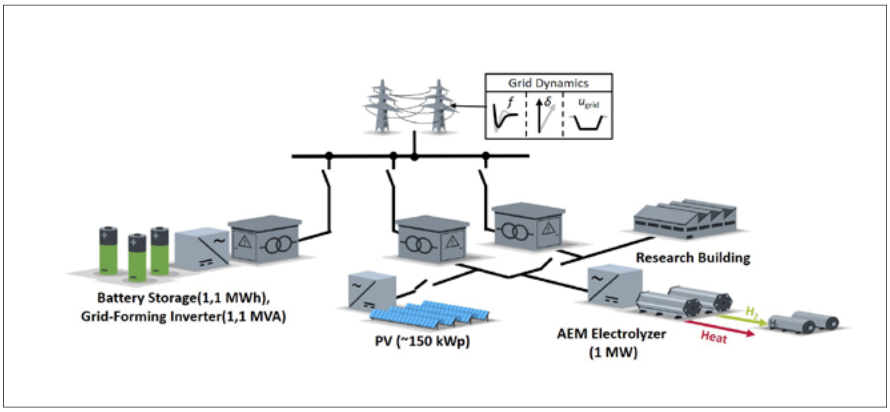

Figure 1: Simplified structure of the electrical components of the H_2 Terminal Braunschweig, Timo Sauer

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Cover picture: Ground-breaking ceremony for the new Hydrogen Terminal Braunschweig in Gerhard-Borchers-Straße on 23 March 2023,
Photo: Timo Sauer

of hydrogen production, storage, feed-in, distribution and reconversion in fuel cells as well as grid-friendly integration into the European electricity grid.

Grid-supporting integration of electrolyzers

The transformation to a climate-neutral energy supply is leading to a structural change in generation technologies towards a converter-dominated grid. The shutdown of fossil power plants creates a need for grid inertia (instantaneous reserve) from renewable energy sources, which was previously provided exclusively by synchronous generators. The kinetic energy temporarily stored in the rotor is used to compensate for power imbalances until downstream control power mechanisms stop the associated frequency change and return the frequency to the nominal frequency. Not only generation plants, but also controllable loads can contribute to the instantaneous reserve. To this end, the converter hardware used must be able to carry out grid-forming control of the system and the system process must enable the necessary dynamic flexibility in the millisecond to second range. The demand for green hydrogen is leading to an expansion in the gigawatt range of electrolysis plants and theoretically offers the potential to cover the future demand for instantaneous reserve by using the plants in grid-serving operation to ensure transient grid stability. This gives rise to the following research questions:

1.) *How quickly can the output of the electrolysis process be adjusted?*
2.) *Is it physically possible to provide instantaneous reserve with electrolysers and what flexibility contribution can the system make?*
3.) *Is negative instantaneous reserve also possible through short-term overload (in the millisecond to second range)?*

In order to obtain answers to these research questions, the electrical behaviour of the electrolyser in conjunction with the battery storage system is to be investigated after the H_2 Terminal Braunschweig has been commissioned. Power ramps of the electrolyser are to be run in order to draw conclusions about the dynamics. The setup also makes it possible to investigate the dynamic behaviour of the electrolyser both in parallel grid operation and in stand-alone grid operation. Due to the grid-forming controlled battery, dedicated grid dynamics can be specified in the stand-alone grid by changing the amplitude and frequency of the voltage and the reaction of the electrolyser, which depends on the converter control used, can be recorded.

Integration of the Hydrogen Competence Center in teaching activities at the TU Braunschweig

A further aim is to integrate the research activities into lectures and laboratories for the continuous development of relevant degree courses. All of the project's research institutes are involved in this. elenia acts as the interface to the electrical engineering, sustainable energy technology, environmental engineering and electromobility courses.

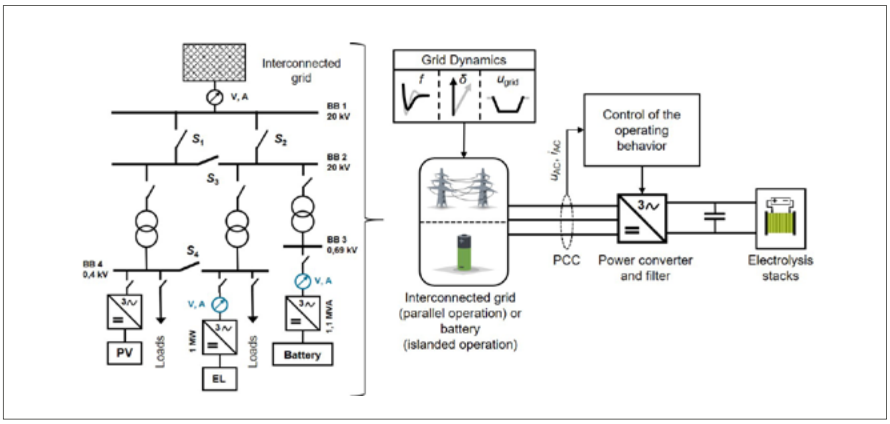


Figure 2: Schematic test setup for investigating the dynamic behaviour of electrolyzers, TU Braunschweig, Timo Sauer

PROJECT TITLE

H_2 Terminal

H_2 Terminal Braunschweig

DURATION

June 2021 – May 2025

CONTACT PERSON

Timo Sauer
t.sauer@tu-braunschweig.de
+49 531 391 7721
Nils Gräfer
n.graefer@tu-braunschweig.de
+49 531 793 893 16

PROJECT PARTNERS

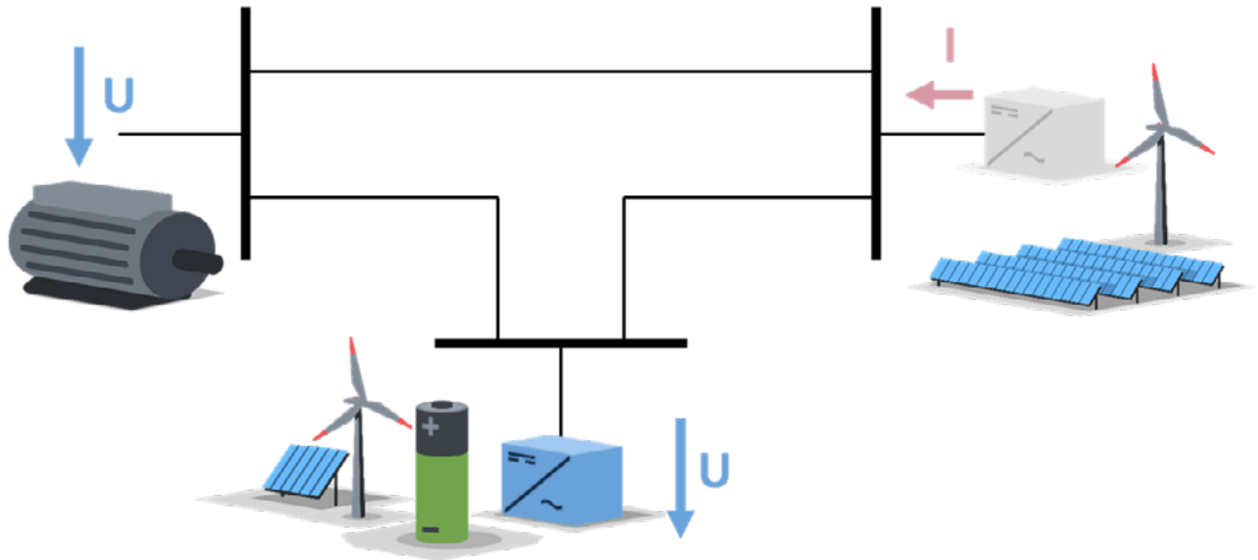
Steinbeis-Innovationszentrum (siz) energieplus, Institute an der TU Braunschweig: Institut für Städtebau und Entwurfsmethodik, Institut für Werkzeugmaschinen und Fertigungstechnik, Institut für Energie- und Systemverfahrenstechnik, Institut für technische Chemie, Institut für Verbrennungskraftmaschinen, Institut für Bauklimatik und Energie der Architektur

FUNDED BY

Federal Ministry of Education and Research

COORDINATED BY

Steinbeis-Innovationszentrum (siz) energieplus



Grid control 2.0

Stable grid operation with 100% renewable energies

Motivation & goals of the project

The electrical energy supply and in particular the control of the electrical grid in Germany are undergoing a process of transformation. While grid infrastructure today is essentially based on the characteristics of large power plants with synchronous generators, inverter-based generation systems are increasingly being used to generate electricity. Grid states in which more than 90 % of the load is covered by renewable energies are already occurring in Germany today. However, to ensure system stability, conventional power plants, so-called "must-run units", must remain connected to the grid at these times.

These and other changes in the supply system and in grid operation entail a far-reaching reorganization. This is where the Grid Control 2.0 project comes in. In particular, new conditions that were not previously present in a power grid based on synchronous generators were addressed within this project.

The overall objective of the Grid Control 2.0 research project was to demonstrate that the electrical grid system in Germany can be operated safely and in a stable fashion with a very high proportion of inverters.

Research at elenia

As part of the joint project, elenia dealt with the integration of grid-forming inverters into the distribution grid. In this context, the focus was on the provision of instantaneous reserve and its effect on the superior grid levels. The aim of the investigations was to examine the contribution of these inverter systems to stabilize the supply grid in the event of rapid load changes in grids with a reduced proportion of feed-in from large power plants. A further focus was placed on the influence of grid-forming converter technology on the distribution grids, in particular on local voltage quality and grid protection measures.

Challenges in integration into the distribution grid

A particular topic in the context of grid protection is the avoidance of unwanted islands as a result of grid disconnection, e.g. caused by maintenance work or a grid fault. In these situations, grid-following inverters must recognize that they are no longer being operated on the interconnected grid and then switch themselves off in a targeted manner. The grid-forming inverter, on the other hand, tries to maintain a stable grid at all times, which is why it is used in the first place. There is therefore also a conflict of objectives here, in that on the one hand such so-called islanded grids must be switched off safely and on the other hand the grid-stabilizing property of the grid-forming inverter should not be impaired.

In the project, it was shown in grid simulation studies and in the laboratory that the mere presence of grid-forming inverters greatly impairs the ability of existing systems to detect islanded grids and greatly increases the likelihood of islanded grids forming. This motivated the development of our own detection methods tailored to the characteristics of grid-forming inverters, which enable them to detect independently. The main challenge here is that these should also ensure detection in interconnected operation in complex grids with other systems. Corresponding promising approaches for this were analyzed and considered in simulation. Figure 01 shows a low-voltage grid model and existing grid-connected systems (red). If only these are active, a formed island is only not detected within 6 s in a few cases marked in red (Figure 01 bottom left). The presence of a single grid former (blue) causes the detection of all existing systems to fail in almost all cases (Figure 01 top right). The developed detection method for the grid former enables a similarly reliable detection of all installations as before (Figure 01 bottom right). The results mo-

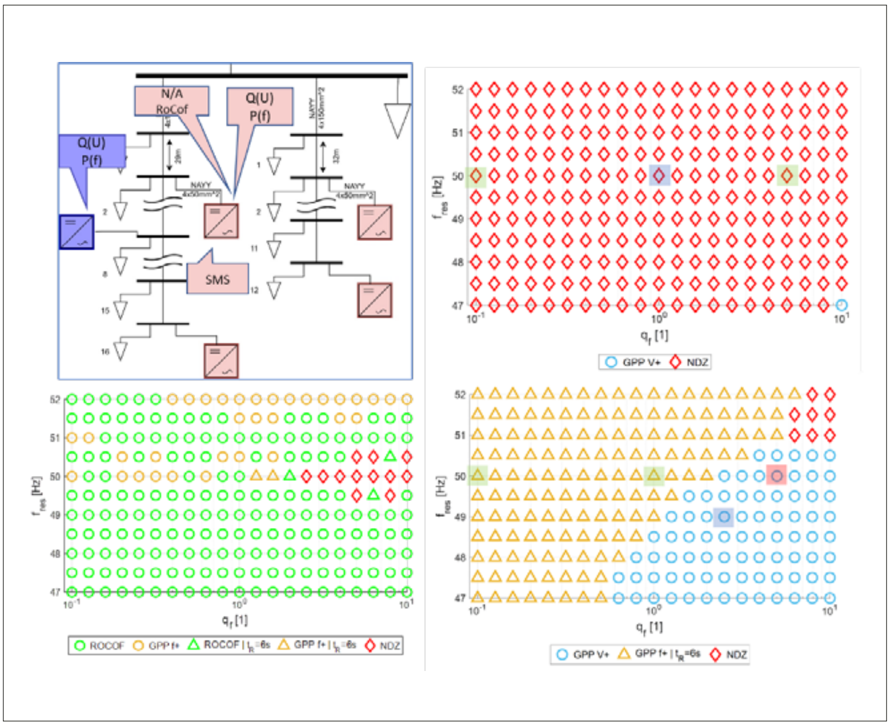


Figure 1: Influence of grid-forming inverters on islanding detection in low voltage grids

tivate the further implementation of these procedures in the laboratory and in more detailed studies in the 'Distribution Grid 2030+' (Verteilnetz2030+) project, which started in May 2023.

Provision of instantaneous reserve from the distribution grid

By simulating a model system consisting of an extra-high-voltage grid (EHV grid) and a subordinate high-voltage grid (HV grid), it was possible to show that grid-forming converters can contribute to the instantaneous reserve for frequency support in the transmission grid. The amount of the contribution of the grid-forming system depends on the impedance between the system and fault location with the same parameterization, but not on the voltage level.

In addition, further simulations in a model grid with all voltage levels showed that the propagation of phase angle jumps in the entire grid takes place within less than a millisecond. From this, it can be concluded that the provision of instantaneous reserve does not have to be technically restricted to certain grid levels.

In principle, instantaneous reserve can therefore also be provided by grid-forming systems from the distribution grid, as shown in Figure 02. However, it remains to be investigated how stable and secure distribution grid operation can be guaranteed in the future when grid-forming converters are connected causing undesirable side effects by new dynamic characteristics of the systems.

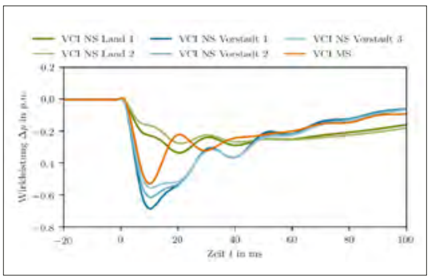


Figure 2: Behavior of grid-forming converters (VCI - voltage controlled inverter) on the LV grid (blue and green) and on the MV grid (orange), source: Rauscher, F. „Dynamics of grid-forming inverters in future distribution grids"

PROJECT TITLE

Netzregelung 2.0

Grid control 2.0

DURATION

December 2016–August 2022

CONTACT PERSON

Timo Sauer
t.sauer@tu-braunschweig.de
+49 531 391 7721

Björn Oliver Winter
bjoern.winter@tu-braunschweig.de
+49 531 391 7748

PROJECT PARTNERS

Other research institutes:
Frauenhofer IEE, University of Kassel

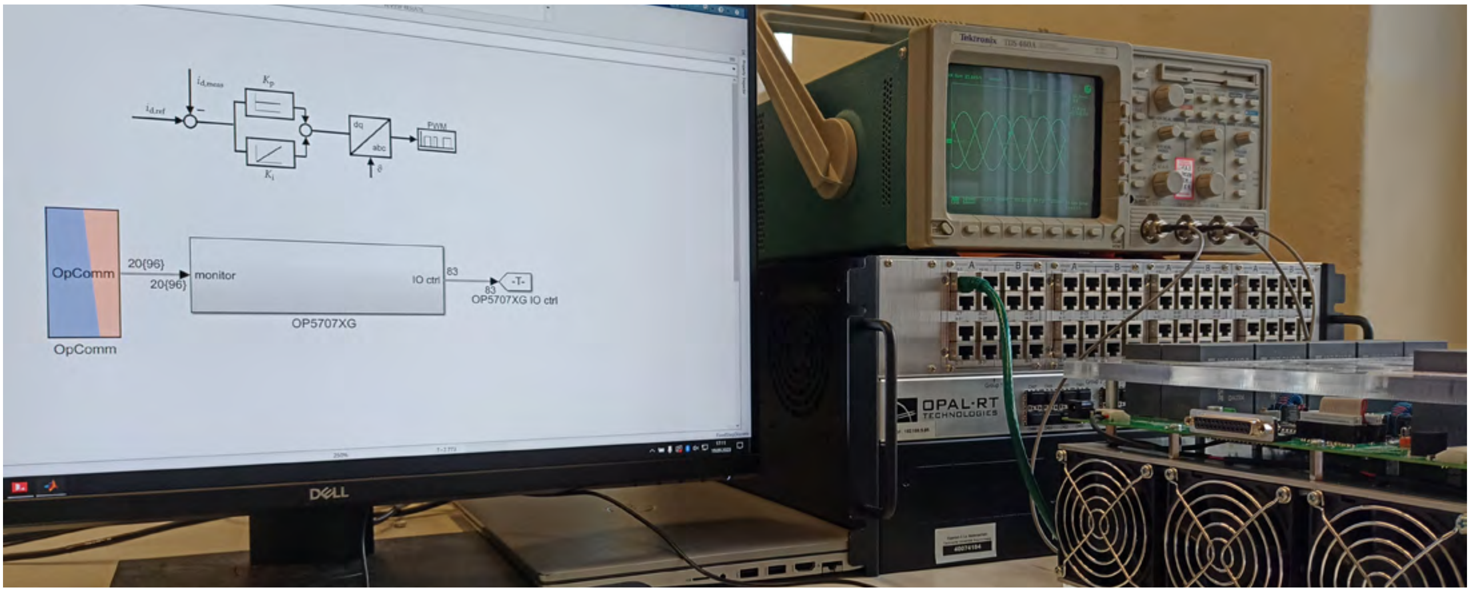
System manufacturer:
Siemens, SMA Solar Technology AG

Grid operators:
50Hertz, Amprion, TenneT, TransnetBW, EWE Netz, Mitnetz, Westnetz

Associations and networks:
VDE | FNN, DERlab, dena

FUNDED BY

Federal Ministry
for Economic Affairs
and Climate Action



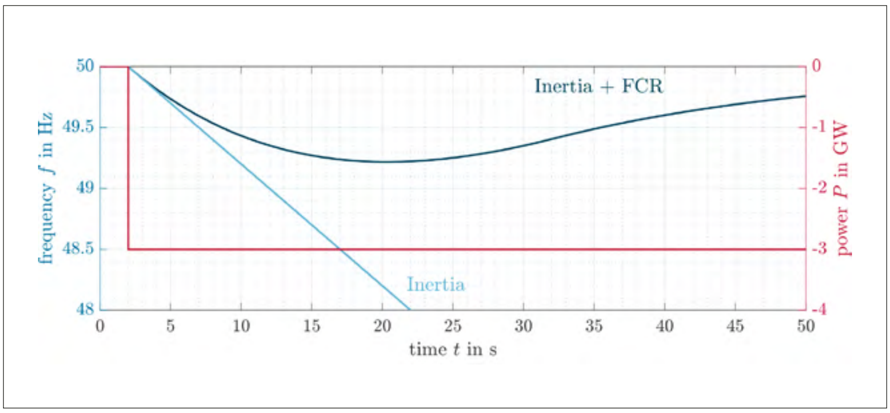
MetroSDL

Development of metrological principles for new types of ancillary services to maintain future grid stability

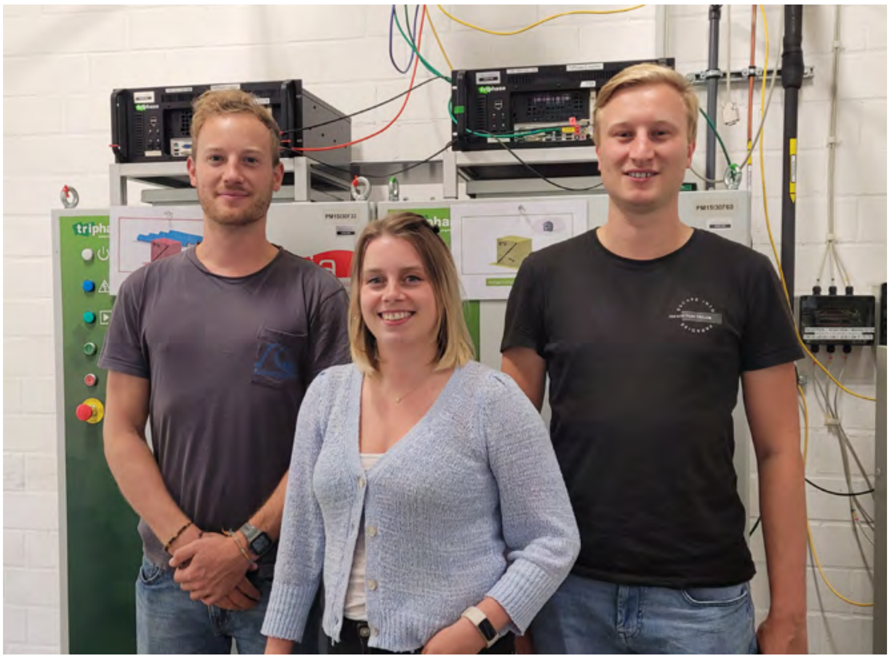
The research project called MetroSDL, which only recently began in July 2023, is investigating technology-specific challenges in maintaining stable interconnected grid operation in the context of converter-based generation systems. In the steadily progressing transformation process of energy supply systems due to the energy transition, there has been a continuous increase in generation plants whose energy sources are described as renewable in recent years. This transformation process will continue in the coming years with the German government's current decisions to phase out coal and nuclear power generation. As a result, conventional power plants will increasingly be replaced by converter-coupled plants. The maintenance of future grid stability must therefore be guaranteed by existing and new renewable energy plants through the provision of ancillary services.

Overarching objectives of the research project

The overarching aim of the MetroSDL project is therefore to create a metrological basis for new types of system services as part of the system stability roadmap currently being developed by the Federal Ministry for Economic Affairs and Climate Protection (BMWK). Maintaining the aforementioned grid stability will be an essential component of this roadmap. In the hypothesis, the use of innovative power converters with a corresponding control function can also guarantee the immediate provision of instantaneous reserves. In contrast to fossil-fired power plants, however, this feature is not inherent to the system. Therefore, in accordance with Section 12h of the Energy Industry Act (EnWG), the "inertia of local grid stability" is also required as a new service for system security that is not dependent on frequency. In future, this service is to be procured on the market by the relevant grid operators. Grid technicians also refer to this inertia as an instantaneous reserve that is immediately available. However, this distinguishes it from conventional control power products. In order to enable market-based procurement of this system service, many parameters still need to be recorded and processed metrologically. These include not only the precise determination of inertia, but also dynamic frequency measurement, which defines the exact requirements for the market-based billing of instantaneous reserve or fast primary control reserve. This metrological work is a prerequisite for the prequalification, certification and billing of electrical generation plants in the grid. As part of the MetroSDL project, these basic



Typical frequency behaviour of the interconnected grid in the event of a reference incident of 3 GW with and without the use of primary control power, diagram: Stefanie Walujski



Future project team members Frederik Tiedt, Stefanie Walujski and Stefan Klöpping in the elenia grid dynamics lab, photo: Tamara Beck

principles are being developed, evaluated and validated in a measurement setup to enable a metrological assessment of innovative ancillary services and their provision by converter-based systems of different types.

Expansion of the elenia grid dynamics laboratory

As part of the research project, the existing grid dynamics laboratory will be expanded to include additional high-performance laboratory equipment. In particular, investigations into transient grid events, whose processes take place within a few milliseconds, must be made reproducible and depictable using laboratory equipment that is as dynamic and precise as possible. For this reason, the grid dynamics lab will be expanded to include a 4-quadrant voltage source with 30 kVA in the form of a linear amplifier. Linear amplifiers are characterized by almost instantaneous and distortion-free signal processing, which is mandatory for transient grid events. When forwarding synthesized and measured signals through the existing real-time computer system, it must also be ensured that they can be exchanged between the devices without coupling. This is made possible by an optical interface. In addition, a power converter prototype with a rated output of 10 kVA is being built on the basis of a pre-assembled B6 bridge as part of the project. It allows completely free specification of the system's internal current or voltage regulation. As a result, it will be possible to simulate the typical electrical characteristics of converter-based systems.

Laboratory voltage source/linear amplifier, Photo: Spitzenberger & Spies

PROJECT TITLE

MetroSDL
Metrologische Grundlagen für neuartige Systemdienstleistungen im Rahmen der Roadmap Systemstabilität

DURATION

July 2023 – June 2026

CONTACT PERSON

Frederik Tiedt
f.tiedt@tu-braunschweig.de
+49 531 391 7708

Stefanie Walujski
s.walujski@tu-braunschweig.de
+49 531 391 7702

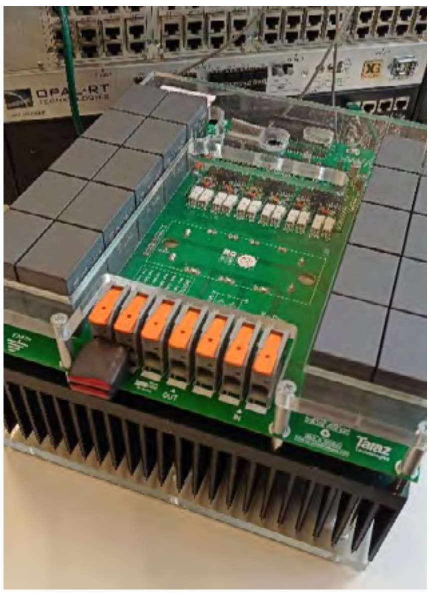
Stefan Klöpping
s.kloepping@tu-braunschweig.de
+49 531 391 7759

PROJECT PARTNERS

PTB Braunschweig

FUNDED BY

Federal Ministry for Economic Affairs and Climate Action



Prototype inverter, Photo: elenia

Grid Forming Seminar

Technical seminar to provide theoretical and practical content on grid forming in the elenia grid dynamics laboratory.

The Grid Forming Seminar is a comprehensive training event dealing with the integration of grid-forming inverters into the electrical grid. This seminar aims to teach participants the basics of grid forming, explain the electrical characteristics of grid-forming inverters and highlight the challenges of integrating them into the grid. In addition, the practical training part in elenia's grid dynamics laboratory offers the opportunity to apply the acquired knowledge in practical scenarios and to examine the functionality of grid-forming inverters in comparison to commercially available grid-following inverters and synchronous machines. The seminar concludes with a debriefing, discussion and feedback session in which the results of the laboratory experiments are analysed and future technical focuses and implementation options for grid-forming systems are discussed.

Introduction and basics of grid forming

In the first part of the seminar, the participants receive a basic introduction to the topic of grid-forming inverters. The main electrical characteristics of grid-forming behaviour in the interconnected grid are presented. Particular attention is paid to the challenges of integrating grid-forming inverters into the grid, which pose special challenges compared to standard grid-following inverters and synchronous machines.

Practical training in the network dynamics laboratory

The practical part of the training takes place in elenia's grid dynamics laboratory, where participants are introduced to the laboratory equipment and methods for investigating grid stability in the context of grid-forming inverters. Various aspects of grid-forming behaviour are covered in practical scenarios, including the synchronization process, grid parallel operation, behaviour in the event of frequency and angle jumps and islanding. A special focus is placed on the comparison between commercially available grid-following inverters and grid-forming inverters in parallel operation and in critical situations such as system splits and load jumps. The

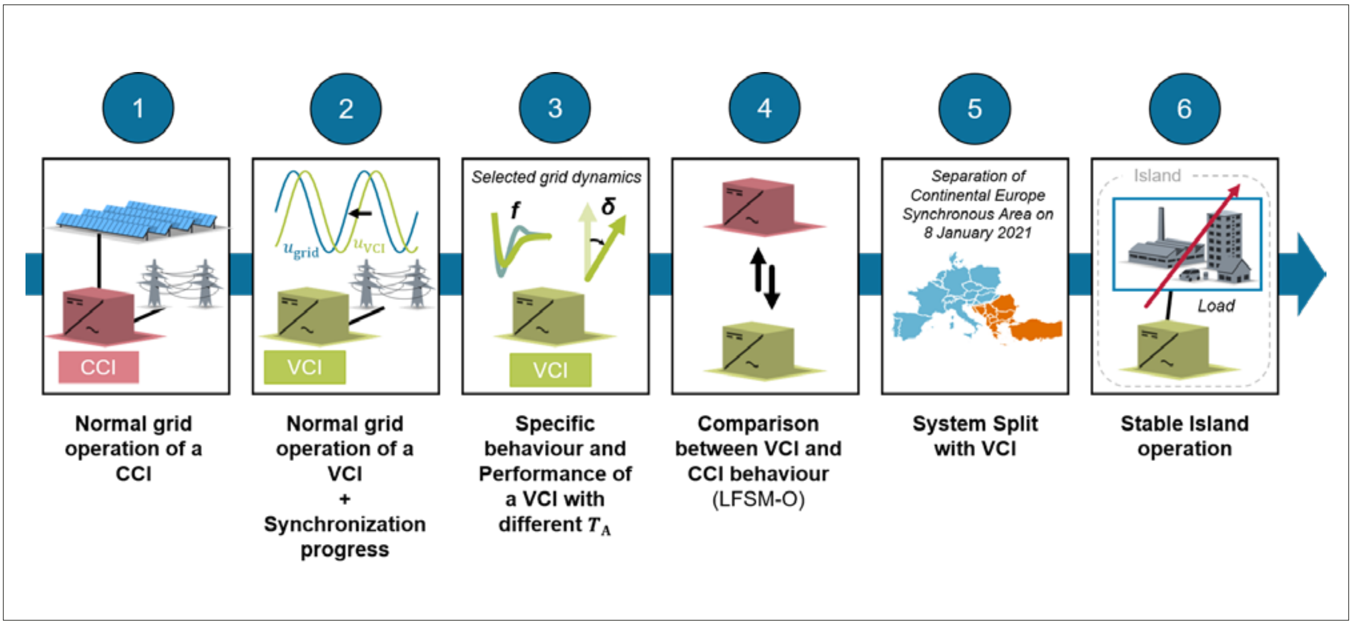


Figure 1: Preview of the experimental scenarios for teaching the basics of grid forming in the elenia grid dynamics laboratory, image: TU Braunschweig, Timo Sauer

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Cover photo: Realisation of the Grid Forming Seminar in the elenia Grid Dynamics Laboratory on 15.09.2022, Photo: Timo Sauer

laboratory tests are carefully evaluated in order to develop a deep understanding of the performance and limitations of the different technologies.

Debriefing, discussion and feedback session

In the last part of the seminar, the results of the laboratory tests are discussed in detail. As during the entire seminar, participants will have the opportunity to ask questions and share their findings. In addition, future technical priorities in the field of grid integration of grid-forming inverters will be discussed. Various options for the introduction process of grid-forming systems will be discussed, including the integration of fully integrated grid components (VINKs) and the market-based procurement of instantaneous reserve. The seminar concludes with a feedback session where participants can share their opinions and suggestions on the technical seminar to further improve the quality of future training events.

This technical seminar provides a comprehensive and interactive learning environment for anyone interested in the integration of grid-forming inverters in the interconnected grid, helping to deepen understanding and skills in this field.

PROJECT TITLE

Grid Forming Seminar

DURATION

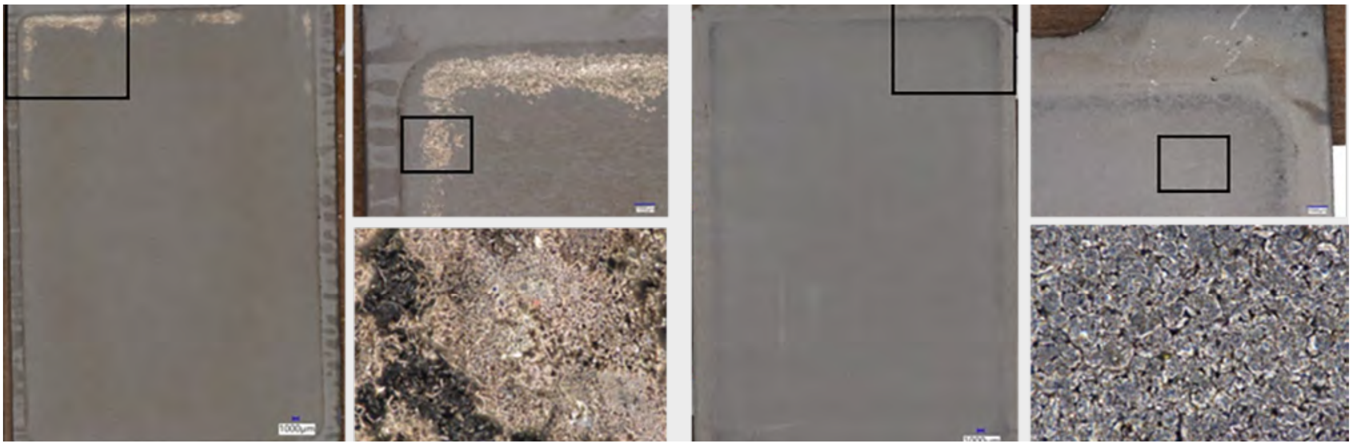
Ongoing

CONTACT PERSON

Timo Sauer
t.sauer@tu-braunschweig.de
+49 531 391 7721

Frederik Tiedt
f.tiedt@tu-braunschweig.de
+49 531 391 7708

Doctoral Theses



Battery Technology

Robin Drees

Model-based Design and Evaluation of Fast-Charging Strategies for Lithium-Ion Battery Formation and Cyclization

The relatively high cost and long charging time of lithium-ion batteries are two of the biggest challenges for the acceptance of electric vehicles. The first charging cycle in cell production often takes 10 - 20 hours and leads to high manufacturing costs. Not only the fast-charging capability during production, but also during the use phase needs to be improved. However, charging too quickly can lead to a shorter service life due to lithium plating. The aim of the dissertation is the model-based design and evaluation of different fast charging strategies for both the formation process and the utilization phase.

Three-electrode button cells and pouch cells were used for the investigations. Two model-based methods were developed to optimize fast charging strategies without lithium plating. The first method is a black box model that enables real-time control of fast charging. The second method is an electrode equivalent circuit model (EECM), which can be used to simulate various fast-charging strategies. Compared to reference formulations (6 h), the black box model approach resulted in a 23% reduction in charging time at 20 °C for the pouch cells. At 40 °C, the charging time was reduced by 42%. Gas generation during formation is a limiting factor for fast charging capability. Slow pre-charging and degassing enabled subsequent fast charging without lithium plating. Although there were no performance differences between the cells after formation, after approximately 3 months all cells formed at 40 °C showed approximately 10% higher resistance compared to cells formed at 20 °C. This correlated with copper corrosion. This correlated with copper corrosion on the outermost graphite electrode side of the electrode stack of the pouch cells formed at 40 °C.

The EECM approach made it possible to simulate and evaluate various fast charging strategies during the utilization phase. Inhomogeneous charging states at the interface to the geometric overhang of the graphite electrode were identified as a limiting factor for the maximum current. The fastest strategy for pouch cells without lithium plating took 18.2 minutes to charge from 0 - 50% SOC at 40 °C. The fast charge strategy was repeated 700x and did not result in accelerated degradation compared to a 1C reference cycling, which was 65% slower. Furthermore, the 700 fast charge cycles resulted in only about 5% capacity loss. Overall, the developed methods and results enable the successful development of safe fast charging strategies without accelerated degradation of cell performance.

Robin Drees

TIME AT ELENIA

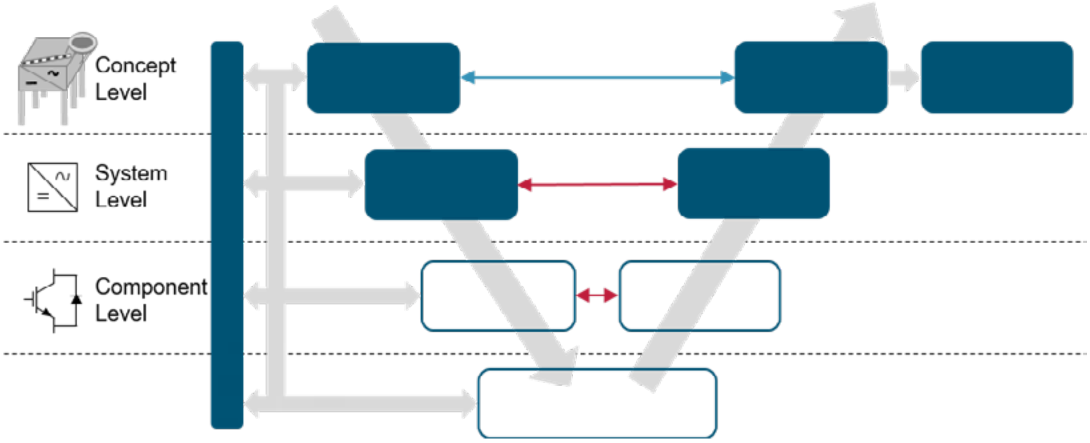
02/2019 – 07/2023

ACTIVITIES AT ELENIA

- Collaboration and team leadership in battery technology
- Working on the OptiZellForm, FormEL, Cell2Pack and many more projects
- Experimental and simulative fast charging optimization

NOW WORKING AS

- Fraunhofer Forschungsfertigung Batteriezelle (FFB) as Post doc



DC Systems and Switching Technologies

Melanie Hoffmann

Model-Based Systems Engineering for Offshore HVDC Grid Integration Systems

To achieve the 1.5 °C target of the Paris Climate Agreement, the conversion of the entire energy system to renewable energy sources is essential. Strong and stable wind conditions offshore make offshore wind energy far away from shore an important energy source. The integration of such Offshore Wind Farms (OWF) has to be safe, efficient, and affordable, which makes High Voltage Direct Current (HVDC) transmission systems often the preferred choice. These consist of many subsystems, components, and interfaces, which characterise them as complex systems. The complexity, many and diverse requirements and a large number of system design alternatives require grid operators and manufacturers to employ a systematic approach to develop the most suitable design that meets all requirements and functions. Systems Engineering has proven itself for many years outside the energy industry as a suitable methodology for the development of complex systems. The extension to Model-Based Systems Engineering (MBSE) allows the specification of a system in a universal system modelling language (SysML), which enables the collaborative system development across disciplines.

In this thesis, a guideline for the development of HVDC transmission systems based on MBSE is developed to improve the system design with an interdisciplinary and model-based approach. This leads to a detailed understanding of the HVDC transmission system elements and their interactions. Discipline-specific models and simulations provide details to the design. At the end of the system design, the SysML model represents a detailed specification of the HVDC system. The advantage of the developed SysML model is to facilitate the design analysis and to identify the impact of requirement changes or changes in the system environment on the system design. The SysML and discipline-specific models allow the verification of system requirements, e.g. of the availability, which has a high influence on LCOE and is used as an assessment criterion on system and component level. The validation procedure is also introduced. Based on the proposed approach for HVDC transmission system development, the potential for the extension of the methodology for energy systems in general is presented to support the realisation of the energy system conversion to renewable energy sources.

Melanie Hoffmann

TIME AT ELENIA

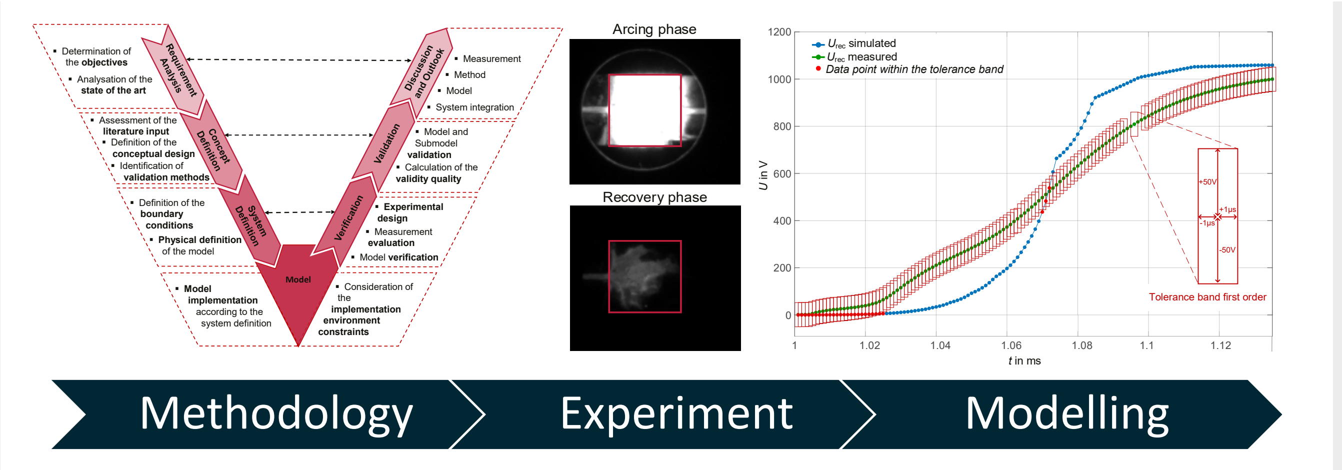
Since 2018

ACTIVITIES AT ELENIA

- Teamlead DC Systems and Switching Technology
- Working on ancillary services for secure power grids in times of advancing energy transition and digital transformation in the SiNED project
- Development of Systems Engineering methodology for offshore wind farm HVDC grid connection systems.

NOW WORKING AS

- Vattenfall Europe Windkraft GmbH als Grid Manager



DC Systems and Switching Technologies

Frederik Anspach

Experimental Research and Modelling of LVDC Hybrid Switch Plasma Recovery

Power transmission and DC grids: Research to improve switchgears

The efficient transmission of large amounts of energy is one of the challenges in electrical power engineering. DC grids are a key technology. In mobile and HVDC transmission systems, they are already state of the art, but the application at stationary low and medium voltage levels is still the subject of research projects. In addition to the grid itself, the requirements on the components, e.g. switching devices, are also increasing. Optimisation of the switching devices alone is no longer sufficient; system interoperability, in the form of "intelligence", must also be increased simultaneously. Previous investigations show a detailed understanding of the deionisation process reduces the switching time of low-voltage hybrid switches (LV HCB) but also supports the development of an intelligent switching device. A structured investigation of the recovery voltage of LV HCBs forms the basis for understanding the deionisation process. Due to the wide range of requirements, the systems engineering method is used for the investigation.

The results show that the chosen model approach is advantageous due to its modularity and the early defined validation possibilities. The developed specific model definition is currently the most efficient method for simulating the recovery voltage due to the unambiguous traceability of the boundary conditions set and their effects on the physical process. Carrying out measurements on a model arrangement expands the understanding of the process compared to the existing literature. The reason for this is the coupled multiphysical evaluation (electrical, optical, barometrical). The comparison of the measurement and model results allow a verification of the model behaviour and the identification of dominant influencing variables. A high model accuracy is achieved within the framework of parameterisation. The model accuracy is confirmed during validation, taking into account influencing factors such as manufacturing tolerances. The determination of the validation coefficient realises the traceability of the investigation results to system level. In the context of the discussion, the results are divided into four categories: Measurements, Method, Model and System Integration. The results are critically scrutinised, classified in the state of the art and optimisation potentials are identified.

Based on this work, three core tasks can be derived for future research: First, continuation of the multiphysical measurement method to optimise the understanding of the plasma recovery process. Second, extension of the model description from the approximated model setup to a real hybrid switch. Thirdly, application of the developed method to other components of the DC system.

Frederik Anspach

TIME AT ELENIA

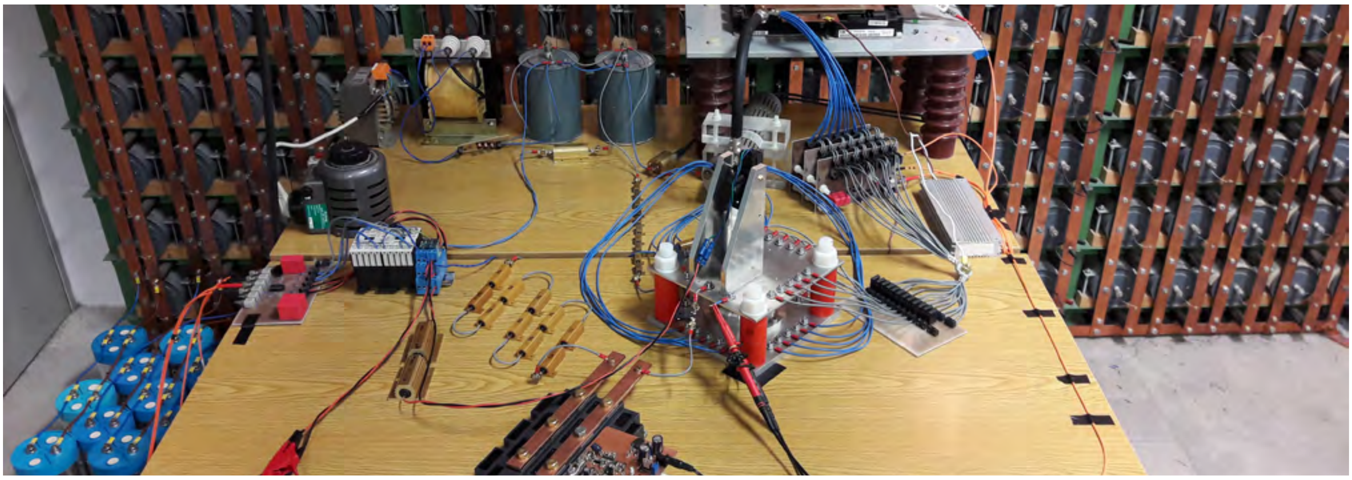
2019–2022

ACTIVITIES AT ELENIA

- Collaboration and team leadership of DC and switchgear
- Processing of the Smart Modular Switchgear II project

NOW WORKING AS

- Volkswagen AG as a specialist project leader



DC Systems and Switching Technologies

Dirk Bösche

Investigation on the residual arc conductance in the mechanical part of Hybrid-Circuit-Breakers before and after current commutation

A lot of the energy is generated by burning fossil fuels. This increases the green house effect, which causes rising temperatures and a climate change in general. To stop this development before hitting a point of no return, the amount of renewable energy sources are increased. Additional efforts try to reduce the demand by increasing the energy efficiency. One promising attempt is to change industrial AC into DC grids. This transition has several advantages. Renewable sources and storage components can be implemented easily, which increases the dependability. But the main benefit is, that energy otherwise lost during the production process can be regained. However, appropriate DC switches are needed to ensure a reliable and save operation of those grids. Designing those switches can be a challenging task. Mechanical switches perform exceptionally well in the on or off state. They provide low conduction losses and a galvanic separation. Transitioning from one state to the other can cause problems. Especially when small currents should be interrupted, that can have changing polarities. The opposite is true for semiconductor switches. Most of them are capable of changing their state fast and without an arc. But they cause significant conduction losses and are sensible to overvoltage. To retain the advantages of both technologies, they were combined into one hybrid switch.

In this thesis different hybrid switch topologies are clustered by their operating principle and evaluated regarding their performance. One example which is particularly suited for the operation in low voltage DC grids is selected. In addition, all necessary electronic components and the switch-off process are explained.

In the selected topology an arc occurs during the switch-off process. It is extinguished by a parallel semiconductor path, which has to stay on for a certain amount of time. This is necessary to allow the arc to subside. However, the on time of the semiconductor is one decisive factor for dimensioning. Therefore, a test circuit to reproduce the hybrid switch- off process was developed and a model mechanical switch designed. This setup is used to investigate the influence of contact distance and current value onto the arc decay process by measuring its resistance. Additionally, a model based on a thermal equivalent circuit is developed. It enables the reproduction of the arc resistance curve progression. In conjunction with determined approximation equations, model and measurement based results are compared. Finally, the results are summarized, challenged and some design considerations for an increase of the arc decay speed given.

Dirk Bösche

TIME AT ELENIA

Since 2015

ACTIVITIES AT ELENIA

- Investigation and development of DC hybrid switching devices
- Support in planning and setting up laboratory tests
- Design and construction of electronic circuits
- Technical manager

High Voltage-, Vacuum- and Plasmatechnology

Benjamin Weber

Investigation of Vacuum Arcs in High Voltage Circuit Breakers

This thesis deals with the automated, multivariate evaluation of vacuum arcs in circuit breakers. Circuit breakers are essential components of the electrical power grid and typically use climate-damaging SF6-gas in the high-voltage level, which must be replaced by alternatives in the future. One possible alternative is the vacuum circuit breaker, whose switching principle is based on the control of the generated plasma by self-induced magnetic fields. The use of transverse magnetic fields (TMF) to move constricted vacuum arcs between the switching contacts, has so far only been used in the medium voltage level. In order to exploit the advantages such as low losses and simple contact design in higher voltage levels, the high current phase of short-circuit interruption at higher contact distances is investigated and demonstrated to be feasible. A method for data analysis from combined optical and electrical data is presented. This is based on a hybrid model to combine acquired data with knowledge about the physics of vacuum arcs. The optical investigation is performed by a high-speed camera and a mirror arrangement. Hereby, two perpendicular perspectives are recorded, which allow a positioning of the vacuum arc. Measured quantities such as current, voltage and contact distance are added. The result is a feature vector that includes local, temporal, electrical and derived data sets. Based on this vector, in addition to the evaluation, a machine learning algorithm is trained to determine the arc appearance.

In the evaluation, varying contact distances from 20 mm to 46 mm at different short-circuit currents up to 31.5 kA are examined for various aspects. Of particular interest is the increase in average arc speed up to 380 m/s with increasing distance. Other parameters, such as arc voltage, radiation and arc mode do not show much change. A newly presented performance indicator representing charge distribution on the contacts shows a comparable surface stress for standard and increased contact distances. The thesis indicates that the TMF switching principle is functional at high contact distances. The presented methods for automatic investigation of switching tests reduce the influence of human errors in the evaluation of optical plasma phenomena and are applicable for a large number of parameter variations.

The results are discussed in front of various aspects with known literature. Investigations with faster opening curves for the alternative AMF switching contacts show comparable effects regarding arc voltage and mode as TMF-contacts. The calculated contact stress points are identifiable on the actual scanned contact pieces.

Benjamin Weber

TIME AT ELENIA

11/2017 – 04/2023

ACTIVITIES AT ELENIA

- Working in the group components for power supply in the research group high voltage and vacuum technology
- Working in the projects Moliboa, Eudo & Eulas
- Experimental interrupting studies of vacuum circuit-breakers

NOW WORKING AS

- Avacon Netz GmbH as Planer for high-voltage grids (110 kV)

Grid Operation and Grid Planning

Stefanie Čelan

Technical and Economic Effects of the Provision of Flexibility by Electricity-only Households from the Perspective of Systems and Grid Operators

Germany's goal of achieving climate neutrality by 2045 requires greater coupling of the electricity, heating and transportation sectors in order to cover energy requirements exclusively with renewable energies. At household level, this will lead to progressive electrification, characterized by the increased installation of photovoltaic systems, battery storage systems, heat pumps and electric vehicles.

However, this electrification poses challenges for the low-voltage grids, as they are not designed for these new consumers and generators with high simultaneities. The analysis in this paper therefore focuses on the potential of grid-supportive heat pumps, electric vehicles and battery storage systems to better adapt consumption demand to the supply of renewable energies and to prevent grid bottlenecks.

The simulation-based analyses show that the provision of grid-serving flexibility by electricity-only households can significantly reduce future low-voltage grid expansion: by up to 81% in terms of line lengths and around 86% in terms of the required transformer power if all flexible components are fully involved in grid-serving operation. This corresponds to potential cost savings of up to 72%. Even if only around 41% of the flexible system components were to participate in grid-serving operation, the costs could be reduced by around 42%.

In order to motivate private system operators to provide their system flexibility, time-variable grid charges were examined in the study. The results show that system operators can generate additional income of around €100 per year on average by operating components in line with the grid. However, the acceptance and economic viability of grid-supportive operation depend primarily on regulatory developments. The study therefore contains recommendations for the necessary adaptation of the regulatory framework.

Consequently, grid-serving electricity-only households represent an important flexibility component as a success factor for a cross-sectoral energy transition.

Stefanie Čelan

TIME AT ELENIA

2013 – 2020

ACTIVITIES AT ELENIA

- Collaboration in research on active distribution grids and in team Grid Operation and Grid Planning
- Working on the research projects EnEff Campus 2020, elenia energy labs, Energy Toolkit
- Effects of heat pumps and electricity-only household concepts on low-voltage grids

NOW WORKING AS

- Business owner of Clean Energy Toolkits LLC

Grid Dynamics and System Stability

Florian Rauscher

Dynamics of grid-forming inverters in future distribution grids

Due to the progressing energy transition, vital inherent properties of synchronous generators of conventional power plants, which are crucial for grid stability, will need to be provided by new components in the future. For the provision of instantaneous reserve, grid-forming inverters will be able to close the emerging gap if combined with energy storage systems. At the same time, grid-forming inverters are in an early stage of development, which is why many questions are still open.

Within the scope of this work, the behaviour of grid-forming inverters in different areas of grid dynamics is analysed through component and system tests. The aim is to reconcile the characteristic properties of grid-forming inverters with the future requirements and to guarantee an effective provision of instantaneous reserve for frequency stabilisation. Due to the increased use of renewable energies and storage systems, the special aspects of their use in the distribution grid are addressed in particular.

For this purpose, the dynamic behaviour of grid-forming inverters will be analysed in the laboratory using prototype inverters. To test the transient stability, grid-forming inverters were subjected to phase angle jumps and their behaviour during local grid faults was investigated. The damping behaviour of grid-forming controls are demonstrated using low-frequency active power frequency oscillations. The frequency stability is characterised based on individual frequency jumps and the positive contribution is shown based on real-time simulations. In addition to the dynamic behaviour of grid-forming inverters, the comparison to grid-following inverters is also demonstrated. Furthermore, potential verification methods for these properties are discussed.

In addition to the component tests, system integration into the distribution grids is also considered. For this purpose, grid studies are carried out in the instantaneous value time range in a grid model spanning all voltage levels and the suitability of instantaneous reserve provision from the medium and low-voltage grid is demonstrated. In addition, it is shown that an aggregated performance behaviour of different grid-forming inverters is possible through suitable parameter selection. Finally, a possible market and regulatory integration of a distributed instantaneous reserve provision is discussed. This shows that even very small systems, such as home battery storage units, can provide instantaneous reserve for the entire system.

Florian Rauscher

TIME AT ELENIA

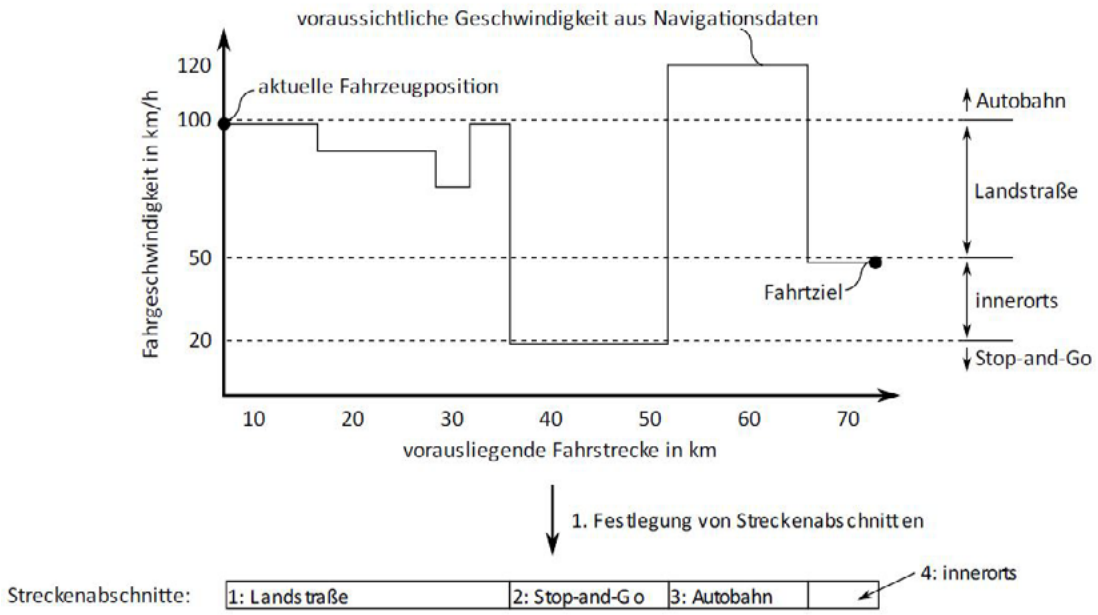
11/2016 – 08/2022

ACTIVITIES AT ELENIA

- Working on the research project Grid Control2.0
- Head of the Energy Systems working group (2018–2021)
- Team leader of the Team Grid Dynamics and System Stability (2019–2021)

NOW WORKING AS

- Engineer for Power Electronics Integration in Energy System Planning at TenneT TSO GmbH



Jan Bellin

Investigation on Predictive Operating Strategies of PHEV

Predictive operating strategies can further reduce the already low fuel consumption of plug-in hybrid vehicles

Predictive operating strategies can further reduce the already low fuel consumption of plug-in hybrid vehicles (PHEVs). However, they often have a high resource requirement and a high sensitivity to disturbances occurring on the route.

Therefore, the present study investigates how different disturbances occurring on the route, such as unforeseen traffic obstructions, affect the fuel saving potential of predictive PHEV operation strategies. Furthermore, it is investigated to what extent already less complex and resource-intensive operating strategy approaches can bring about significant fuel savings and where this is only possible by means of complex approaches.

For this purpose, a benchmark study was carried out during which the performance of three software approaches for operating strategy optimization was simulatively compared in various test scenarios. The least complex software approach used was a non-predictive, rule-based operating strategy optimizer. Furthermore, a predictive resource-efficient approach optimized for in-vehicle use was evaluated, as well as - as a benchmark - a predictive ideal operating strategy optimizer. The operating strategy optimizers used as well as the simulation environment were developed in the course of this thesis. The results from the simulations were then validated in real world driving tests.

A high practical significance of the simulation and real-world evaluation results was achieved on the one hand by selecting particularly practice-relevant test scenarios for the simulation. On the other hand, the operating strategy optimizers were designed for a near-production PHEV prototype which was also used for the simulation and the driving tests.

Finally, the simulation and real-world evaluation results were used to derive potential improvements to predictive PHEV operating strategies in terms of resource efficiency and robustness. Possible further research is also suggested.

Jan Bellin

TIME AT ELENIA

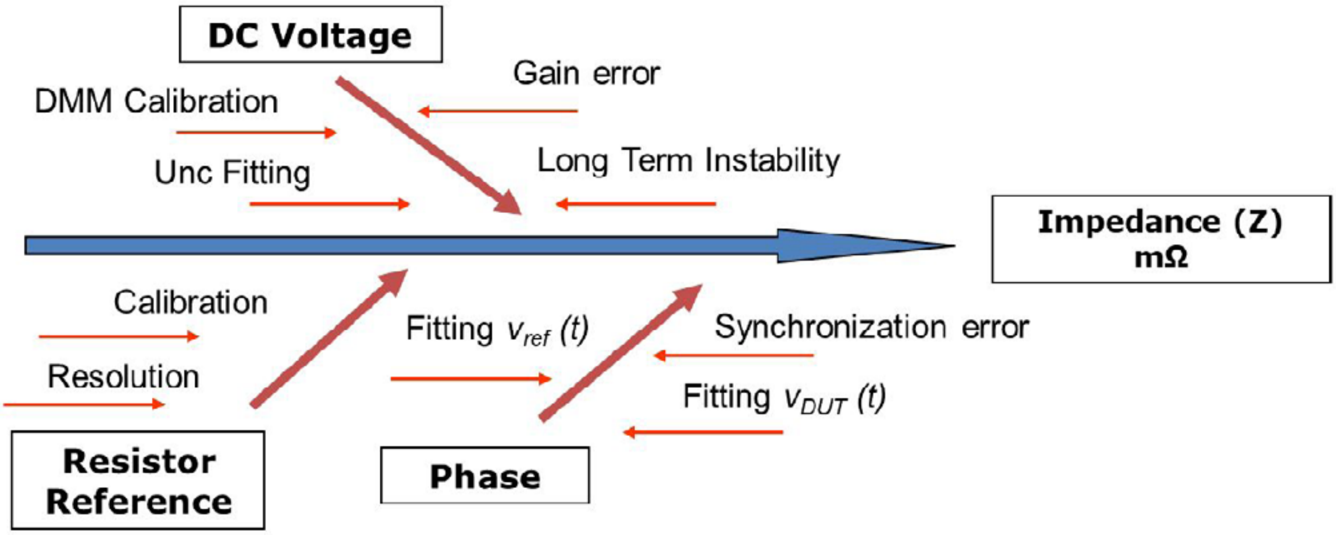
2012–2022

ACTIVITIES AT ELENIA

- Doctoral Student

NOW WORKING AS

- Volkswagen Group as Patent Officer



Benyamin Heryanto Rusanto

Development of a primary measurement method to characterize low-impedance reference standard

Investigating low impedance standards for Li-ion battery EIS, introducing a precise measurement method

Impedance standards having impedance values in the low mΩ range, with non-zero reactances, and operable with AC-currents of a few Amps and up to a few kHz are needed for appropriate impedance meter calibration. These challenging operation parameters are most relevant for electrochemical impedance spectroscopy of high energy Li-ion battery cells. We present a primary measurement method that can be used for the characterisation of respective impedance standards traceable to the SI.

This thesis describes the development of a primary measurement method to characterize low-impedance reference standard. Basically, two calibrated high precision DC voltage meters are used to measure AC voltages across a characterised reference resistor and the impedance standard. The measured voltages are fitted with sin waves and the complex impedance value is calculated from the amplitudes and phase difference of the voltage curves. Therefore, this research begins with determining the optimum parameters in using DMM for DC voltage sampling and determining the effective synchronization technique of two DMMs so as to obtain precise phase measurement results. Acquisition software development is also carried out to control all instruments and carry out continuous measurements based on a predetermined frequency list.

We present the measurement results of a reference impedance standard in mΩ range, including a full uncertainty budget. Moduli of the measured impedances are compared with those of another method that has been presented recently. The results are equivalent up to 1 kHz and within a relative expanded uncertainty of around 0.42 %.

Benyamin Heryanto Rusanto

TIME AT ELENIA

10/2017 – 04/2022

ACTIVITIES AT ELENIA

- Doctoral Student

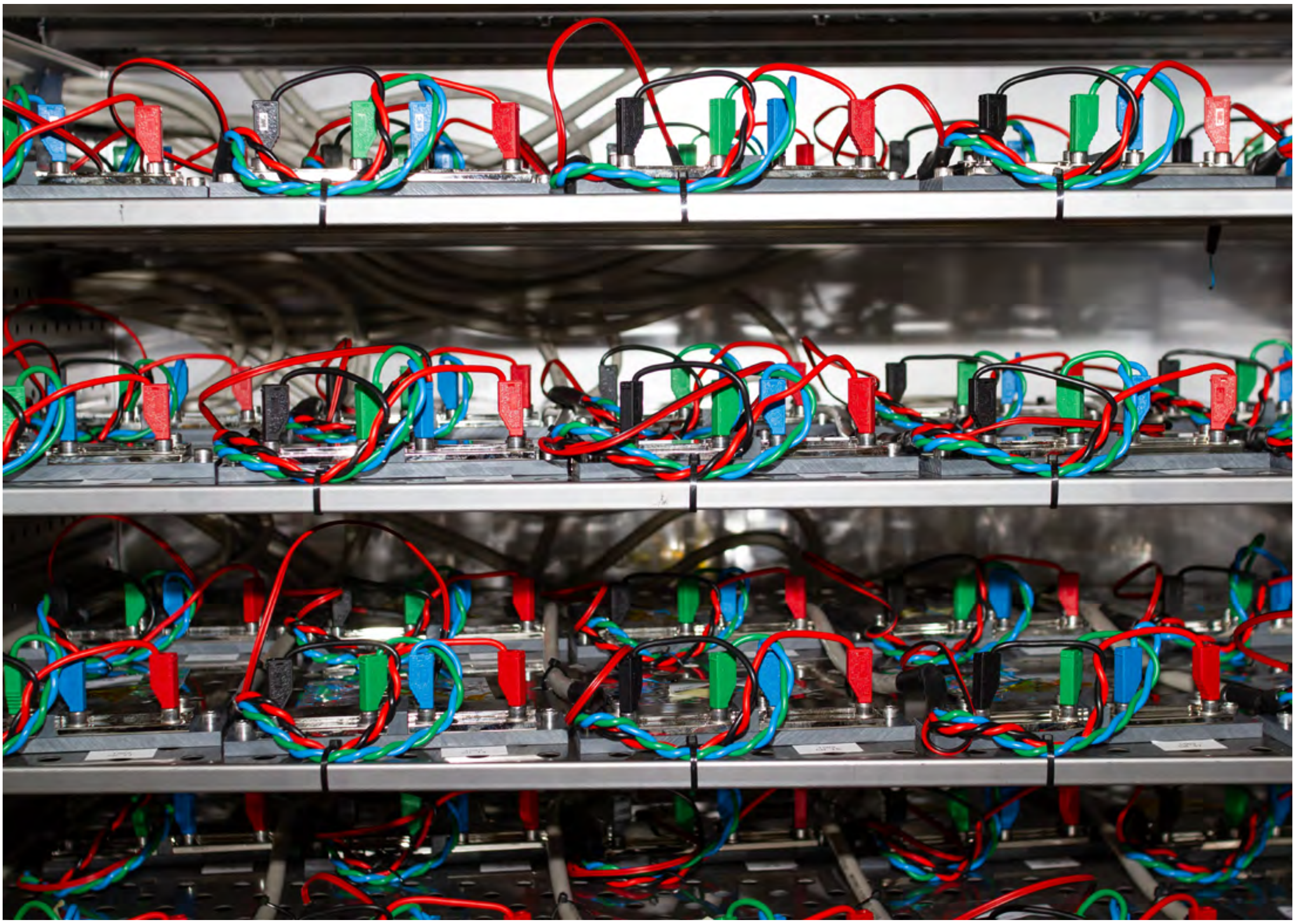
NOW WORKING AS

- Researcher at BMKG Calibration Laboratory

Labs and Workshops


BINDER

Battery Test Laboratories



CONTACT PERSON

Oliver Landrath, M.Sc.
o.landrath@tu-braunschweig.de
+49 531 391 7742

Anna Rollin, M.Sc.
anna.rollin@tu-braunschweig.de
+49 531 391 9734

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/batterieprueftechnik

TASKS AND SERVICES

- Cell production of 3-electrode cells
- Formation of battery cells
- Electrical characterization
- Ageing tests
- Modeling and simulation
- Post-mortem analyses using digital microscopy

Battery Test Laboratories at elenia

Testing and inspection options at cell, module and system level.

Battery technology continues to advance due to the increasing demand for electrical energy storage systems for mobile and stationary applications. As a result, the topic is increasingly becoming the focus of current research projects. Lithium-ion batteries play a key role here, as they can provide comparatively high energy and power densities as electrical energy storage devices. Their high efficiency and long-term stability also contribute to their pioneering position. Nevertheless, there is still great potential for research in the field of battery technology in order to meet the demanding requirements for these energy storage systems.

The elenia Institute for High Voltage Technology and Energy Systems has a large number of battery test facilities at various locations. Thematically, these can be differentiated as follows in terms of research focus:

In the Battery Test Laboratory (BatLab) in the basement of elenia, there are test systems for special three-electrode measuring cells, which have a lithium reference electrode in addition to the positive and negative poles. This makes it possible to electrically characterize the electrodes separately. Since the beginning of 2020, these cells can be produced in a glovebox under an argon atmosphere. Current research work is focusing on the model-based design of fast-charging strategies for different cell material systems, among other things.

At the Battery LabFactory Braunschweig (BLB) and the associated hall (formerly the Institute of Energy and Systems Process Engineering, InES), the focus is on investigations with large-format cells without a reference electrode. This mainly involves testing cells manufactured in the pilot line, but also commercial cells or cells provided by project partners. Current research activities include the influence of formation on cell performance, electrical and electrochemical characterization for quality assessment and long-term cycling to identify ageing mechanisms.

In our laboratories at the Physikalische Bundesanstalt Braunschweig (PTB), the focus is on the module and system level. The focus of the investigations is on battery module and system diagnostics. Current projects include the characterization of battery modules to identify their suitability for second-life applications. Furthermore, electrical and thermal safety tests are carried out at cell and module level.

A wide range of battery testing equipment is available at the four locations for the various tests. The portfolio includes equipment from Ametek, BaSyTeC, Digatron, EL-Cell GmbH, Gamry Instruments and Greenlight. Temperature test chambers with a wide temperature range are available to guarantee constant ambient conditions during the tests. To ensure a safe test environment, in addition to an F90 temperature cabinet and the battery testers, all test benches have comprehensive safety equipment that takes effect in the event of a battery thermal runaway. This consists of a cabinet extinguishing system from Wagner as well as an exhaust air system and a multi-stage emergency filter from Stöbich technology. According to the EUCAR hazard classification for battery faults, it can be used to test up to Hazard Level (HZ) 5.

The battery test systems can be used to load lithium-ion batteries of various formats with current and voltage profiles in order to characterize the electrical properties. So-called capacity tests are carried out at a constant current load in order to determine the energetic properties. Current rate, internal resistance and impedance measurements allow the electrical performance to be assessed. Periodic charging, discharging and storage cycles are used to record the decreasing available capacity and the increase in internal resistance. This enables the cyclical ageing properties of various materials or load procedures to be derived. In addition, the results of these ageing studies have been supported by post-mortem analyses since 2021. This involves opening and microscoping the cells in an inert gas atmosphere. Using special methods such as differential voltage analysis and electrochemical impedance spectroscopy, various causes of battery ageing can be determined. In addition, calendar ageing in safety cabinets is the subject of investigation, e.g. to determine the self-discharge over a certain period of time or to quantify the influence of calendar ageing using various electrical characterization tests.

In addition to the classic test procedures for determining the electrical properties of battery cells, special pulse methods are also used to parameterize battery models with the help of battery test systems. The focus here is on electrical equivalent circuit diagram models, which allow the electrical behavior of the battery to be simulated. As with the other battery test methods, care must always be taken to ensure that the batteries are tested under constant and identical environmental conditions. Several temperature chambers with a wide temperature range are available for this purpose. These also allow the battery models to be parameterized depending on the permissible operating temperature. With the help of electro-thermally parameterized battery models, the use of the tested battery cells can be checked for different areas of use and applications.

GLOVEBOX FROM M. BRAUN

Provision of a workstation in an argon protective atmosphere

- 0,8 m³ box volume
- Airlock furnace up to 120 °C

KEYENCE DIGITALMIKROSKOP VHX7000

Optical investigations of electrode materials

- 20 × – 2500 × magnification 3D measuring software

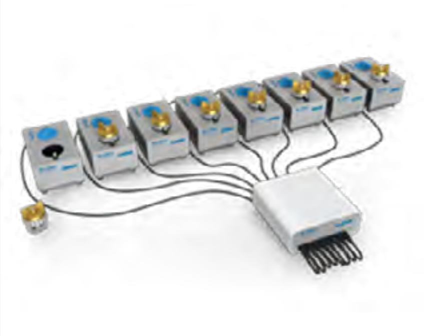
TEMPERATURE TEST CABINETS

Provision of a defined and constant test environment

- 6 × KB 420/S*, KB 700/S*
  - Test volume 6 × 420 l und 2 × 700 l
  - -5 °C bis 100 °C
- MK 240/S*
  - Test volume 240 l
  - -40 °C bis 180 °C
- 2 × BF 115
  - Test volume 112 l
  - 30 °C – 100 °C

TEMPERATURE TEST CHAMBERS FROM WEISS AND VÖTSCH

- Test volume 600 l und 34 l
  - -40 °C bis 180 °C und -20 °C bis 80 °C
  - S* incl. cabinet extinguishing, exhaust air and emergency filter



3-ELECTRODE CELL TESTER FROM EL-CELL

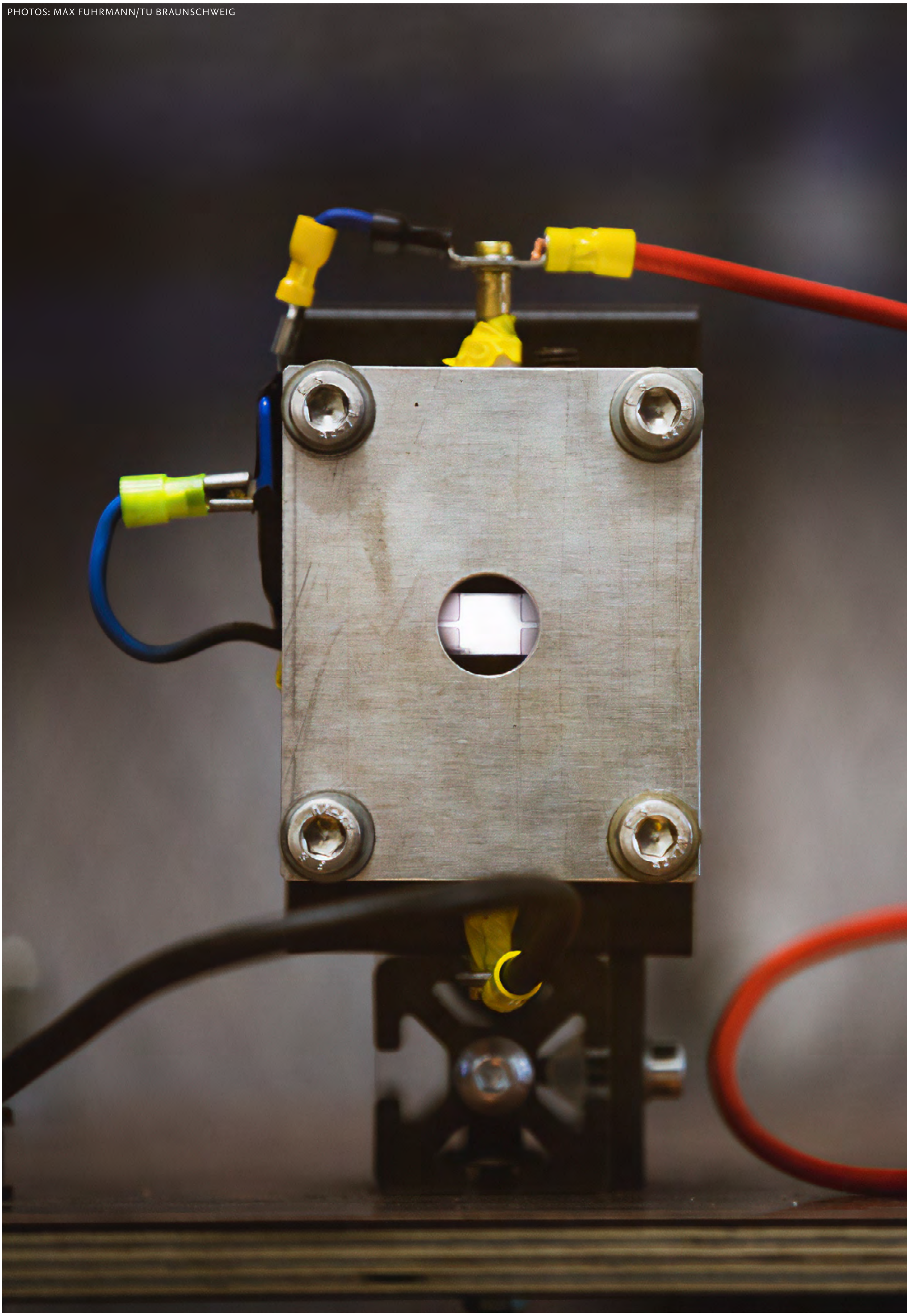
- Test system for three-electrode measuring cells
- 32 channels ± 0,1 A, 0–6 V, EIS
- 8 docking stations for other cell testers

CELL TESTER FROM BASYTEC

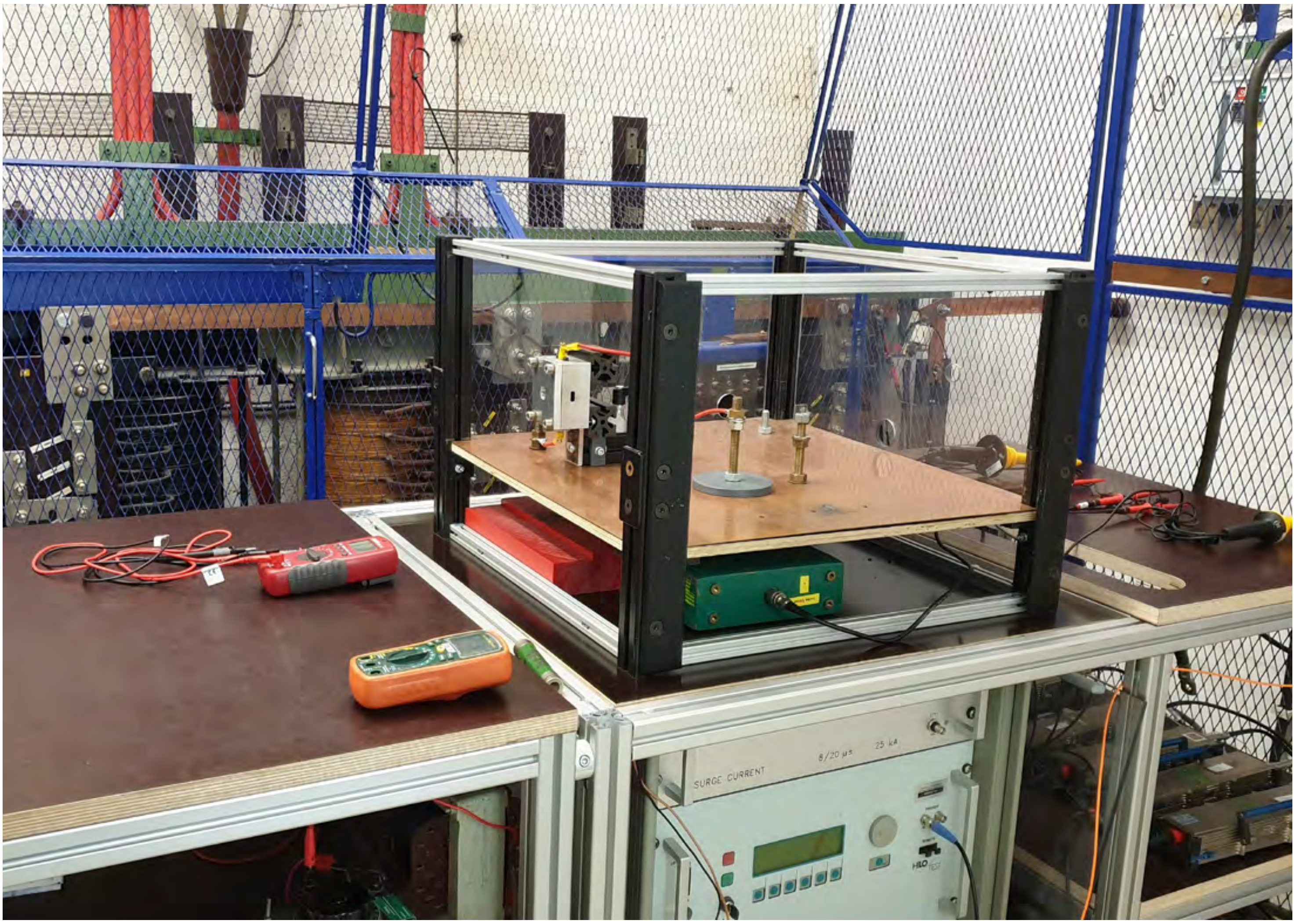
Test stand for cell tests

- 48 Channels ± 50 A, 0–6 V, parallel connectable
- 48 Channels ± 25 A, 0–6 V, parallel connectable
- 52 Channels ± 20 A, 0–6 V, parallel connectable
- 90 Channels ± 5 A, 0–6 V, parallel connectable
- 3 Channels ± 30 A, 0–150 V, parallel connectable

PHOTOS: MAX FUHRMANN/TU BRAUNSCHWEIG



Lightning Protection Laboratory



CONTACT PERSON

Enno Peters, M.Sc.
e.peters@tu-braunschweig.de
+49 531 391 7701

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/blitzschutzlabor

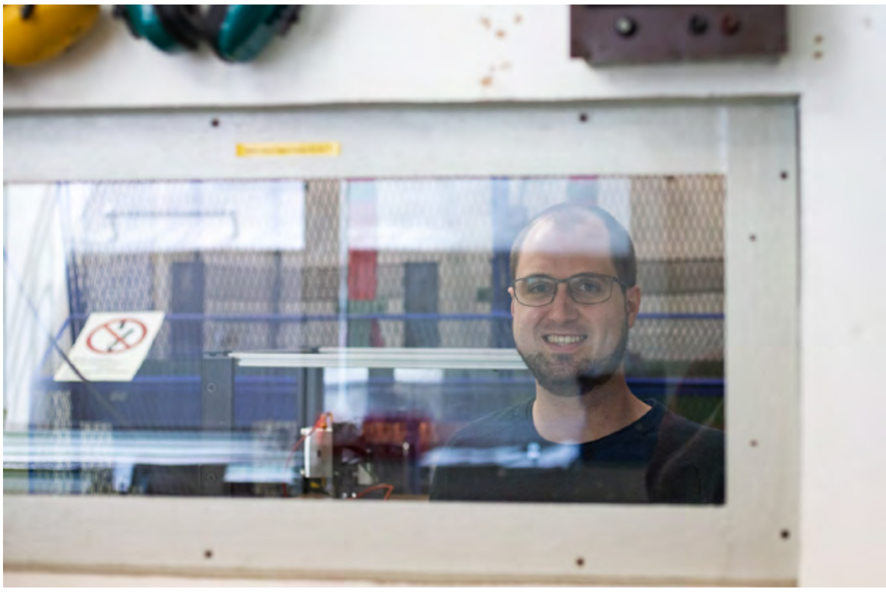
TASKS AND SERVICES

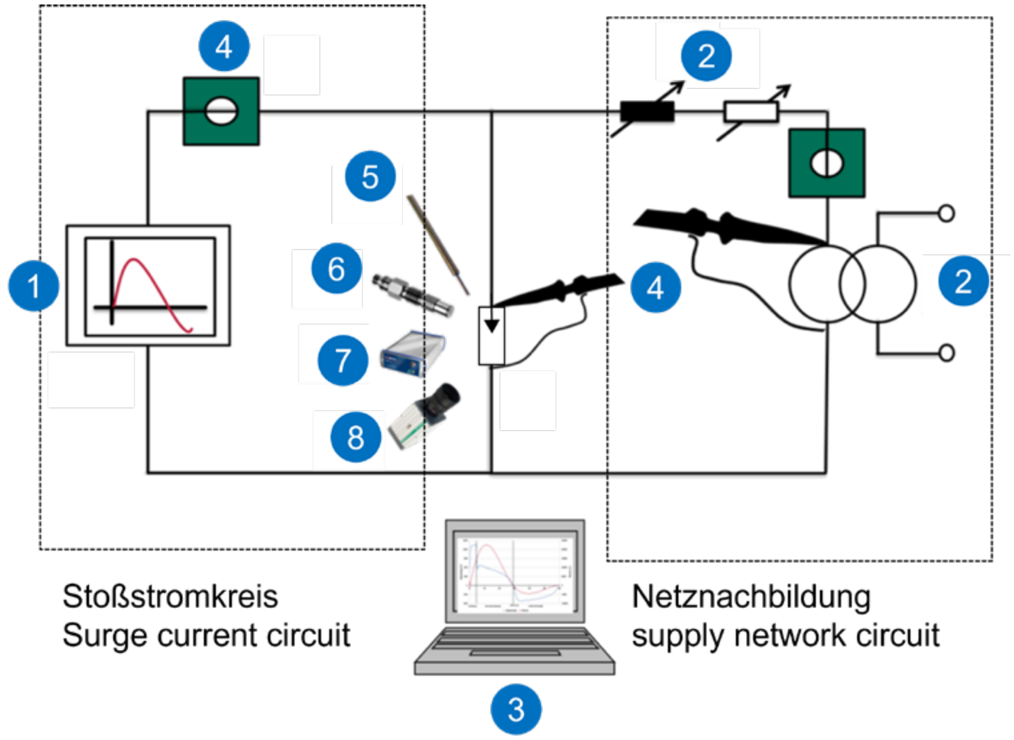
- Measurements on the low-voltage grid with voltages from 50 V to 750 V
- Prospective short-circuit currents up to 15 kA at 250 VAC
- Investigation of spark gap arresters with surge currents up to 25 kA (8/20 µs) or 600 A (10/350 µs)
- Various mains synchronization angles, triggering of the surge current to 1° Accuracy
- Measurement of transient plasma properties (pressure, temperature and conductivity)

Lightning Protection Laboratory

AC power test field with high short-circuit power and surge currents of up to 25 kA

Surge protectors (Type 1) are used as a primary protective mechanism to ensure the uninterrupted operation of electrical and electronic devices. They limit the occurrence of surges resulting from lightning strikes or switching operations in the grid. In surge protectors based on spark gap technology, exceeding a characteristic overvoltage leads to the formation of plasma between two electrodes. This plasma creates a momentary short circuit to the grounding system, establishing a low-impedance potential equalization and enabling the safe dissipation of high energies. Due to the short circuit to the grounding system, interactions occur with the connected power supply network, allowing a network-induced short-circuit current to flow through the plasma path (so-called network follow-up current). This network follow-up current should extinguish as quickly as possible after the successful discharge process, so that the upstream fuses or circuit breakers do not need to actuate. Various impulse voltage and impulse current generators are available at elenia for the investigation of surge protectors. Particularly noteworthy is the „lightning protection laboratory“. In addition to an impulse current, a low-voltage supply can be connected in parallel. The low-voltage network is connected to the medium-voltage network at the 6 kV level via three power transformers. This enables the investigation of both the impulse current and the network follow-up current. Figure 1 shows the simplified schematic diagram of the laboratory. In addition, a special test circuit for investigating re-solidification has been set up. This test circuit is based on a capacitor-based current source connected to the surge protector via a high-impedance resistor. This allows a measuring current in the range of 100 mA to flow through the still heated residual plasma path immediately after the current zero crossing in the spark gap. This enables the analysis of the plasma properties specifically after the high-current phase. The impulse current is generated using an impulse current generator (1). 8/20 µs impulses with up to 25 kA, but also 10/350 µs impulses with up to 600 A, can be generated. The grid feed is realized via three parallel-connected 130 kVA transformers (2). Resistance and inductance banks are available for adjusting the ohmic-inductive ratio of the grid emulation (2). In these very rapid plasma processes, stable and time-discrete measurement technology is necessary. For this purpose, measurement probes with a sampling rate of 100 MS/s are available. The measurement probes are optically isolated connected to the measurement system via optical fibers (3). Additionally, additional sensors are available, such as Pearson probes, high-voltage probes (4), potential probes (5), pressure sensors (6), spectrometers (7), and a high-speed camera (8). The current research goal is to investigate the transition from highly conductive plasma to the insulating state after the impulse current load. Using the measurement technology described in Figure 1, these experimental investigations take place. Precision mounts are available in the laboratory for these investigations, which facilitate the optical alignment of the camera to the combustion chamber of the model spark gaps. The research enables the modeling of spark gap arresters and thus a targeted development of surge protection.





OVERVIEW OF THE EXPERIMENTAL FIELD FOR DETERMINING THE PLASMA PROCESSES

1.) Surge current generator EMC 2004
2.) Low-voltage network up to 750 VAC with adjustable network impedance
3.) Connection of measuring system to PC
4.) Voltage and current measurement
5.) Conductivity via potential probes
6.) Pressure measurement
7.) Spectroscopy
8.) High-speed camera

HIGH-SPEED CAMERA NOVA S6 FROM PHOTRON

High-speed camera for analysing plasma distribution

- Resolution up to 1024 × 1024 pixels
- Black and white recordings
- Maximum frame rate of 800 kfps
- Minimum exposure time of 200 ns
- External triggering possible

SURGE CURRENT GENERATOR EMC 2004

Surge current generator for generating partial lightning currents

- Max. Charging voltage of 10 kV
- Max. Energy 1500 Ws
- Various waveforms possible
- Max. Surge current of 25 kA
- External control possible


AC
Engineering GmbH
DC
RÜCKLAUF
DC
ES Engineering GmbH
RÜCKLAUF
DC
DC

DC Demonstration Grid Laboratory

CONTACT PERSON

Lars Claaßen, M.Sc.
l.claassen@tu-braunschweig.de
+49 531 391-9715

Patrick Vieth, M.Sc.
p.vieth@tu-braunschweig.de
+49 531 391-9725

WEBSITE

www.tu-braunschweig.de/elenia/forschung

TASKS AND SERVICES

- Investigation of dynamic state changes in the grid
- Development and testing of DC protection systems
- Investigation of the switching characteristics of commercially available DC switching devices
- Investigation of DC network topologies
- Characterization of various operating and fault scenarios in a variable grid structure
- Development of a new type of DC protection system

DC Demonstration Grid Laboratory

Investigation of cross-voltage-level DC networks with variable source and load characteristics

The ongoing energy transition in Germany and technical advances in the field of modern power electronics mean that DC technology is becoming increasingly important in the industrial sector as well as in energy transmission and electromobility. And for good reason: energy transmission and distribution offers a wide range of application benefits such as efficiency advantages, material savings and the possibility of easily integrating renewable energies and storage. On the other hand, it also brings with it new challenges and questions that need to be answered in order to ensure safe use. The DC-laboratory at elenia enables the investigation of a wide range of grid topologies through a flexible, quickly adaptable setup and a wide range of different source and load characteristics. Two voltage levels (0-380 V and 1 kV) are already in use. A medium-voltage level (± 1.5 kV DC) will be added to the setup by the end of 2023.

Structure, components and goal of investigation

The DC-laboratory offers a wide range of tests for investigating DC grid topologies. The planned overall setup, including the performance data for all voltage levels and a detailed description of the laboratory components, can be found in the table on the next page. The DC-laboratory is currently working on general grid characterization and modelling for DC grids. The largest possible test space is achieved by using a wide range of variable load impedances and active source and load components. A DC protection system is also being developed and investigated in various fault scenarios. In addition to current and voltage, the time constant, grid topology and internal regulation of selected sources and loads can also be adapted. Another advantage is that additional equipment can be easily integrated into the existing setup. The measurements carried out are recorded using state-of-the-art measurement technology. Grid-states during dynamic load changes as well as switching operations and the reaction of the protection system can therefore be precisely analyzed.

Expansion of the existing network structure

The existing voltage levels will be supplemented in future by a further voltage level (± 1.5 kV DC). This will significantly expand the range of applications that can be simulated. The preparatory measures for this have already been completed with the installation of the MVDC control cabinet and the AFE power modules. The delivery of the DC/DC converter for connection to the medium-voltage level is due at the end of the year. This will be installed alongside the AFE power modules in a modular plug-in design in the MVDC control cabinet.

The test field in its design as a real grid structure spanning different voltage levels is a unique selling point of elenia.

LVDC CONTROL CABINET WITH LVDC-AFE & DC BUSBAR

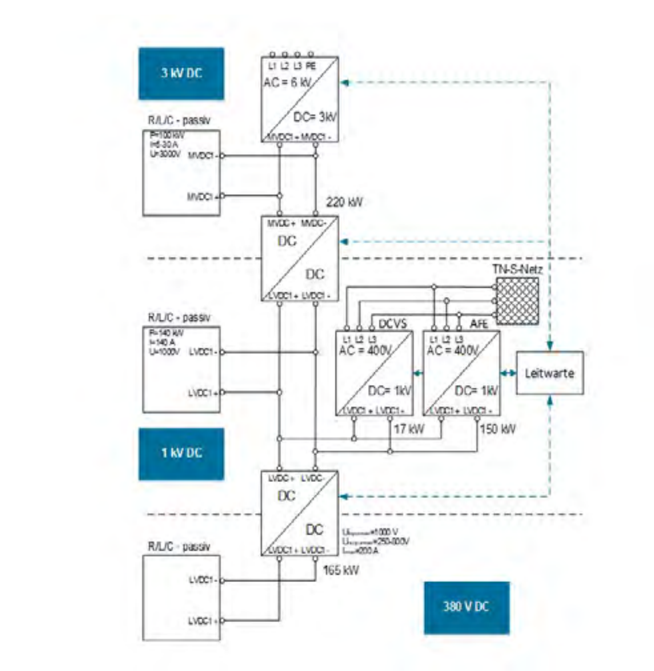
Coupling and protection of the low-voltage components

- Connection of low-power loads and a plug-in system for topology formation via string circuit-breakers
- DC circuit breakers protect DC/DC converters to the subordinate, variable LVDC voltage level
- LVDC-AFE can be used as a sink in regenerative mode
- Integration of a braking resistor

LVDC CONTROL CABINETS WITH PASSIVE LOADS & CONTROLLED VOLTAGE SOURCES

Simple construction of variable grid topologies via a PV plug-in system

- Simulation of a variety of DC on-board, industrial and distribution network structures
- Network characterization and modelling of DC networks using statistical test planning
- Development, investigation and optimization of innovative DC protection systems with a focus on switchgear coordination in the event of current faults



COMPLETE NETWORK OVERVIEW AS BLOCK DIAGRAM

Structure and core functions

- Three grid levels (3 kV, 1 kV & < 1 kV variable)
- MVDC-side connection of the test field directly to the 6 kV AC medium-voltage grid of TU Braunschweig
- LVDC-side connection via AC low-voltage grid
- Two active front ends (AFE): one each in the MVDC and LVDC levels
- Coupling of the voltage levels via DC/DC converters
- Bidirectional power supply of the levels
- Additional supply of the LVDC levels via controlled voltage sources (DCVS)
- A wide range of applications can be simulated by combining the operating resources
- Control and monitoring of all laboratory components via central control room
- Variable test duration and parameters can be set via digital sequence control

CONTROL CARD OF THE MVDC CONTROL CABINET

Central monitoring and control of laboratory components

- Connection of the control cabinets to the control room via CAN / CAN FD
- Manual and automated control of the protection technology
- Setting the relevant control parameters
- Transmission of measured values for monitoring & recording to the control room & elenia server

MEDIUM-VOLTAGE CONNECTION

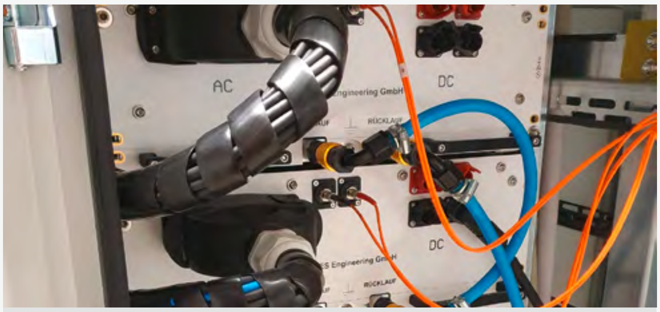
Upgrading the medium-voltage outgoing circuit with protection technology

- Connection: 6 kV AC - medium-voltage network of the TU Braunschweig
- Fuse protection of the medium-voltage transformers: 63 A
- Fuse protection of the laboratory outgoing circuit: 31.5 A
- Additional protection via two VD4 vacuum switches directly in the laboratory and at the outgoing circuit to the laboratories

MEDIUM-VOLTAGE TRANSFORMER

Supply of the AFE power modules from the medium-voltage grid

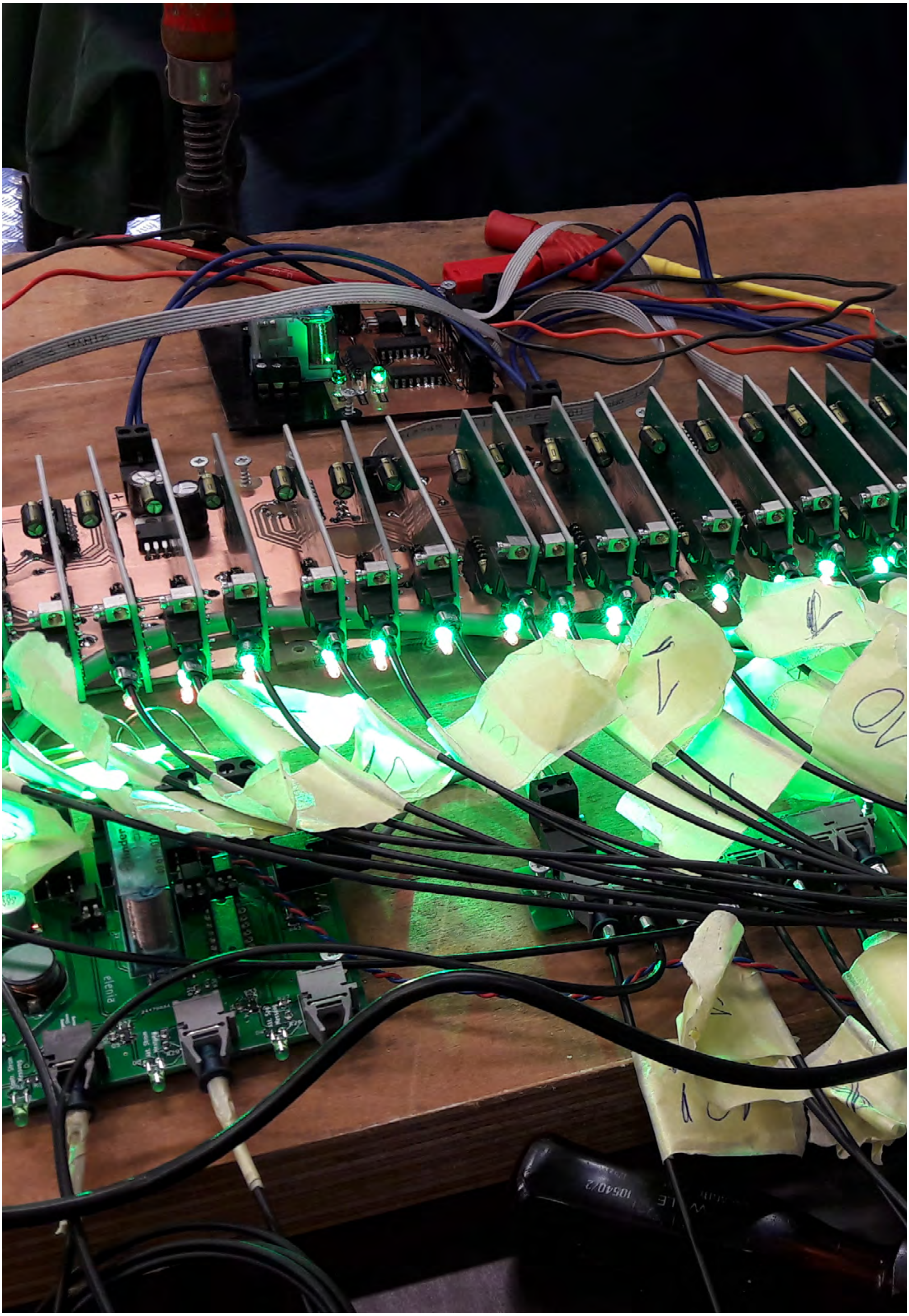
- Rated power: 220 kVA
- Primary side: 6 kV AC
- Secondary side: 4 windings á 375 V AC
- Switching group: Dyn5



MVDC-AFE POWER MODULES

Filtering and rectification of the AC voltage

- Input voltage per module: 375 V AC
- Output voltage per module: 750 V DC
- Integrated EMC filters and chokes
- Symmetrical connection of the modules: ± 1.5 kV DC
- Rated power per module: 50 kW
- Total power: 200 kW



DC-Test Facilities

CONTACT PERSON

Dirk Bösche M.Sc.
d.boesche@tu-braunschweig.de
+49 531 391 7745

TASKS

- Development and optimisation of DC switches.
- Investigation of switching properties of commercially available DC switchgear.
- Investigation and development of hybrid switchgear.
- Insulation coordination and investigation of switching processes at low air pressure.

PERFORMANCE DATA

- Power: up to 18 MW
- Nominal voltage: up to 12 kV
- Testing current: up to 30 kV
- Supply from the 6 kV universal or 20 kV public grid

DC-Test Facilities

Laboratory for the research and development of DC switchgear for a successful energy transition

In addition to the expansion of renewable energies, one component of the energy transition is the reduction of consumption. Especially in industrial applications, the advantages of direct current networks over classic alternating current networks become clear. Efficiency increases as a result of a changeover, also because direct current grids can absorb energy generated in the process. The trend here is towards ever higher voltage levels. As a result, the demands on the switchgear, which have to guide and interrupt the operational currents, are increasing. In order to develop and test these switchgears, suitable test equipment is essential. These must be able to provide the required currents and voltages. For this reason, the new high-performance DC test field was built in the institute's high-voltage hall during the Universal Power Switch project. It impresses with its performance data and can provide a wide range of test voltages at low ripple and high currents. The maximum DC voltage is 12 kV and the maximum current provided is 30 kA. However, this cannot be accessed at all voltage levels, but is limited by the connected grid at 18 MW. Essentially, the primary equipment consists of the medium-voltage switchgear, the two test transformers and the rectifier including circuit breakers.

Medium-voltage switchgear

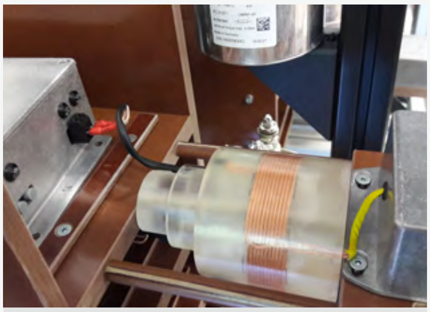
The power supply of the high-performance DC test field is ensured by an in-house switchgear. This has two different feed-in options. On the one hand, the university's 6 kV network can be accessed without prior registration. However, the connected load is much lower than with the 20 kV connection, which is also available. However, the release by the network operator is only granted after prior registration. Then the maximum power of 18 MW can be extracted. The system is protected by a short-circuit current limiter (IS limiter), also in order to minimize possible grid feedback.

Test Transformers

The medium-voltage switchgear feeds into two test transformers. Both secondary sides are connected in Y-connection and have two separate windings per phase. These have a large number of taps, which can be connected almost arbitrarily by means of quick adjustment. As a result, a variety of voltages can be set. On the primary side, one transformer is connected in Y and the other in delta. This achieves a phase rotation of 30°, which allows the use of a B12 rectifier.

Rectifier

The two transformers provide a six-phase system for the rectifier. In each case, one transformer feeds one of the two B6 bridges connected in series. The upstream circuit breakers act as a safety switch and disconnect the rectifier from the mains after each test run. The entire test sequence is ensured by a programmable digital sequence control.

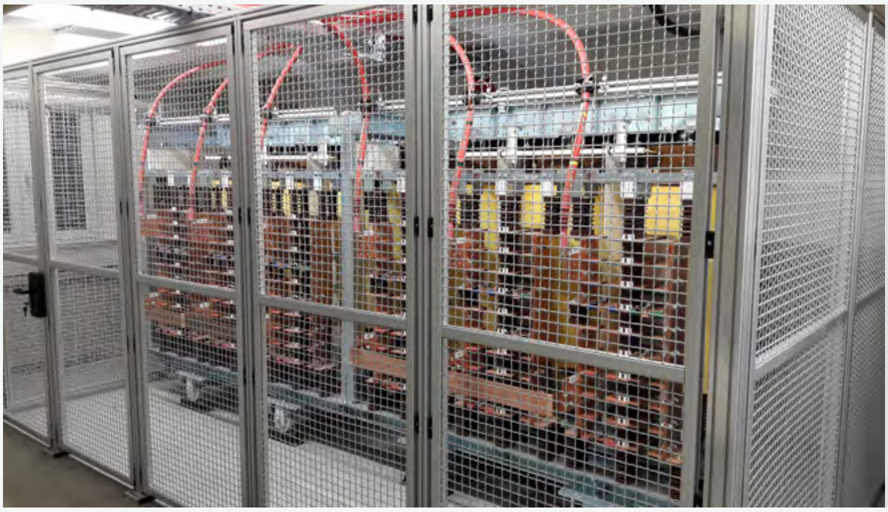


HIGH FREQUENCY TRANSFORMER TO SUPPLY THE THYRISTOR DRIVERS

B12 RECTIFIER INCLUDING UPSTREAM CIRCUIT BREAKER

- Max. current 30 kA
- Max. 12 kV

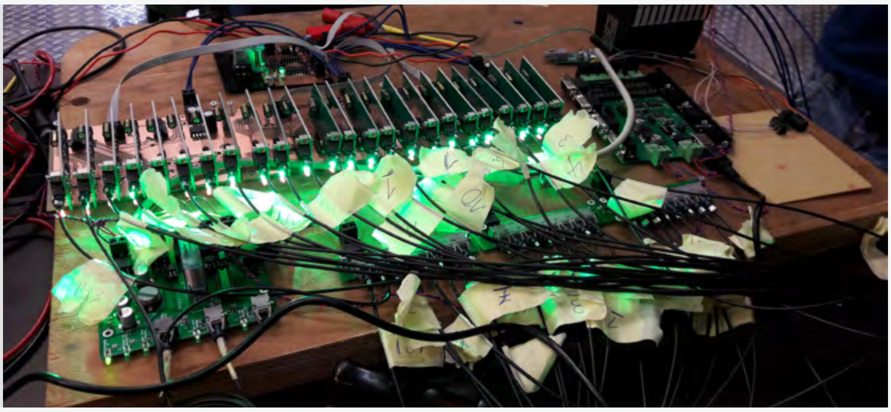
SUBSTATION FOR CONNECTION TO THE 6 KV UNIVERSITY NETWORK OR 20 KV NETWORK OF THE MUNICIPAL GRID OPERATOR.



TEST TRANSFORMERS WITH TAPS AND QUICK ADJUSTMENT FOR SETTING THE DC VOLTAGE

- Power 1155 kVA
- Short-term power 11258 kVA
- Groups Diii(y) & Yiii(y)
- Year of construction 2021
- Total weight per transformer approx. 6800 kg

CONTROL DURING INITIAL COMMISSIONING



High Voltage Laboratory

CONTACT PERSON

Karen Flügel, M.Sc.
k.fluegel@tu-braunschweig.de
+49 531 391 7785

Timo Meyer, M.Sc.
timo.meyer@tu-braunschweig.de
+49 531 391 9739

WEBSITE

www.tu-braunschweig.de/elenia/forschung/hochspannungshalle

TASKS AND SERVICES

- High voltage measurements (flashover/discharge) with AC, lightning impulse and DC voltage on model structures or prototypes in accordance with IEC 60060-1
- Partial discharge measurements and interpretation on low-, medium- and high-voltage models and components, if necessary in accordance with IEC 60270
- Dielectric material tests such as dissipation factor, relative permittivity and volume resistances at variable frequencies and temperatures
- Various high-speed cameras are available for the visualization of discharges

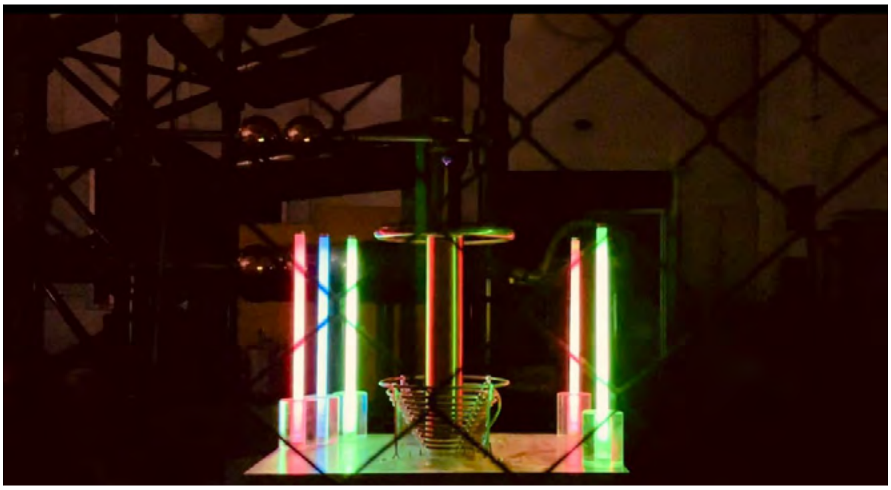
High Voltage Laboratory

The investigation of the insulation properties of power system components requires high voltages.

The institute's high-voltage laboratory offers many testing options. The large test field contains two systems for high-voltage generation of AC and impulse voltage, the modular construction system for setting up various generation and measurement circuits and the electrically shielded partial discharge measurement cabin. The large test field offers the classic high-voltage tests for examining electrical strength, including the use of the Greinacher cascade, which generates a DC voltage from an AC voltage on the input side, allowing three voltage forms to be generated in the large test field. This allows, for example, high-voltage insulators, switchgear or complex insulation systems to be tested for their electrical strength under different conditions. The voltage amplitudes that can be achieved are up to 800 kV for AC and DC voltage and up to 2 MV for lightning impulse voltage. In addition, a wide range of circuits in the voltage range up to around 300 kV can be constructed using the modular system that is also available. In addition to generation, appropriate measuring devices and voltage dividers are also required. Here, too, there is a suitable divider for every voltage form and level, be it the damped capacitive (Zaengl) divider suitable for up to 2 MV, various capacitive dividers up to 400 kV, resistive dividers up to 200 kV or installed in the Greinacher cascade up to 800 kV. The voltages can be transmitted potential-free via measuring satellites of transient recorders, thus ensuring the safety of the experimenters.

In addition to generation and measurement, the right experimental vessel is also required for correct investigations. Countless setups are already available and new ones can be manufactured in the institute's workshop. These include a cryostat for investigations up to $\hat{U}$ = 200 kV at temperatures of -190 °C in liquid and gaseous nitrogen with options for visual observation of the discharge via high-speed cameras and sight glasses, as well as irradiation of the set-up. Alternatively, investigations can also be carried out in a vacuum test vessel with up to 400 kV at 10^{-5} mbar. Current investigations in this test vessel are used for the optical observation of breakdowns during tests with lightning impulse voltages. In the partial discharge measurement cabin, which is protected with mains filters against mains-side interference and electrically shielded, a partial discharge measurement system for partial discharge measurements from 1 pC and a parallel test system with 10 measuring stations are available. A setup for generating high-frequency voltages is also available in the PD cabin. It can be assumed that high-frequency interference will become more relevant in the future, particularly due to the use of power electronics.

In order to inspire enthusiasm for high-voltage technology at an early stage, a number of show experiments were set up. As part of lectures or the Future Day, guessing the musical pieces, which were impressively reproduced by the music Tesla, or experiencing electrostatic charging, which makes hair stand on end, on the tape generator were well received.



Music-Tesla

Impression from the test field during impulse voltage tests

IMPULSE VOLTAGE GENERATOR

- Surge voltage generator for switching and lightning impulse voltages with 400 kV / 50 kJ (up to 2 MV possible)
- Load capacity and resistors adjustable for standardized 1.2/50 pulses
- Damped capacitive divider up to 2 MV

AC VOLTAGE TRANSFORMER

- 50 Hz AC voltage transformer up to 400 kV / 400 kVA (up to 800 kV possible)
- Compressed gas capacitor for voltage measurement

PARTIAL DISCHARGE MEASURING CABIN

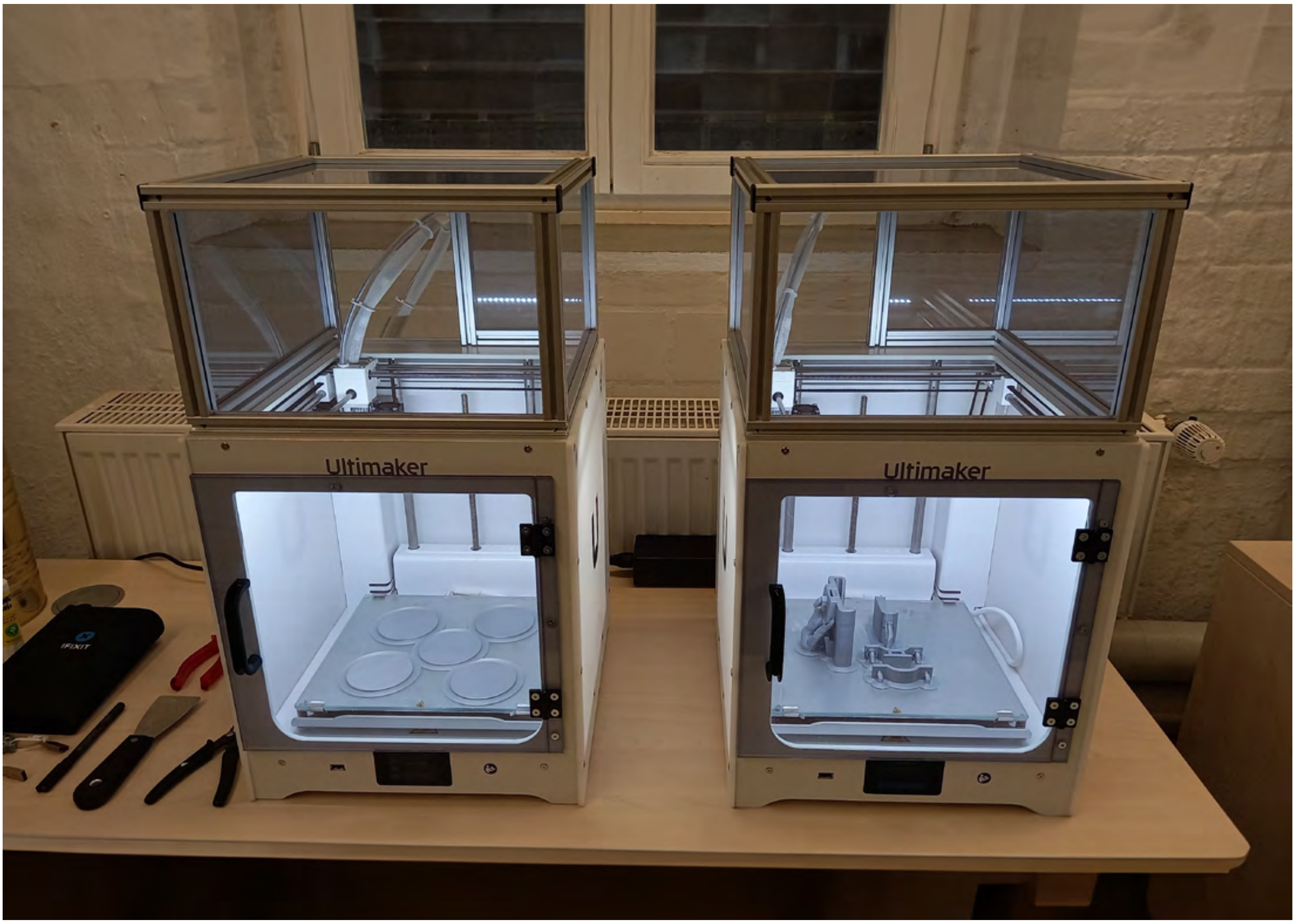
- Partial discharge test bench for AC voltages up to Û = 100 kV and basic interference level < 500 fC - 1 pC, at temperatures up to 150°C
- Parallel test system for breakdown tests in oil and air

HIGH-VOLTAGE MODULAR SYSTEM

- 50 Hz AC voltage transformer up to 200 kV
- Various modular components consisting of capacitors, resistors and diodes
- Cryostat up to -190 °C and approx. 200 kV up to 3 bar absolute pressure
- Vacuum test vessel up to 400 kV at 10^{-5} mbar with sight glasses


formlabs

Insulating Materials Laboratory



CONTACT PERSON

Maik Kahn, M.Sc.
m.kahn@tu-braunschweig.de
+49 531 391 7741

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/hochspannungstechnik

TASKS AND SERVICES

- Partial Discharge Measurements and Interpretation on Models and Components
- Dielectric Material Testing
- Long-Term Behavior of Insulating Materials
- Model Formation and Simulation
- Test Specimen Manufacturing

Insulating Materials Laboratory

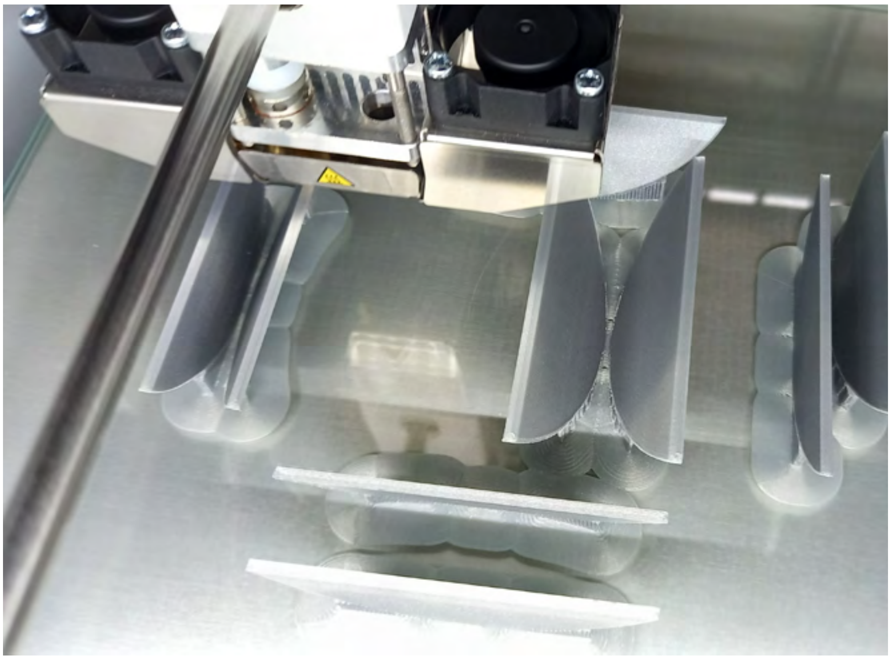
3D Printing in Insulating Material Technology: New Ways for Tailor-Made Solutions

Insulating materials, which are used, for example, in electromobility or high-voltage applications, are facing increasingly increasing requirements. In order to meet these requirements, new approaches and methods are required in addition to the conventional testing methods for insulating materials. These are intended to help improve the evaluation and service life estimation.

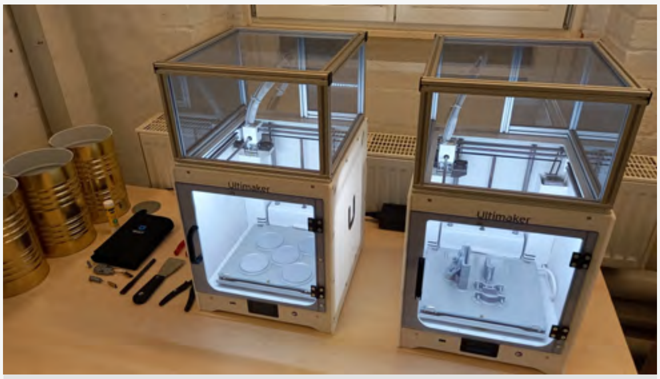
As part of our commitment to the continuous improvement of insulating materials used in critical applications such as electromobility and high-voltage technology, the insulating materials laboratory has been expanded and modernized. This includes the purchase of several 3D printers. Two of these printers are based on Fused Filament Fabrication (FFF) technology. In order to facilitate access to additive manufacturing for students as well, a workstation was set up. This enables seamless integration of the entire workflow, from CAD design to 3D printing hardware. Subsequent dielectric tests can be carried out directly after the printing process. In addition, a 3D printer with stereolithography (SLA) technology, which is based on liquid resin printing, was purchased. Here, the photosensitive liquid resin is cured by means of a laser beam with a high power density (250 mW). This also allows the use of various synthetic resins, including temperature-resistant, flexible, robust and transparent resins. To optimize the workflow, two additional devices for automatic cleaning and post-curing of printed components were also purchased.

Setup of an automated PD measurement under DC voltage load

The detection of partial discharges (PD) has been an integral part of quality assurance measures in the production and operation of high-voltage components for many years. Due to the current restructuring of the energy supply system towards decentralised feed-in and the increased integration of high-voltage direct current (HVDC) transmission systems into the transmission system, the need for partial discharge measurements under DC voltage conditions is increasing. For this reason, an automated test setup was developed for partial discharge measurement under DC voltage loading. Using the LabVIEW platform to automate measurements enables an efficient and reproducible measurement process. The targeted measurements that were carried out provide fundamental insights into the behavior of insulating materials under DC voltage loads. The developed automated control of partial discharge measurement opens up new possibilities for efficient partial discharge measurements under DC voltage conditions.



Production of test specimens in a 3D filament printer



3D PRINTER WITH FUSED LAYER PROCESS

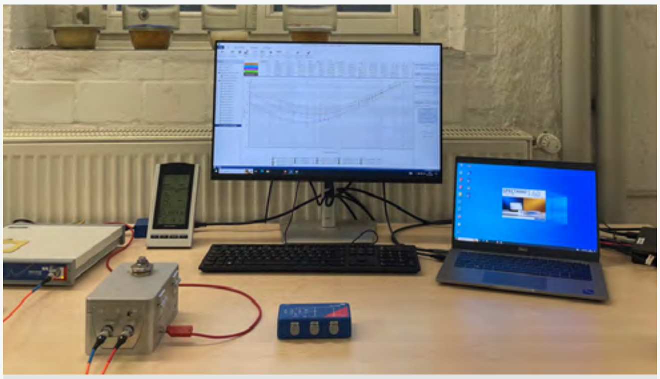
Test specimen construction for dielectric testing

- Single Extrusion
- Material: PLA
- Build volume: 223 x 220 x 205 mm
- XYZ resolution: 12.5, 12.5, 5 µm

3D PRINTER WITH STEREOLITHOGRAPHY

Test specimen construction for dielectric testing

- 250-mW-Laser
- Material: synthetic resin
- Build volume: 145 × 145 × 185 mm
- XYZ resolution: 25, 25, 25 µm



DIELECTRIC MATERIAL ANALYZER

Measurement of dissipation factor and relative permittivity

- Output voltage up to 200 V
- Frequency range from 5 µHz to 5 kHz
- PDC and FDS method
- Specimen Holder DSH100

DC VOLTAGE SOURCE UP TO 70 KV

Provision of high DC voltage

- Output voltage up to 70 kV
- Output current up to 3 mA
- Continuous short-circuit proof
- Remotely controllable and expandable through built-in analogue or (optional) digital interface

ELECTROMETER / HIGH RESISTANCE METER

Measuring device for measuring currents and resistances

- Output voltage up to 1000 V
- Current resolution of 0.01 fA
- Resistance measurement up to 10 PΩ


Wechsel-/Drehstrom 400V/230V
triphase
OPAL-RT
TECHNOLOGIES

Joint Laboratory

CONTACT PERSON

Marc René Lotz, M.Eng.
m.lotz@tu-braunschweig.de
+49 5331 939 4322 0

WEBSITE

www.tu-braunschweig.de/elenia/forschung/komponenten-der-energieversorgung/dc-systeme

TASKS AND SERVICES

- Validation of meshed DC systems with real-time simulation (HiL PHiL, RCP)
- Operation, control, and protection principles for MMC-based DC systems
- Modelling and simulation

Joint Laboratory

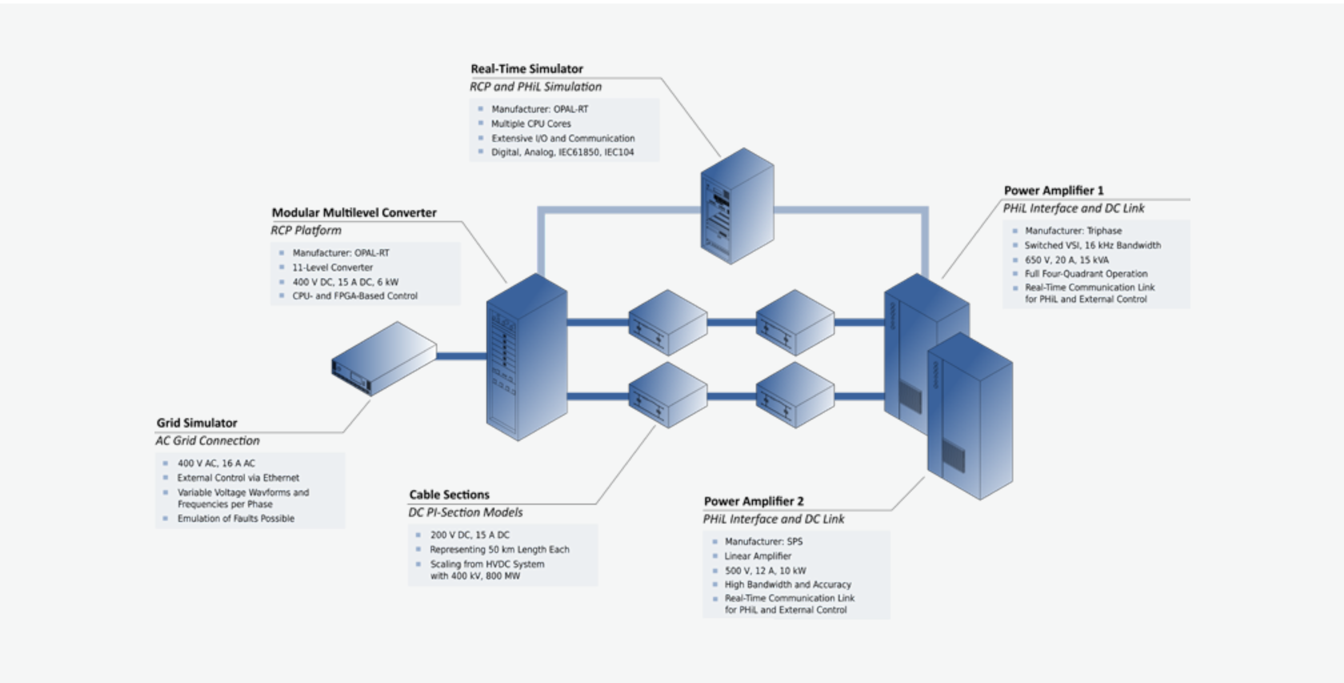
MMC-Based DC System for the Validation of Operation, Control, and Protection Principles with PHiL Simulations

The validation of meshed DC systems in the field of High-Voltage Direct Current (HVDC) Transmission is a major challenge due to the complexity of such systems. The main focus here lies on the validation of operation, control, and protection concepts, whereby the performance of the converter technologies used, including Modular Multilevel Converters (MMCs), is of particular importance. There is a great need for proof-of-concept with the help of prototypes in a laboratory scale. These prototype implementations form the link between simulation and realization on a large scale. The experiments can be carried out safely and under defined conditions in the laboratory. The results obtained in this way clearly support the validity of plain simulations.

Due to the complexity of the DC systems, not all system elements can be implemented in the laboratory. However, with the Power-Hardware-in-the-Loop (PHiL) simulation methodology, components can be simulated in real-time, while interacting with the actual hardware components. A power amplifier forms the interface. Simulated signals are converted into signals of higher power in order to excite the hardware components. As there is a close link within this area of research between the development and simulation of complex topologies, and the validation and implementation of laboratory-scale demonstrators, the elenia Institute for High Voltage Technologies and Power Systems has created a joint laboratory together with the Institute for Electrical Systems and Automation Technology (IfEA) at Ostfalia University of Applied Sciences.

The IfEA has a suitable laboratory infrastructure and focuses on the validation of DC systems with laboratory-scale prototypes, control and performance of MMCs, and concepts and applications of PHiL simulations. The real-time simulators and power amplifiers used are the key components. In the laboratory, the process of developing and validating PHiL experiments with real-time simulation of MMCs and DC systems is demonstrated. It is analyzed, how, especially the application of PHiL simulations, can support increasing the Technology Readiness Level (TRL) of new developments.

The focus of current work is on analyzing interactions between AC and DC systems, as well as protection and control principles for MMCs and DC grids. With the help of the flexible laboratory equipment, the stability and performance of concepts and topologies can be considered, such as the effects of requirements for Fault-Ride-Through (FRT) and dynamic voltage control, the comparison of grid-following and grid-forming concepts, as well as the validation of protection concepts and algorithms for DC systems. PHiL simulations are of great importance, as AC/DC systems, protection devices, and power electronics components can be simulated in real-time and connected to the hardware laboratory components via power interfaces.



MODULAR MULTILEVEL CONVERTER (MMC)

RCP Platform for the Validation of Operation, Control, and Protection Principles

- OPAL-RT OP1200
- 400 V DC, 6 kW
- 11 Level
- 5 kHz PWM Frequency

REAL-TIME SIMULATOR

Simulation of AC/DC systems and MMCs in Real-Time

- OPAL-RT OP5707XG
- Analog/Digital IO
- Communication protocols like IEC61850
- Interface with Power Amplifiers for PHiL Simulations

LINEAR POWER AMPLIFIER

Flexible Amplifier with High Bandwidth

- Spitzenberger und Spies
- 22,5 kW, 424 V DC
- > 52 V/µs Slew Rate
- Interface with Real-Time Simulator for PHiL Simulations

SWITCHED POWER AMPLIFIER

Amplifier with Full 4Q Operation

- Triphase PM15
- 15 kW, 650 V DC
- 16 kHz PWM Frequency
- Schnittstelle zu Echtzeitsimulator für PHiL

GRID SIMULATOR

Flexible AC Voltage Source

- 15 kVA, 350 V
- DC, as well as 30 Hz to 100 Hz
- Independently Controllable Output Phases

Performance Laboratory

CONTACT PERSON

Timo Meyer, M.Sc.
Timo.meyer@tu-braunschweig.de
+49 531 391 9739

Enno Peters, M.Sc.
e.peters@tu-braunschweig.de
+49 531 391 7701

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/synthetisches-leistungspruefeld

TASKS AND SERVICES

- Performance testing
  - Testing of circuit breaker up to U_N=72,5 kV
  - Short-circuit single-phase
- Contact geometry investigation
  - Investigation of innovative contact geometries
- Thermography investigation
  - Investigation of surface temperatures of different materials

Performance Laboratory

Synthetic generation of test conditions for circuit breakers of the medium and high voltage level

The institute's synthetic test field is used to research vacuum circuit breakers for the high-voltage level. For this purpose, short-circuit conditions to be switched, which represent the maximum stress on circuit breakers, are simulated synthetically in the test field.

To establish the vacuum circuit breaker at the high-voltage level, various options with two vacuum interrupter chambers connected in series or variable contact gaps are being investigated. A special vacuum switch was designed that allows variable contact gaps. Breaking tests are carried out on this vacuum interrupter. For this purpose, the switch is first stressed by a high short-circuit current. The switch is opened during the current flow and a metal vapor arc is formed. After this arc is extinguished, the switch is subjected to a damped voltage oscillation (transient transient voltage). The short-circuit current and the transient voltage are generated during a disconnection process in the grid, which can be triggered by a grid fault. A high-current capacitor bank is used to generate the short-circuit current. This bank is charged with a maximum voltage of 3 kV and thus generates a half sinusoidal current oscillation of maximum 63 kA (RMS) at a frequency of 35 Hz / 50 Hz.

The high-voltage capacitor bank generates the transient voltage, which is switched via a triggered spark gap just before the current zero crossing. The capacitor bank can be charged up to 150 kV. For safety reasons, the bank is charged with a voltage up to 90 kV. This results in a peak transient voltage of 140 kV. The remaining elements of the high-voltage circuit are modular, producing different voltage slopes and frequencies. The frequency of the transient voltage is between 5 and 40 kHz, which corresponds to the frequencies in the medium and high voltage levels during the fault case and even beyond to generate a larger stress for the switch.

The metal vapor arc generated during the tests is observed through a observation glass and a high-speed camera. Through this process, the arc is characterized and various model ideas are verified. In many contact geometries, such as the transverse magnetic field (TMF) contact, the arc rotates at a very high speed up to 1000 m/s on the contact piece surfaces, resulting in different phenomena. These fast phenomena are displayed by the high resolution (1024 x 1024) and a maximal frame rate of 800 kfps of the camera.

In order to test new contact geometries as well as individual shielding and control arrangements for vacuum applications, temperatures up to 1200°C are generated in a hinged tube furnace under vacuum. Ceramics with diameters up to 200 mm can be soldered.

SINGLE-PHASE SYNTHETIC TESTING OF CIRCUIT BREAKERS

High current (left) / high voltage (right) capacitor bank

- Max. current 63 kA(RMS)
- Max. 140 kV TRV
- Circuit frequency: 35 Hz / 50 Hz
- TRV-frequency: 5 to 40 kHz

CARBOLITE GERO TS1

Free-standing hinged tube furnace for vacuum brazing of test assemblies and contact pieces

- Usable diameter 200 mm
- Temperature until 1200°C
- Temperature gradients freely selectable

VACUUM TEST SWITCH

Investigation of plasma phenomena between switching contacts possible

- Custom vacuum recipient
- Vacuum pump ($p < 10^7$ mbar)
- Variable gap up to 2 × 40 mm
- Series connection of 2 circuit breakers possible

NOVA S6 BY PHOTRON

A high-speed camera is available for visual examination of the arcs:

- Resolution up to 1024 × 1024 pixel
- Black and white images
- Maximum frame rate 800 kfps
- Maximum integration time of 200 ns


10 M Ω
250 W
PHENIX
TECHNOLOGIES
1200 pF

Partial discharge measurement equippment in shielded cabine for PD-measurement

CONTACT PERSON

Maik Kahn
m.kahn@tu-braunschweig.de
+49 531 391 7741

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/hochspannungstechnik

TASKS AND SERVICES

The research focuses on the study of partial discharges (PD) under DC voltage loading to better understand the performance of insulating materials in modern power transmission systems. An automated experimental setup was developed to precisely measure partial discharges under DC voltage conditions.

PD-Diagnostics

Setup of an automated partial discharge measurement at DC voltage load

Partial discharges do not only occur under AC voltage load, but can also be observed under DC voltage load. Due to the different behaviors of partial discharges under these two types of loads, the measurement and analysis of each requires specific approaches.

The further development of partial discharge measurement at elenia contributes to a more in-depth investigation of the performance of insulating materials in modern energy transmission systems. This allows for a better evaluation of the stability and reliability of these systems. As a result of these advances, an automated experimental setup was developed to measure partial discharges under DC voltage loading. Using the LabVIEW platform to automate these measurements enables a highly efficient and reproducible measurement process. The developed automated control of the partial discharge measurement thus opens up new possibilities for efficient partial discharge measurements under DC voltage conditions. This setup consists of a source for DC voltage and a suitable partial discharge measurement system. The automated program offers the possibility of applying tension ramps with variable steepness and inserting rest periods between voltage changes. This makes it possible to analyze PD events under both dynamic and static conditions.

Despite some challenges, such as the non-detection of some PD events at high event density and the influence of an offset on the voltage measurements, the results of exemplary measurements confirm the functionality of the experimental setup and its suitability for future research. Overall, this setup opens up the opportunity to enable a comprehensive investigation of the behavior of partial discharges under DC voltage loading. In addition, there is an opportunity for further investigations on various test objects in order to gain a deeper understanding of the PD mechanisms under DC voltage loading.

Research needs for future insulation systems

The introduction of the new generation of semiconductors, based on silicon carbide and gallium nitride, marks a significant advance in the field of electromobility and renewable energies. These materials offer outstanding performance benefits such as higher switching speeds and energy efficiency, which are of great importance in these industries. However, these benefits also come with challenges. The fast voltage edges generated by these semiconductors require innovative approaches in the protection of electric drive systems. Conventional insulation systems are reaching their limits and require adaptations to meet the requirements and thus increase the efficiency and reliability of the energy transition and drive technologies. Partial discharge diagnostics in these systems are particularly challenging, as they are still poorly researched due to the high frequencies and fast switching processes. It is crucial to develop new methods and technologies to detect and analyze these phenomena in order to ensure the safety and efficiency of energy systems. Overall, the new semiconductor materials open up exciting opportunities for electromobility and renewable energy, but they also bring challenges that need to be overcome. This requires the collaboration of researchers, engineers and technologists to develop innovative solutions for these forward-looking industries.

DC-PD SETUP

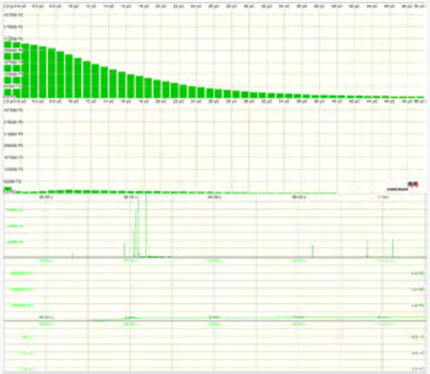
Partial Discharge Measurement under DC Voltage Load

- High voltage source up to 60 kV and 3 mA
- Pulse current measurement according to DIN EN 60270
- Shielded PD measuring cabin with basic noise level < 1 pC
- Digital measuring system with active interference suppression

HIGH VOLTAGE SOURCE

High Precision Power Supply

- High Voltage Source
- High reproducibility through automation and remote controllability
- Long-term stable voltage generation with low ripple < 0.001 %



PD ACTIVITY OF A TIP-PLATE ASSEMBLY WITHOUT DIELECTRIC BARRIER WITH RAPID VOLTAGE INCREASE

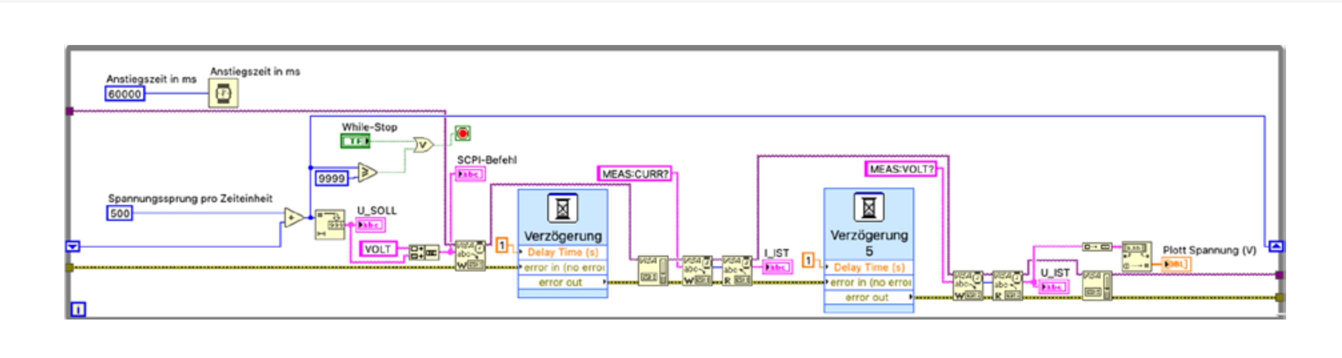
Sample Measurement for the Detection of PD

- PD Pulse Number Sorted by Apparent Charge Height
- PD Pulse count at specified interval

PD MEASUREMENT SYSTEM

Fully digital measuring system for PD detection

- Coupling quadripole CPL 542A
- PD Acquisition Unit MPD 600
- Control unit MCU 502
- MPD 600 Battery



BLOCK DIAGRAM VIEW IN LABVIEW

Voltage Control Programming

- Control of the high-voltage source via TCP protocol
- While loop to control ramp function
- Switch-off delay and closing of the VISA controller

elenia-Charging Park

CONTACT PERSON

Gian-Luca Di Modica, M.Sc.
g.di-modica@tu-braunschweig.de
+49 531 391 7704

Lukas Ebbert, M.Sc.
l.ebbert@tu-braunschweig.de
+49 531 391 9727

Robin Herman, M.Sc.
r.herman@tu-braunschweig.de
+49 531 391 7702

WEBSITE

https://www.tu-braunschweig.de/elenia/forschung/elektromobilitaet

TASKS AND SERVICES

- Testing concepts for grid and system integration of electric vehicles
- Investigation of grid-oriented charging strategies
- Research on generation-oriented and grid-oriented charging
- Solutions for increasing the absorption capacity of BEVs in the low-voltage grid
- Charge management for electric vehicle fleets

Charging-park at the Mühlenpfordthaus

Testing of concepts and strategies for the successful integration of electric vehicles in the grid

The elenia charging park on the idyllic banks of the Oker river right next to the Mühlenpfordthaus not only offers six charging parking spaces for the increasing number of electric vehicles in Brunswick, but also a wide variety of different charging points and wallboxes. The charging infrastructure there offers three permanently installed charging stations within the institute. However, most of the other charging equipment is installed on mobile item racks and can be moved around as required. This means that a large number of different test setups can be realized in elenia's Grid Dynamics Laboratory (GDL) and Energy Management Laboratory (EML). The data obtained from the charging processes in the institute's internal infrastructure is stored online in a specially created backend for further evaluation and can thus be used profitably in ongoing projects at the institute, such as MELANI or NetFlexum. Furthermore, the permanently installed charging stations are also monitored by an SMA Energymeter. Through this they can be integrated into an energy management system in which, for example, generation-oriented charging strategies are examined. The whole park is rounded off by an electrical coupling of the charging park with the EML and the GDL. Latter makes it possible to investigate the influence of charging processes on specific grid topologies and use cases. Furthermore, innovative grid-supporting functions, such as a Q(U)-control integrated into the charging station, can be analyzed and tested. Overall, the charging infrastructure and laboratory equipment are constantly being developed and improved in order to respond to the changes and innovations of the constantly growing electromobility market.

Interoperability of charging equipment and BEV

Another focus is on communication between the vehicle and the charging station. This is essential for the smooth running of a charging process and thus for the acceptance of electromobility in general. In the project LISA4CL, an inductive charging system for outputs of up to 22 kW is being developed in collaboration with partners. One of elenia's tasks is to develop and test standard-compliant communication between the primary and secondary sides of the inductive transformer. During the charging process, parameters such as the charging power or the state of charge of the battery (SoC) are exchanged. In order to implement grid-supporting functions such as bidirectional charging of BEVs, this communication must be read out and then intervened in. This is done by means of so-called developer boards for the vehicle and infrastructure side, which are used in the industry for communication development and are made available to us by our project partners. These can read out the communication in CAN format and thus make it available for further programming. This means that, for example, if there is a local voltage drop in the grid, a signal can be transmitted to nearby charging vehicles so that power from their batteries is fed back into the grid. This allows the voltage at the corresponding grid node to be raised again and prevents damage to equipment or consumers.

Another practical application is the use of developer boards in a built-up charging-replication for laboratory tests (s. photo). The replication can be used to simulate AC charging processes with various charging stations in the laboratory. It emulates the BEV part of the communication and the vehicle battery can be represented by an AC load. In addition, it is also possible to use a bidirectional rectifier and a battery emulator to record the DC parameters of the AC charging process and simulate the behavior of different battery types and sizes.

The charging equipment is rounded off by a specially installed AC charging station for the practical electromobility course offered at the institute (s. photo hardware). This is operated with a programmable logic controller (PLC) and can thus simulate various charging situations on the institute's own eGolf. In order to be able to investigate DC charging processes in the practical course, a DC charging station has also been set up. This in turn is equipped with a developer board and can thus simulate DC charging processes using scripts developed in the Python programming language and a DC source that can be controlled via CAN bus. This allows students to gain a holistic insight into the charging processes and investigate the communication between the vehicle and the charging station. This provides practical insights into the fundamentals of electromobility and attempts to familiarize students with the challenges of grid and system integration of BEVs.

AC charging replication

CHARGING-PARK AT THE MÜHLENPFORDTHAUS

BEVs can be charged here in 6 parking spaces

- 3 charging stations with 6 charging points
- Max. 22 kW three-phase AC charging (32 A)
- Max. 20 kW DC charging (via CCS and CHAdeMO plug)

LABORATORY CHARGING STATION OF THE EMOBILITY PRACTICAL COURSE

Three-phase, PLC-controlled AC charging station

- Max. Power 22 kW (32 A)
- Insight into the safety and control components
- Bidirectional charging possible

PION WAVE

Mobile three-phase wallbox for laboratory tests

- Max. Power 22 kW (32 A)
- One connection point
- Innovative design in exposed aggregate concrete look

SMA EV CHARGER BUSINESS

Mobile three-phase charging station for laboratory tests

- Max. Power 22 kW (32 A)
- Two connection points
- For the commercial sector

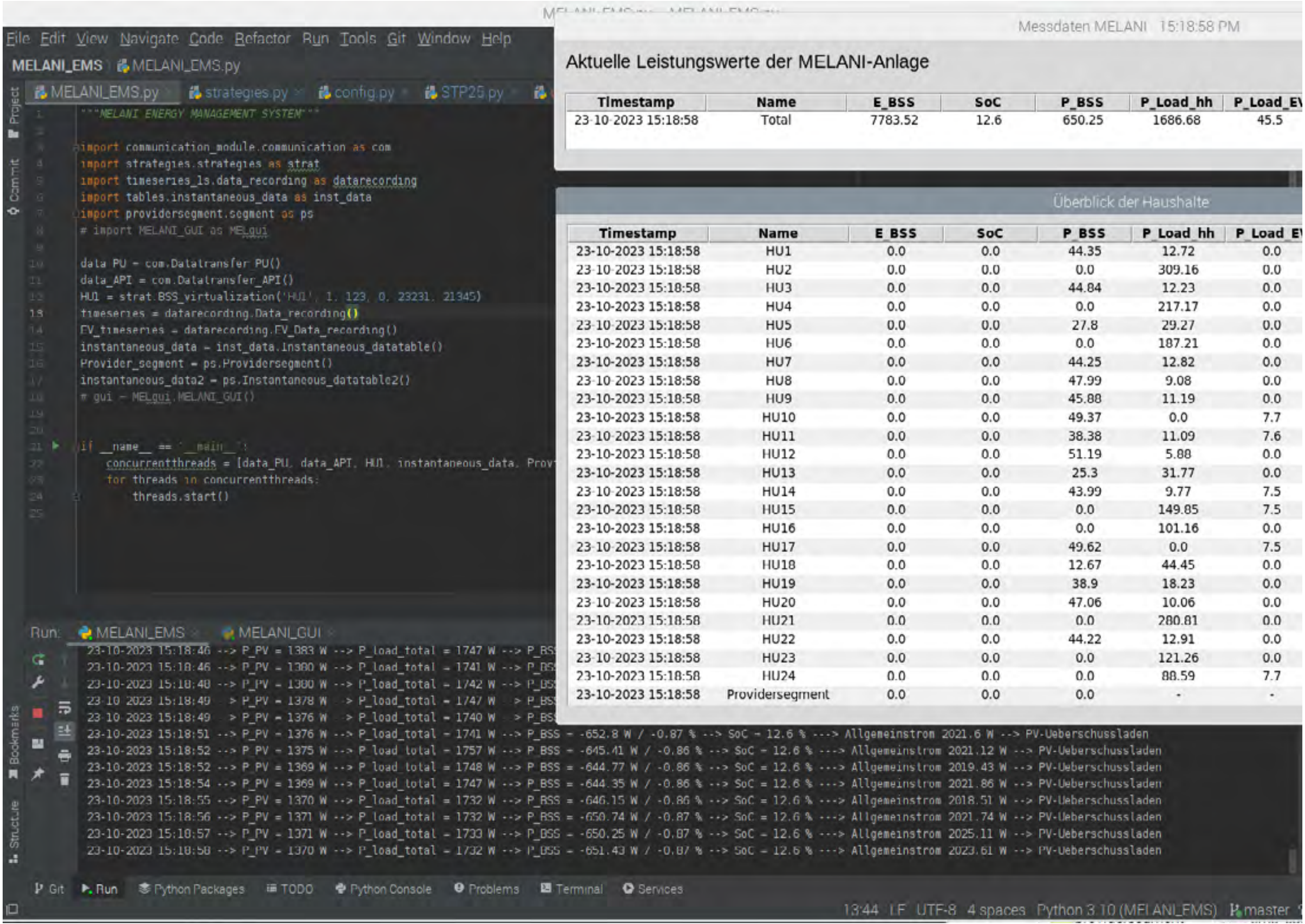
MENNEKES AMTRON PREMIUM

Mobile three-phase wallbox for laboratory tests

- Max. Power 22 kW (32 A)
- One connection point
- Same model as at the Oker river


235 0.50
238 0.45
238 0.50

Energy Management Laboratory



CONTACT PERSON

Dr.-Ing. Frank Soyck
f.soyck@tu-braunschweig.de
+49 151 6511 9141

Frederik Tiedt, M.Sc.
f.tiedt@tu-braunschweig.de
+49 531 391-7708

Marcel Lüdecke, M.Sc.
m.luedecke@tu-braunschweig.de
+49 531 391-9726

Julien Essers, M.Sc.
j.essers@tu-braunschweig.de
+49 531 391-9716

WEBSITE

www.tu-braunschweig.de/elenia/forschung/labore/energiemanagementlabor

TASKS AND SERVICES

- Carrying out storage efficiency measurements
- Testing control methods and communication protocols
- Combined tests with hardware devices, simulation models and control systems with a modular control environment (HiL)
- Energy and performance measurements
- Control and evaluation tools for storage efficiency measurements
- Compatibility test for technical evaluation of the operation of battery storage systems with inverters
- Validation of operating strategies for energy management systems at building level

Energy Management Laboratory

Research, innovation and practical experience for a sustainable energy future

The energy management laboratory offers plenty of space to investigate innovative energy management concepts for electricity-only household and prosumer demonstrators. Research focuses on prosumer behavior in the context of electromobility, the coupling of the heat and electricity sectors, load and storage management as well as newly developed metering and measurement concepts. Numerous devices, such as various AC loads, DC sources, a charging infrastructure with charging stations from various manufacturers and a heat pump test stand consisting of an air-to-water heat pump, a climate chamber and a heating circuit, can be used for this purpose. With the help of a large number of mobile measurement setups, various energy-related parameters can be recorded, stored and evaluated. Thanks to the power and data technology of the energy management laboratory with the grid dynamics laboratory, there is also the option of cross-laboratory measurements. This enables the processing of innovative projects and newly emerging research questions in the field of integrated laboratory-based research, such as the effects of a smart building smart building on grid stability.

Since the laboratory opened at the end of 2018, the construction of a prosumer demonstrator has already been realized in the NetProsum2030 project and studies on various mobility concepts have been carried out in the EnEff Campus: blueMAP project. The energy management laboratory is currently working on the flexess and MELANI research projects. The flexess project is investigating the targeted use of flexibility in technical systems in the household, GHD, commercial trade and electromobility fleet sectors. In this context, households with different characteristics are simulated and measured in the energy management laboratory. In the MELANI research project, for example, measurement methods and meter concepts for the multiple use of PV home storage systems are being developed. The laboratory environment of the energy management laboratory is used to evaluate an image of the developed concept. The operating strategies for energy management systems at building level developed for MELANI can also be validated in the laboratory. More information on the exact procedure can be found on the pages of the respective research project.

Energy management systems are also being investigated in the KEMAL research project (customer-oriented energy management with autonomous load control). However, the focus here is on the usable potential in combination with an SMGW. The project is concerned with the further development and testing of existing standards relating to the Smart Meter Gateway (SMGW) and takes a holistic view of the intelligent metering system. The focus here is on the development of a Home Energy Management System (HEMS), which ensures the standard-compliant connection of fully flexible prosumers to the smart metering system. This system is now being tested in the laboratory and under real conditions.

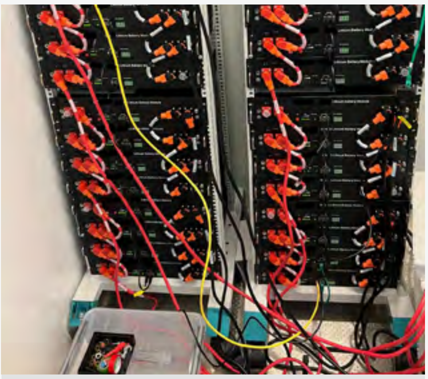
In addition to the research area, teaching also benefits in the form of numerous student projects that can be carried out in the laboratories and the additional laboratory experiments offered in parallel to the lectures. Students can gain practical experience in the laboratory in experiments on topics such as energy management or heat pumps and consolidate their theoretical knowledge through hands-on practicals.

Compatibility tests are also carried out in the laboratory to technically evaluate the operation of various battery storage systems in interaction with inverters. In addition, the extensive equipment of the energy management laboratory enables the processing of service projects in the context of efficiency measurements of PV storage systems according to efficiency guidelines and thus expands the service area of the institute.

MOBILE CHARGING STATION IN THE LABORATORY

SMA EV CHARGER BUSINESS:
Charging electric vehicles

- Charging with up to 2 × 22 kW per charger (230 VAC / 400 VAC, max. 32 A)
- Fully integrated electromobility solution also for charging with solar power
- RFID and OCPP interface
- Protection against overload of the grid connection point



COMPATIBILITY TEST FOR THE TECHNICAL EVALUATION OF THE OPERATION OF BATTERY STORAGE SYSTEMS

Aims of the tests:

- Determine the compatibility of battery storage systems with inverters
- Analyze system behavior (under normal operation, overload and overcharge conditions)
- Confirmation of safety measures during initial commissioning
- Inrush current test and DC ripple analysis

ENERGY STORAGE FOR COMMERCIAL, INDUSTRIAL OR MULTI-FAMILY HOUSES

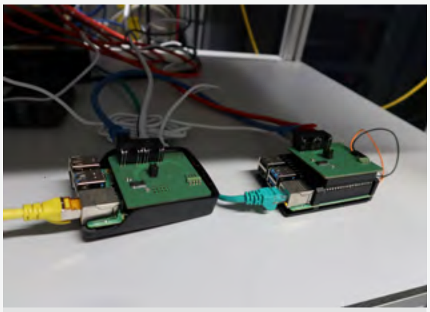
TESVOLT TS HV 70

- Lithium storage system (NMC)
- Continuous charge/discharge rate: 1C
- 8000 full cycles (guaranteed for 10 years)
- Safest cell technology
- High-voltage system

ELECTROMOBILITY AT THE ELENIA INSTITUTE

e-Golf „emilia“

- In use in the Braunschweig joint project “emil” since 2014
- Research in the areas of inductive charging and grid connection
- Charging using the institute’s own infrastructure
- Range of approx. 150km without a charging stop



POWERFUL SINGLE-BOARD COMPUTER

Raspberry Pi 4 Model B

- 8 GB RAM, SSD card as fixed memory
- Used in the MELANI project to test the developed energy management system
- Development of CAN interface in cooperation with „Physikalisch Technische Bundesanstalt“ (PTB): Reading of various electricity meters in 1-second resolution possible → Measured values are used for efficient power flow control in the energy management system processed

MEASURING RACK

- Used in the MELANI and KEMAL research project to map a building network
- Connection of various electronic loads and DC sources possible
- Recording of energy-relevant measured variables through integrated power measurement

Grid Dynamics Laboratory

CONTACT PERSON

Björn-Oliver Winter, M.Sc.
bjoern.winter@tu-braunschweig.de
+49 531 391-7748

Frederik Tiedt, M.Sc.
f.tiedt@tu-braunschweig.de
+49 531 391-7708

Timo Sauer, M.Sc.
t.sauer@tu-braunschweig.de
+49 531 391-7721

TASKS AND SERVICES

Studies on topics such as:

- Behavior of components to frequency and voltage changes
- Overcurrent limitation and short-circuit behavior of decentralized generation systems
- Provision of conventional and fast primary control power
- Behavior and stability of voltage control inverters in stand-alone grid operation or parallel grid operation
- Effects of variable voltages on controls such as Q(U) and P(U))
- Anti-islanding detection and oscillating circuit tests up to 33 kVAr in accordance with DIN EN 62116
- Development and testing of novel control functionalities to provide system-supporting properties for the interconnected grid
- Investigations into controllable local network transformers using our own simulation model

Grid Dynamics Laboratory

Grid stability in times of converter-dominated grids – milliseconds matter

The grid dynamics laboratory, the name says it all: current research topics on the integration of renewable energy generation plants into the low-voltage grid are investigated here. The focus is on highly dynamic, transient processes - range: milliseconds to a few seconds.

A dedicated team consisting of scientific staff, scientists and our institute's own workshop work together actively. Introducing the laboratory and its team:

About the laboratory – Central questions

The aim of the investigations in the grid dynamics laboratory is to think ahead of the energy transition. While the stability of conventional energy supply systems is primarily based on generator-based large-scale power plants from higher voltage levels, the generative side is currently undergoing major changes. There is an increase in decentralized feed-in from converter-based, smaller plants at lower voltage levels. Generation plants using renewable energy sources supply their power to the grid via converters and thus differ from conventional thermal power plants, which provide power using large synchronous generators. The requirements for modern generation plants with regard to their behavior in a highly volatile, dynamic grid are diverse and subject to a high degree of complexity due to their power-electronic characteristics, communication structures and their regulation.

By means of scenarios in which these future power supply infrastructure is already being mapped in the laboratory today, opportunities as well as challenges in the supply of a high proportion of renewable energies and electromobility should be recognized and investigated in advance.

This means fundamental changes in the characteristics of future grid infrastructures, under which the interplay of conventional and new types of energy supply systems and regulations to ensure grid stability must be constantly re-evaluated. The grid dynamics laboratory has the right infrastructure for this: sources that can be flexibly arranged, grid simulators, loads, generation plants, freely parameterizable full converters and power hardware in-the-loop real-time simulators enable the mapping of a wide range of scenarios, especially critical situations: many things that you do not want to see in the real energy supply infrastructure can be tested and run through here without any consequences.

This means that it focuses in particular on experiments and scenarios that deal with special load situations of grid components and the grid-supporting potential of decentralized generation plants.

The Grid dynamics laboratory as a service provider for research and industry

Figure 1: PION AG charging station in the 7-hour 44kW continuous load test

In addition to our day-to-day research work, we also regularly process orders for external partners - from start-ups to larger industrial customers.

The main focus for our clients is on issues relating to the safe operation of operating equipment, software and/or hardware components in a mappable low-voltage environment.

Typical external assignments include:

- Characterization of the behavior of devices, e.g. as a result of different parameterized controls under reproducible scenarios
- Recording the robustness of developed devices in special load situations such as short circuits, overvoltages, harmonics, etc.
- The initial assessment of the conformity of prototypes with (newly developed/existing) grid connection guidelines

Presentation of laboratory components – design, construction and use of automated grid replicas

At the heart of most experiments in the grid dynamics laboratory is a grid replica - a replica of a low-voltage line that is as electrically identical as possible and on which various components of the energy transition, consumers and generators, are tested for their interaction. In particular, the fast and flexible connection of various grid components, the simple and repeatable testing of grid scenarios and the safe handling of the components are important features of a grid simulation.

A concept for a new network replica has been designed to meet the increased requirements, in particular for precise tests with easy-to-change network impedance. In particular, its modular concept allows flexible interconnection in different, parallel and serial connections of mains strings. A design for currents up to 125A allows sufficient capacity, even for future extensions of the laboratory and parallel tests.

The laboratory engineers at elenia took on key components of the design, layout, procurement, construction and commissioning of the grid simulation. The resulting devices have already been used for experiments in the 'Grid control 2.0' project and other follow-up projects to simulate various fault situations such as voltage dips, harmonics or island grid situations in the laboratory.

At the heart of the replica are open source PLCs that enable central control, monitoring and flexible expansion. This enables us to carry out repeatable test series that include automatic adjustment of the mains impedance and switching of laboratory components from central computers. Pre-installed measuring taps for current and voltage enable flexible modular measurement of the grid status at the component or in the line, depending on the requirements of the test. The status of the simulation can be monitored at any time during the test.

Figure 2: Interior view of the new network replica - Author: M. Gand

Presentation of laboratory components – OPAL Real-Time Simulator

The tests in our laboratory offer a decisive advantage for our research: scenarios or behaviors that have been conceived in abstract and necessarily simplified simulations can be tested under more realistic conditions.

These tests are often more meaningful, as control algorithms can prove their correct functioning in the real world for the first time. However, before control algorithms are implemented in hardware, it is advisable to test their functionality in more flexible embedded scenarios. In order to be able to map grid faults and controller behavior in the millisecond range, the laboratory requires an integrated measurement and control facility that works reliably and without delay in these areas.

Figure 3: OPAL real-time simulator with analog interfaces for controlling components in the laboratory

To this end, the laboratory was expanded to include a real-time simulator. The real-time simulator makes it possible to create hybrid use cases from simulation and hardware in „quasi“ real time. This has several advantages: simulations can be transferred to the laboratory step by step. Part of the test set-up is carried out by laboratory devices, the rest takes place in the real-time simulator. The devices and simulation model work together in parallel and in real time. Analog measured values, such as the voltage and current of individual devices, are fed to the real-time simulator via measuring devices, where they are calculated internally using various simulation parameters and output as new analog manipulated variables. The result is a so-called Power-Hardware-In-The-Loop (PHIL) system - the coupling of very fast simulations with electrical and mechanical hardware. Simulation step widths of less than 100 μs are achieved in the Grid dynamics laboratory. In contrast to pure laboratory operation at hardware level, a real-time simulator enables the flexible mapping of elements of the low-voltage grid, e.g. machines with different inertias, batteries with different outputs, grids with different arrangements, which can only be simulated with great effort in the laboratory. All of this can be changed at a single mouse click. Faults in live elements can be mapped in simulations, an advantage for personal safety and equipment protection.

News from the lab - Testing the impact of faster grid support on the ability of inverters to detect unwanted islands

In view of the ever-increasing penetration of inverter-based renewable energies in the grid, they are becoming increasingly important for future stable grid operation. Considerations as to how their behaviour can be designed in such a way that they make the best possible contribution to stabilizing operation in the event of grid faults are therefore an integral part of technical standardization work. In a study for the FNN, elenia's grid dynamics laboratory is currently evaluating whether the extended involvement of inverters in grid support could have a negative impact on their ability to detect stand-alone grids. By testing a commercially available device, its behaviour in fault situations and the effectiveness of its ability to detect island grids under varying initial conditions and working points is being characterized in reference recordings. The behavior of the device is then adapted as well as possible to various currently discussed requirements and the series of islanding tests are repeated in each case. The evaluation of the several hundred planned islanding tests alone will then enable a comprehensive answer to the question. The new grid replica and the code adapted to it for semi-autonomous test execution make it possible to master the complexity required for this.

Photos: Frederik Tiedt/TU Braunschweig

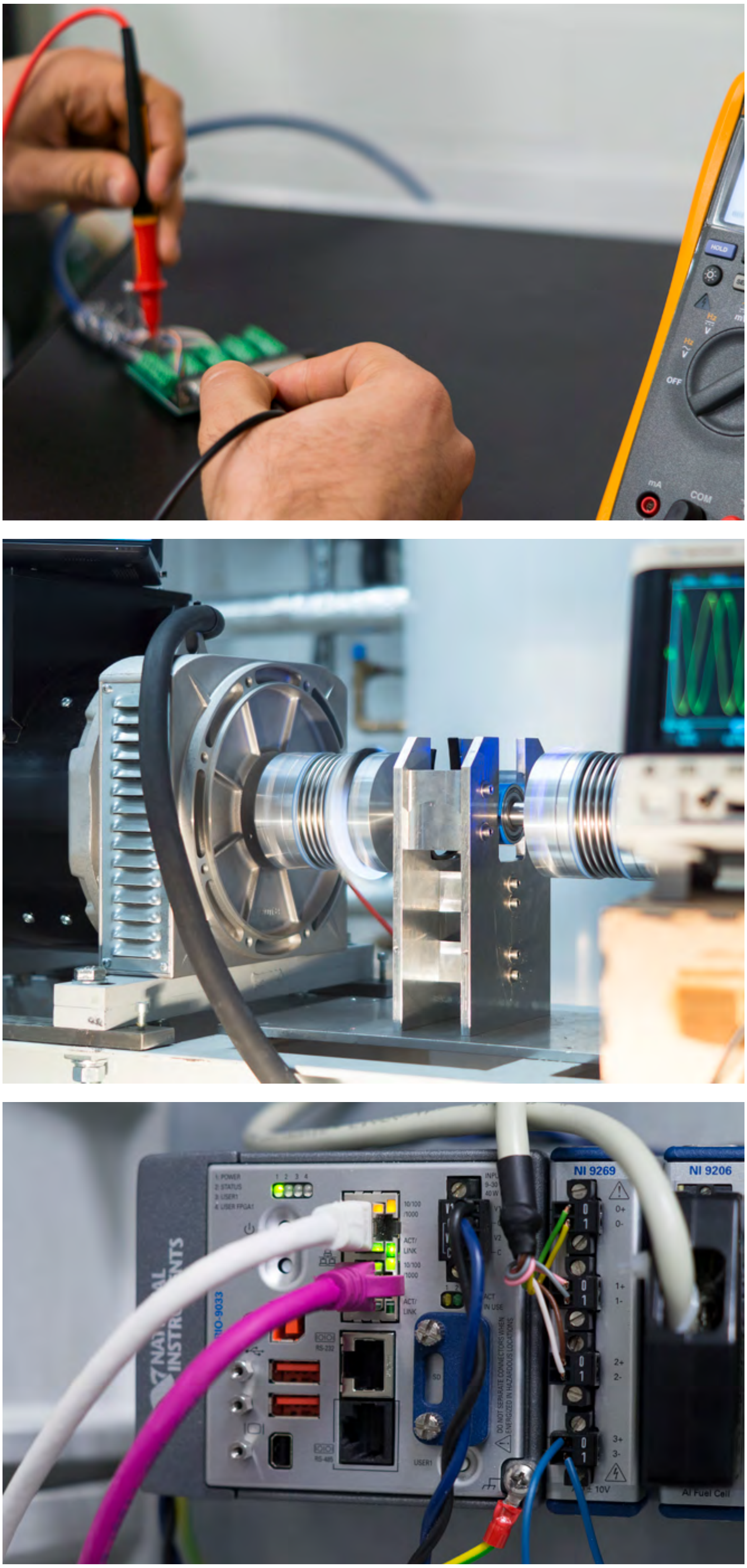


Figure 4: Diverse working and learning areas at different laboratory interfaces

Figure 5: Line-replicating elements correspond to up to 1.8 km of low-voltage cable

Training and working with student assistants

Several research assistants are regularly active to support scientific staff in the laboratory. This includes tasks such as the software implementation and control of components in the laboratory using programs such as LabVIEW or MATLAB/Simulink, or the installation of electrical components or hardware - in the laboratory, students can gain practical experience in the field of electrical installations, but also in the applicable theory of control and measurement technology.

Facts & figures about the grid dynamics laboratory

Various components such as inverters, AC and DC sources and loads as well as a 50 kVA single line regulator make it possible to simulate or reproduce a complete low-voltage line in the laboratory. To complete the low-voltage environment, up to 1.8 km of low-voltage cable can be simulated using flexibly adjustable resistors and inductors.

A powerful and precise measuring system with 16-bit measuring resolution and a sampling rate of 500 kS/s enables accurate and precise work. Voltages of up to ±1400 V and currents of up to 200 A can be recorded and processed at various measuring points in the laboratory environment. The core elements and test components, which define the central core points of the laboratory, can be found below:

GRID SIMULATOR AMETEK MX-45

Fully regenerative grid simulator for simulating different grid states with variable grid parameters:

- 45 kVA connected load
- Voltages up to 300 VRMS und 400 VDC
- Currents up to 50 ARMS
- Frequency range 16–800 Hz
- 4-wire connection (unbalanced load)
- Integrated measuring system
- Analog interfaces for precise control of individual phases in amplifier operation

MAINS SIMULATOR REGATRON TC.ACS.30

Fully regenerative grid simulator for simulating different grid states with variable grid parameters:

- 30 kVA connected load
- Voltages up to 305 VRMS and 800 VDC
- Currents up to 43 ARMS
- Frequency range 16–1000 Hz
- 4-wire connection (unbalanced load)
- Integrated measuring system
- Analog interfaces for precise control of individual phases in amplifier operation
- Operation as simulated RLC load
- Automated sequence control using Python-based scripts
- Fast edge rise times of up to 4 V/us for investigating transient events

OPAL 5700 REAL-TIME SIMULATOR

Real-time simulator with high computing power for power hardware in-the-loop applications and real-time laboratory control:

- Analog/digital inputs and outputs for coupling various laboratory components
- Communication interfaces via protocols such as MODBUS, EtherNet, EtherCAT, CAN, Time Stamp, GOOSE, etc.
- FPGA technology for faster command processing
- Working in the MATLAB/Simulink development environment
- Real-time capable simulations of hardware and electrical networks with simulation step widths of less than 100 µs

TRIPHASE - FULLY PROGRAMMABLE INVERTERS

Freely programmable full inverters for implementing and analyzing your own control models:

- Two full inverters with 15 kVA rated power each
- 1 × 3-wire connection, coupled rectifier and inverter, can be used as a battery simulator
- 1 × 4-wire connection, unbalanced operation, zero-system embossing
- Control and parameterization via MATLAB/Simulink

30 KW COUPLED MACHINE SET (ASYNCHRONOUS MACHINE AND SYNCHRONOUS MACHINE)

Coupled machine set, consisting of asynchronous and synchronous machine with freely parameterizable inverter:

- 30 kW connected load at 1500 rpm nominal speed and 150 Nm nominal torque
- Synchronization unit for connecting external sources to the machine set network
- Generator and motorized operation possible
- Control via LabView and cRio system

Mechanical & Electrical Workshop

CONTACT PERSON MECHANICAL WORKSHOP

Kerstin Rach
Master in mechanical engineering,
Workshop manager and trainer
k.rach@tu-braunschweig.de
+49 531 391-7747

Julia Musebrink
Precision mechanic specializing in mechanical engineering, State-certified technician
j.musebrink@tu-braunschweig.de
+49 531 391-7507 / 7749

Matthis Grosche
Precision mechanic specializing in precision mechanics
m.grosche@tu-braunschweig.de
+49 531 391-7507

Frank Haake
Precision Mechanic
f.haake@tu-braunschweig.de
+49 531 391-7507

Claas Narup
Industrial mechanic
c.narup@tu-braunschweig.de
+49 531 391-7507

CONTACT PERSON ELECTRICAL WORKSHOP

Christian Ryll
Workshop management
State-certified technician
c.ryll@tu-braunschweig.de
+49 531 391-7507 / 9731

Henning Krüger
Electronics technician for industrial engineering
h.krueger@tu-braunschweig.de

WEBSITE

https://www.tu-braunschweig.de/elenia/team/mechanische-werkstatt

https://www.tu-braunschweig.de/elenia/team/elektrische-werkstatt

Mechanical & Electrical Workshop

Elenia's two workshops support academic staff and students in the production of components and systems for teaching, student research projects and final theses. In close cooperation with the employees/students, solutions to problems are developed and tested for feasibility. In addition to lathes and CNC milling machines for machining, the mechanical workshop has had several 3D printers (FDM/SLA) for additive manufacturing at its disposal since this year.

SLA 3D printing of an adapter for mounting pressure sensors.

Manufacturing of an adapter from stainless steel to accommodate copper switch contacts

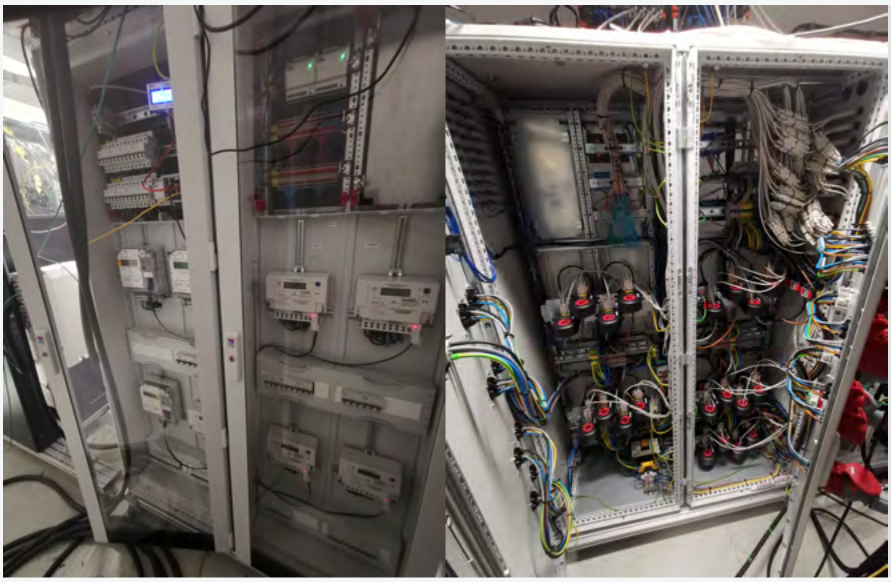
CNC-milled housing for a measuring adapter

Manufacturing Switchgear replica

Assembly of a 6kV disconnect switch and connection via copper busbars

Manufacturing of a keychain for Future Day

6KV supply with two safety circuits and control of a top switch, a safety disconnector, an earthing disconnector and a load-break switch; Project SMS2



Meter measurement cabinet for the development of measurement methods for multiple use of PV home storage systems with an output of up to 70kW; Project MELANI


DELLEMC
Elenia
AD01
HAUPTSCHALTER
USV01 - HP
DELL USV 1
DELLEMC
Dell USV01
Last
487 VA
Online
UPS01
DELLEMC

IT-Department

CONTACT PERSON

Fabian Scholz
✉ f.scholz@tu-braunschweig.de
📞 +49 531 391 7753

Lukas Oppermann
✉ lukas.oppermann@tu-braunschweig.de
📞 +49 531 391 9712

WEBSITE

https://www.tu-braunschweig.de/elenia/team/it-administration

TASKS AND SERVICES

- Procurement and management of servers and clients
- Provision of workstations and software
- Software-License procurement and management
- Support and training for employees and students (service desk)
- Analysis and specification of IT systems in accordance to DSGVO
- Permanent monitoring and maintenance of the institute and research networks
- Initial setup and maintenance of individual project-related IT systems
- Administration of institute and project websites

The Information technology at elenia

Is it possible to make progress with digitalization in the public sector?

Enhancement of the server room

This year, we have extensively expanded the central element of our IT infrastructure and brought it up to date. A new 42U rack was installed to meet the growing demand for storage and processing capacity. Outdated servers were replaced with modern rack servers. In addition to renewing the hardware, it also included a comprehensive data migration to the new systems. Furthermore, additional servers were procured and placed into operation in order to cope with the institute's growing requirements. A particular challenge was the redesign of the entire cabling, which we carried out as part of the server room expansion. This ensures greater efficiency and reliability and sets the foundation for future expansions.

Elenia Intranet

An internal communication network has been set up to optimize the exchange of information within the company. In the coming years, we are planning a comprehensive expansion of the intranet in order to drive forward the digitalization of organizational and administrative processes in a targeted manner. This will enable us to further optimize and streamline our internal processes.

Homepage migration

Another important milestone this year was the migration and relocation of our website to a new, more powerful infrastructure. This ensures that we can guarantee smooth and fast online access for our employees, students and customers.

Additional IT services

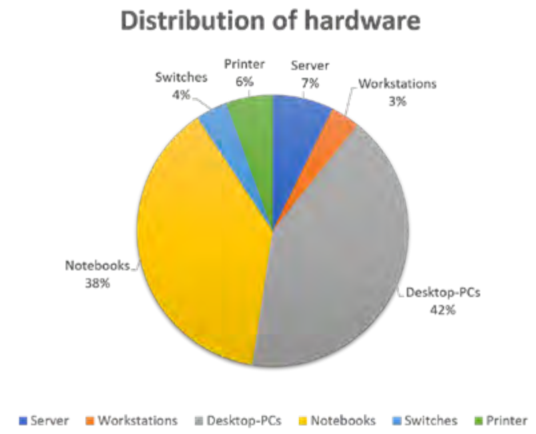
A customized ticket system is currently being developed on behalf of the Equal Opportunities Officer of Faculty 5 and is to be implemented in the coming year. This will enable them to distribute and manage tasks and requests more efficiently.

In August 2022, the Institute for Electromagnetic Compatibility (EMC) was expanded with the establishment of the Chair of Mobile Electrical Energy Systems (MEES) and the appointment of Prof. Dr.-Ing. Michael Terörde. In the course of this, we expanded our IT services for the new chair in order to optimally support its research and development work for setting up a new infrastructure.

With anticipation and commitment, we are looking to the future and will realize further innovations and improvements in the coming years.

Fabian Scholz
Head of IT

Lukas Oppermann
IT Administration

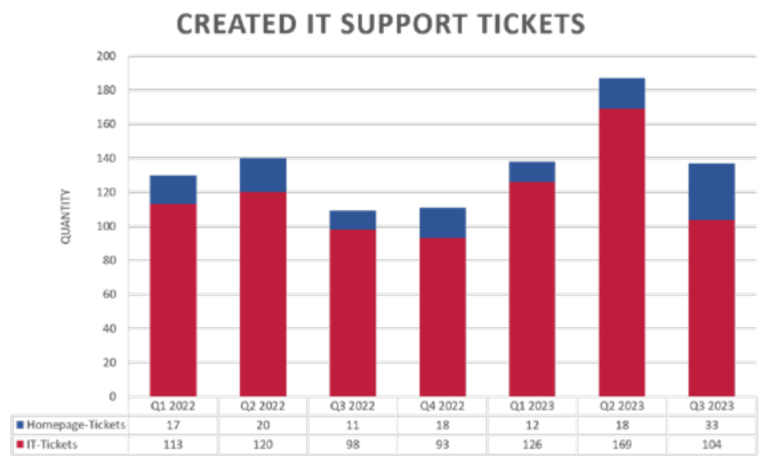


HARDWARE COMPOSITION 2023 (DATA COLLECTION ON: SEPTEMBER 30TH, 2023)

- 21 Server systems (physical and virtual, Windows and Linux)
- 120 PCs
- 110 Notebooks
- 10 High performance Workstations
- 18 Printer
- 11 52-Port Network switches (managed)

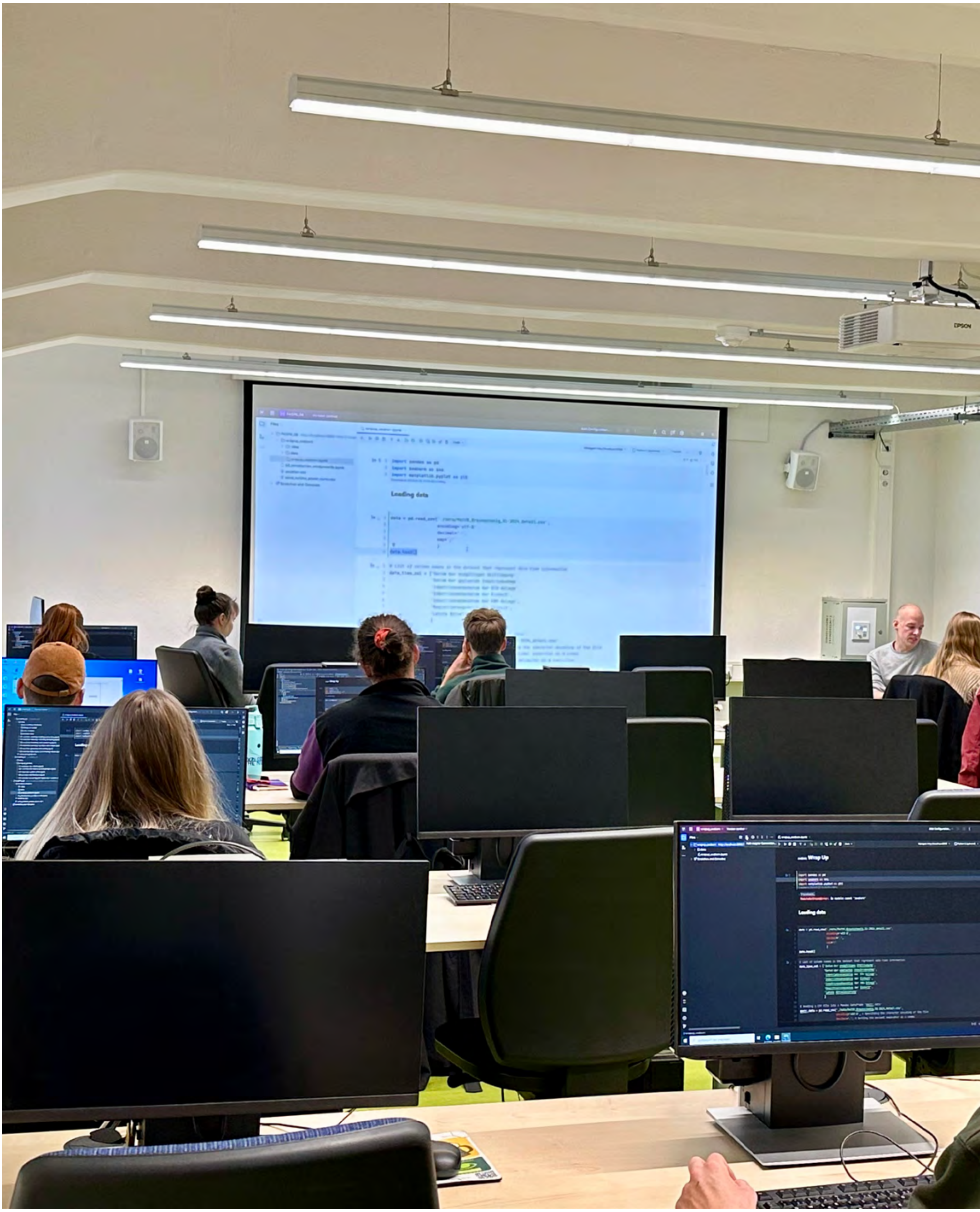
IT SUPPORT TICKETS CREATED

- Time period: Januaryy 1st, 2022 – September 30th, 2023



A LOOK INTO THE SERVER ROOM

- Left: Expansion with first new servers
- Right: Stock with already replaced devices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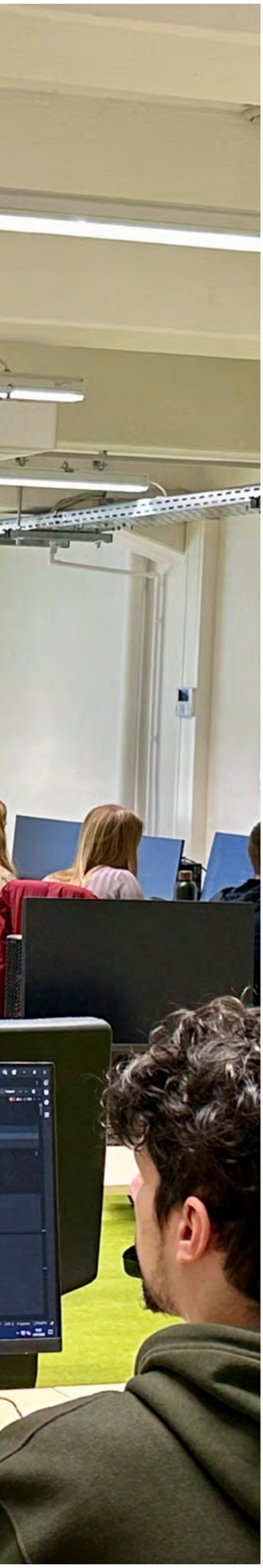
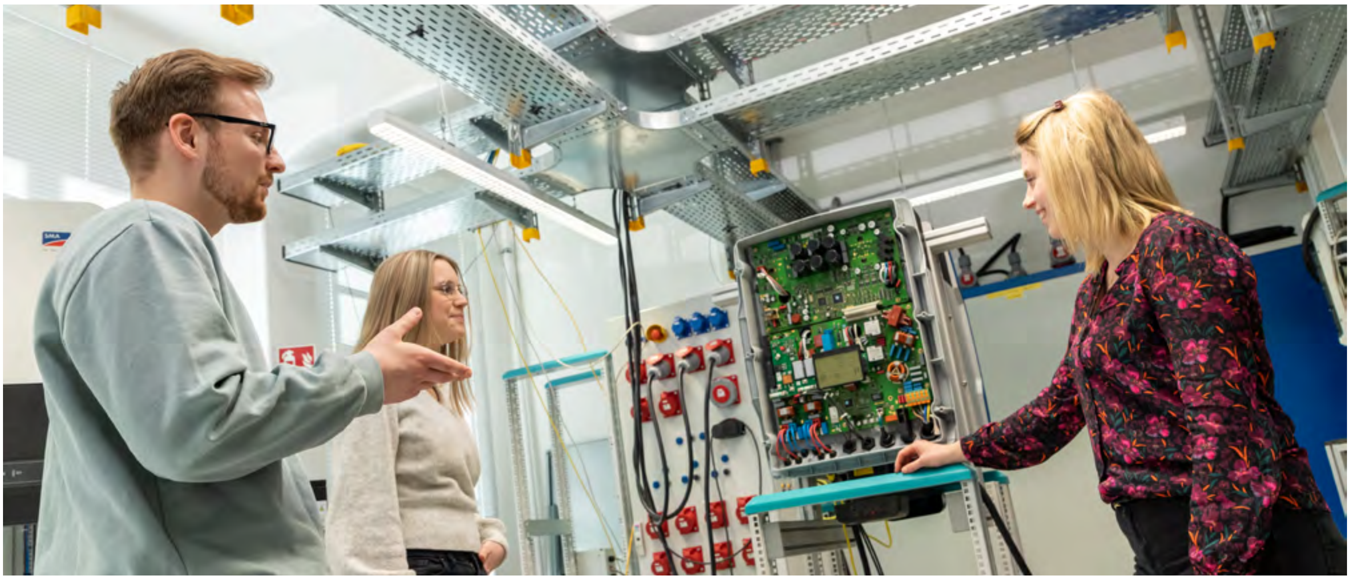


Teaching



New Bachelor‘s degree program NEEMO successfully launched!

NEEMO: Sustainable Power Systems and Electromobility

The elenia Institute for High Voltage Technology and Power Systems is researching energy technology solutions for the world of tomorrow. With this in mind, a new engineering bachelor‘s degree course has been launched in collaboration with the faculty and other institutes.

As an interdisciplinary degree program with a focus on electrical engineering, NEEMO prepares students for shaping the future in the fields of electrical, energy and automotive engineering. During their studies, students learn what a sustainable energy system of the future will look like, how this will affect mobility and urban development, and how climate neutrality can be achieved in Germany by 2045.

Structure of the study program

The structure of the degree program is multi-layered and includes various specializations. In the first year, students learn the basics of mathematics, physics, chemistry and electrical engineering. In addition, the study program offers in-depth courses on sustainable engineering from the first semester onwards. For example, in the lecture "Sustainable Energy Systems", students acquire knowledge about the structure and functioning of various renewable energy solutions such as photovoltaic and turbines. The "Electromobility" course, on the other hand, teaches post-fossil drive technologies and how this can lead to a clean and sustainable transport sector. In addition to the various technologies at component level, students also learn about cross-sectoral system modeling and holistic technology assessment. In addition, initial in-depth specialist knowledge is acquired in optional specializations and interdisciplinary qualifications are obtained.

Various laboratory practicals in different subject areas enable students to apply and consolidate the knowledge acquired in the lectures in exciting laboratory experiments. Excursions to research institutions and companies in the surrounding area, such as a thermal power plant in Braunschweig, give students the opportunity to think outside the box and see how abstract concepts and theories are applied in reality. The industrial internship in the fifth semester offers students their first insights into organizational and operational processes and working methods, as well as optimal preparation for their later transition into professional life.

Excellent career prospects

Engineering training in key future-oriented areas such as the transition of energy, heating and transportation offers promising career prospects on the road to a neutral climate in Germany. In addition to direct entry into the profession, postgraduate Master's degree courses such as Electrical Engineering, Electromobility and Sustainable Energy Engineering are also available for specialization.

Courses

Lectures: Workgroup Energy Technologies

Lecture	Contents	Lecturer
Design and calculation of direct current systems	Calculation and design of DC grids, operation of DC grids, fault detection and localization, system technology, components for power generation, distribution and storage, industrial grids, stand-alone grids, on-board grids.	Prof. Dr.-Ing. Michael Kurrat
Electric Power Systems Engineering	Fundamental knowledge of power systems, Formulate research problems, Select adequate abstraction level, Use scientific theories and model concepts, Analyze social, economic and cultural consequences, Apply Systems Engineering for system design.	Prof. Dr.-Ing. Michael Kurrat, Dr.-Ing. Melanie Hoffmann
High-Voltage Technology 1	High-voltage grids, overvoltages, insulation systems, gas discharges, insulating materials, high-voltage direct current transmission.	Dr.-Ing. Michael Hilbert
Structure and function of storage systems	Charging infrastructure, storage parameters, system design, storage technologies, double-layer capacitor, energy storage in the form of hydrogen, structure and operation of lithium-ion battery storage, battery aging and diagnostics.	Dr.-Ing. Frank Lienesch
Electrical power systems	Thermal and mechanical load capacity of equipment, behavior of the mains voltage after interruption of the current flow and the effect on the switching path, design of various switching devices and fuses of different voltages.	Prof. Dr.-Ing. Michael Kurrat
High Voltage Direct Current Transmission Technology	Introduction to HVDC transmission systems, Operation of LCC and VSC based HVDC systems, Main components of HVDC converter stations, Interaction between AC and DC systems, Basic principles of modeling, analysis and control of dynamic systems.	Dr.-Ing. Nasser Hemdan, Dr.-Ing. Melanie Hoffmann
High-Voltage Test- and Measurement Systems	Fundamental Knowledge of High-Voltage and High-Current Tests, Fundamental Analysis of High-Voltage and High-Current Test and Measurement Circuits, Quality Assessment, Evaluation and Documentation of Test Performance for High-Voltage Components.	Prof. Dr.-Ing. Michael Kurrat
High-Voltage Technology 2	Introduction, basics of high-current and high-voltage testing technology, quality assurance and measurement uncertainty determination, generation and measurement of high DC, AC and impulse voltages.	Dr.-Ing. Johann Meisner
Numerical calculation methods	Basics for the numerical solution of systems of linear equations, DGL 1st order (initial value problems), partial DGL (finite difference method), computer exercises LT-Spice.	Prof. Dr.-Ing. Michael Kurrat

Lecture	Contents	Lecturer
Transmission grid technologies	Basics of transmission networks: structure, components, developments, operating methods, challenges; calculation of transmission networks with equivalent circuit diagrams: Overhead lines, cables, synchronous generators, transformers, compensation elements; Basic technologies of high voltage direct current (HVDC) transmission.	Prof. Dr.-Ing. Michael Kurrat, Dr.-Ing. Christian Schulz

Lectures: Workgroup Energy Systems

Lecture	Contents	Lecturer
Electrical fundamentals of energy technology for transportation and environmental engineering	Fundamentals of electrical power supply. Complex alternating current calculation and its application in three-phase systems and network components. Electrical safety topics.	Prof. Dr.-Ing. Michael Terörde, Prof. Dr.-Ing. Bernd Engel, Prof. Dr.-Ing. Markus Henke
Energy economics and market integration of renewable energies	Teaching the market roles and players in the energy industry. Fundamentals of energy trading (markets, grids, etc.), as well as mechanisms for the integration of renewable energies into the electricity markets.	Prof. Dr.-Ing. Bernd Engel
Innovative energy systems	Development of energy supply and climate targets, innovations in conventional power plants, renewable forms of energy, power-to-X and sector coupling (transport, heat, gas), storage systems, hydrogen use, stand-alone grids, prosumer households.	Prof. Dr.-Ing. Bernd Engel, Dr.-Ing. Jonas Wussow
Fundamentals of electrical energy technology (Part 1)	Introduction to the fundamentals of electrical energy transmission and distribution. Fundamentals and calculation of three-phase systems, transformers and synchronous generators.	Prof. Dr.-Ing. Bernd Engel, Prof. Dr.-Ing. Markus Henke, Prof. Dr.-Ing. Regine Mallwitz
Electrical power systems and grids	Introduction to electrical power supply, electrical equipment such as synchronous machines, power flow and symmetrical as well as asymmetrical short-circuit calculations, stability, grounding, protection measures.	Prof. Dr.-Ing. Bernd Engel
Control of Electric Power Systems	Introduction to grid control, transmission of electrical energy, dynamic behavior as well as frequency and voltage control of synchronous generators in power plants, higher-level control of power grids, control of DC systems, converter technology, grid-following and grid-forming converter controls.	Dr.-Ing. Stefan Laudahn
Electrical equipment of rail vehicles	Electric traction, brakes, auxiliary systems, signaling and safety systems, control systems on rail vehicles, passenger information and multimedia, vehicles in service, future developments.	Prof. Dr.-Ing. Bernd Engel

Lecture	Contents	Lecturer
Electrical bus and railroad technology	Repetition of the relevant fundamentals of electrical engineering, introduction to rail technology, overview of electrical bus systems, national and international traction current systems, DC and AC, drives for electric railroads, brakes, auxiliary systems, signaling and interlocking systems, vehicles in operation, future developments: Fuel cells, Contactless energy transmission, Electric road bus systems (trolleybus, battery bus with inductive/conductive charging), BEMU and its charging infrastructure.	Prof. Dr.-Ing. Bernd Engel
System Technology in Photovoltaics	Systemic analysis of photovoltaic power systems: System configurations, inverter topologies and technical functionality of grid-tied inverters. Challenges in the grid integration of PV systems. Analysing off-grid grid systems as well as grid-connected PV systems combined with battery storage systems.	Prof. Dr.-Ing. Bernd Engel
Regenerative Power Engineering	Basics of the structure of the German and European electricity supply system and its components, such as overhead lines, cables and transformers, technical basics of grid operation by grid operators and their handling of system services.	Prof. Dr.-Ing. Bernd Engel
Distribution grid technologies	Role of distribution grids in the energy supply, grid structures, operating equipment (cables, overhead lines, transformers, switchgear), protection concepts, ancillary services, grid charges, future developments in the distribution grid (Smart + X).	Dr.-Ing. Johannes Schmiesing
Sustainable Power Systems	Large-scale power plants, solar technology, offshore wind farms, hydropower, geothermal energy, biomass, hydrogen, energy distribution, systems engineering, Industry 4.0, DC industry, grid integration of renewable energies, e-mobility, battery storage, sector coupling.	Prof. Dr.-Ing. Michael Kurrat, Prof. Dr.-Ing. Bernd Engel

Seminar: For students

Seminar	Contents	Lecturer
Study seminar energy systems	Lecture series and presentation training on energy technology and energy industry topics.	Prof. Dr.-Ing. Michael Kurrat, Prof. Dr.-Ing. Bernd Engel
Technology evaluation	The energy and mobility transition offers great potential for limiting climate change. The challenges are how to use the opportunities offered by the new technologies in such a way that the social problems can be overcome without causing significant risks and side effects. To this purpose, technology impact evaluations will be developed and presented.	Prof. Dr.-Ing. Michael Kurrat, Prof. Dr.-Ing. Michael Terörde, Prof. Dr.-Ing. Markus Henke, Prof. Dr.-Ing. Bernd Engel

Seminar: For PhD students

Seminar	Contents	Lecturer
High voltage engineering for PhD students	Knowing and understanding systems thinking, understanding systems theory, Sustainable energy systems.	Prof. Dr.-Ing. Michael Kurrat, Prof. Dr.-Ing. Bernd Engel

Internships

Internship	Contents	Lecturer
Analysis, Simulation, and Planning of Networks	Introduction to Network Modeling and Calculation with DIgSILENT PowerFactory, Introduction to Data Processing and Modeling with Python, Application of Python in Energy System Modeling and Analysis.	Prof. Dr.-Ing. Bernd Engel
Innovative energy systems	The aim of this course is to provide a compact insight into energy systems that contribute significantly to the energy transition in prosumer households. The focus is on key components such as photovoltaic cells, PV inverters, stand-alone grid systems, heat pumps and energy management.	Prof. Dr.-Ing. Bernd Engel
Electromobility	Battery diagnostics, electrode production, electrode packaging, power electronics and electrical machines, powertrain simulation.	Prof. Dr.-Ing. Michael Kurrat, Prof. Dr.-Ing. Bernd Engel
High voltage technology	High-voltage measurement technology, insulating material technology, generation of high DC and AC voltage, lightning impulse voltage, breakdown tests, use of augmented reality and circuit breaker opening tests.	Prof. Dr.-Ing. Michael Kurrat
Electrotechnical laboratory practical course specializing in battery technologies	Impedance spectroscopy, pressure distribution in LIB, surface analysis of electrodes, explosion tests with LIB, simulation and modeling of batteries.	Prof. Dr.-Ing. Michael Kurrat

Student Projects and Theses 2022

Student Projects

Author	Title
Filipe Budnik	Development of a simulation environment for testing fallback strategies in an active reactive power management system
Dirk Wilhelm Franke-Hameke	Research and evaluation of different approaches and projects of bidirectional charging
Caroline Hampe	Modeling of relevant parameters influencing future net electricity consumption in Germany in 2030
Niklas Hardebusch	Development of an optimization model to cover the demand for ancillary services using offers from prosumer households
Eric Krupp	Identification of possible future charging technology scenarios for a comprehensive charging infrastructure for battery electric heavy-duty vehicles
Nils Reinköster	Ecological evaluation of new construction measures in the German power grid
Victor Schnell	Research, conceptualization and evaluation of strategies for the provision of ancillary services by prosumers in the low-voltage grid
Birte Sönnichsen	Techno-economic analysis of hydrogen imports against the backdrop of Germany's climate targets for 2045
Kim Maria Tigelaar	Development of operating strategies for HEMS for the provision of decentralized frequency control by households
Zhaoxian Ye	Concepts for superconductor use in aviation
Amelie Zech	Flexibilization of modern consumption devices of prosumers for grid-serving operation

Bachelor Thesis

Author	Title
Alexandra Aumüller	Partial discharge measurements and dielectric investigations on additively manufactured insulating material samples
Julika Dertnig	Conception and implementation of a semi-automated load flow calculation for Avacon's low-voltage grids to evaluate the integration of charging points
Lisa Ermer	Development of a dynamic model to analyze the potential of providing instantaneous reserve from electrolyzers

Author	Title
Mats Göhrmann	Investigation of harmonics caused by charging electric vehicles in the industrial grid and their effects above the 50th order
Nils Hartau	Research and comparison of different approaches to battery ageing through bidirectional charging
Sophie Herbeck	Voltage control in distribution grids with sensitivity factors
Marius Hinz	Requirements analysis for investigations of high-temperature superconductors in electrical flying
Tobias Jesberger	Investigation of the influence of external field control rings on the electric strength of vacuum interrupter
Firas Jmili	Technical applications of home storage systems to improve voltage quality ("unbalance") through local voltage stability
Simon Löbel	Laboratory investigation of phase-precise charging of electric vehicles to reduce unbalance in the low-voltage grid
Ingtyas Megahayu	Offshore Transformer Design through Dynamic Loading
Lukas Meuer	Determination and comparison of the operating characteristics of a battery storage system
Corvin Nothdurft	Measurement analysis of resulting interactions regarding harmonics between electric vehicles and the industrial grid
Marlene Pape	Prediction of reactive power behaviour in electrical power systems using machine learning forecasting methods
Sebastian Prien	Statistical study of the development of prosumers' energy systems up to 2030 and analysis of the impact on low-voltage grids
Röthig Thomas	Investigation of the dependence of the formation of the recovery voltage in an LVDC model arrangement on the arc mapping using a high-speed camera

Master Thesis

Author	Title
Jonas Biniek	Investigation of the temperature behavior of lithium-ion pouch cells during fast charging tests using thermal equivalent circuit models
Paul Broschinski	Implementation and simulative evaluation of the synergies of the multi-use of residential battery energy storage systems
Lei Chen	Communication of home storage systems in PowerFactory to reduce unbalance through coordinated operating strategies
Miguel Dorantes Ledesma	Investigation of the effects of communication interruptions on the TG-DG interface in electrical power systems

Author	Title
Levente Egyházi	Development of a methodology for the economic evaluation of future agri-photovoltaic projects in the context of changing agricultural crops
Julien Essers	Development of a platform for realistic testing of energy management sytems in prosumer households and apartment buildings
Johann Fetköter	Optimization of production costs for Power-to-X products in Python
Gerrit Fröhlich	Options for optimizing the grid integration of charging facilities to increase the connection potential in medium-voltage grids
Sophia Giere	Analysis and comparison of the options for implementing alternative drives in bus operation
Johanna Grobler	Creation of an overall concept for charging electric vehicles from decentralized and centralized renewable energy
Yifan Gu	Comparison of measuring devices for the characterization of permittivity and dissipation factor and creation of an evaluation routine for their representation
Benjamin Hoppe	Concept development for the use of photovoltaic systems in the proximity of railroad lines in the German rail network
Markus Klages	Normative, simulative and economic analysis of possible applications of private home storage systems to improve unbalance
Alexandra Klinger	Determination of load profile time series for different charging concepts for depot charging of battery-powered light commercial vehicles
Jasper Klinkig	Conceptual design and evaluation of the distribution of external control signals by household energy management systems
Julius Kohlhepp	Implementation and simulative evaluation of congestion management with flexible prosumer systems at the low-voltage level
Felix Korff	Development of a techno-economic methodology for estimating active power losses in wind and PV parks when providing reactive power
Hendrik Kösjan	Investigation of methods to reduce unbalance in the low-voltage grid with a focus on phase-precise charging of electric vehicles
Ilja-Pascal Krecker	Implementation of electrochemical impedance spectroscopy in the hardware of the cell controller of an automotive battery system
Karsten Laaken	Implementation of current limiting of grid-forming inverters for unbalanced grid fault situations
Jannes Langemann	Metrological characterization of the effects of charging facilities for electric vehicles on grid connection points and measurement technology
Jiao Li	Investigation of the post-current behavior of a vacuum interrupter in high-current circuits using statistical design of experiments methodology

Author	Title
Lennard Meinecke	Modeling and simulative evaluation of the control of innovative grid components for use in voltage control
Katja Metzler	Investigation of measures to allocate future electricity system costs for PV self-consumption systems in a grid-friendly and polluter-pays manner
Kai Newmann	Investigation of the influencing variables of a series circuit in a vacuum
Jannik Pohl	Investigation of plasma conductivity in a model spark gap in the period of the recovery voltage
Daniel Rausch	Modeling, analysis and evaluation of hydrogen-powered agricultural machinery in field cultivation
Andre Rehbock	Simulations and laboratory testing of voltage and unbalance control for single-phase battery inverters
Nelly Schulz	Development of an electrical electrolyser model including dynamic power control for the provision of frequency-stabilizing measures
Buri Sen	Economic and technical evaluation of the use of decentralized battery energy storage systems for charging infrastructures
Mike Stefan Skroch	Creation of typical vehicle driving profiles and hot-spot analysis of charging points and times based on empirical data
Benedikt Skurk	Analyse, Simulative implementation and systematic comparison of concepts for voltage maintenance with inverter-based systems at the low-voltage level
Lei Song	Experimental investigation of the vacuum arc with parameter variation
Peirui Song	Investigation of the influence of different components on the effectiveness of stand-alone grid detection with current and voltage inverters
Lia Stücke	Development and validation of solution strategies for the handling of incorrect measurements in distance protection systems
Jaruwan Suisuwan	Development of a model for the optimal dimensioning of power engineering devices for residential buildings
Marten Thomes	Validation of a semi-empirical model to describe the recovery voltage of an encapsulated model arrangement after current loads in the operating range of an LVDC hybrid switch
Laura Tiedemann	Partial discharge tests on enameled wires to detect the influence of different insulating media
Rui Wang	Optimization and validation of a unified power quality controller (UPQC), in particular consideration of critical applications
Yang Wang	Optimization and validation of a unified power quality controller (UPQC) and transformation options in other components
Emil Weymann	Development and testing of the communication infrastructure for an inductive charging system for electric vehicles

Author	Title
Till Zeumer	Investigation and development of DC protection concepts for on-board electrical systems in electric aircraft using model-based systems engineering
Yusheng Zhou	Regulation in the low-voltage distribution grid with a focus on charging infrastructure
Shaojie Zhu	Implementation of a power quality controller in the form of a Simulink model on inverter hardware to create a prototype
Maximilian Zirkler	Analysis, simulative implementation and systematic comparison of concepts for voltage stability with inverter-based systems at the low-voltage level

Student Projects and Theses 2023

Student Projects

Author	Title
Paulina Bilic	Price-based modeling of the balancing power market to investigate innovative bidding strategies
Thea Böttcher	Regionalized consumption forecast of future electricity consumption by industry in Germany in 2030
Ayscha El Menuawy	Status quo and future trends for alternative power systems in field management
Gerrit Everwin	Analysis of the data quality and deviations of the EnergieMonitor as a digital solution for the regional electricity balance
Merle Ferk	Conceptual design, simulative implementation and evaluation of frequency control by prosumers in low-voltage grids
Janina Gottschalk	Investigation of the chemical reactivity of various metal oxalates in lithium-ion batteries
Henning König	Economic analysis of partial renewables energy supply on farms
Klaas Koring	Analysis of the potential of electrolyzers to cover future instantaneous reserve requirements
Leon Küchler-Völkel	Analysis and conceptual design of the aggregation of small-scale devices in prosumer households for grid-serving services
Rasmus Offt	Energy-economical potentials of energy storage plants against the backdrop of the provision of control energy
Aicha Platzdasch	Investigation of machine learning models for time series prediction in electrical power systems
Lara Prüßmeier	Potential analysis of semi-public charging in Braunschweig
Eike Schwarz	Development of a methodology for estimating the potential for rooftop photovoltaic systems on agricultural buildings
Thorben Wehmeier	Development of a methodology for assessing the potential of waste-to-energy biogas plants in agricultural regions

Bachelor Thesis

Author	Title
Ibtissam Bel Khattar	Analysis and evaluation of grid-orientated charging concepts for electric vehicles
Steffen Bollhorn	Design and application of data pre-processing for machine learning forecasting methods
Selim Dimassi	Concept study and planning of a test park for different solar generation and regenerative transformation systems in Tunisia
Claas Ebert	Evaluating, analysing and assessing agricultural electricity consumption in the context of the energy transition
Stefan Hofmann	Analysis, modelling and transformation of the energy supply of irrigation systems in agriculture in the context of the energy transition

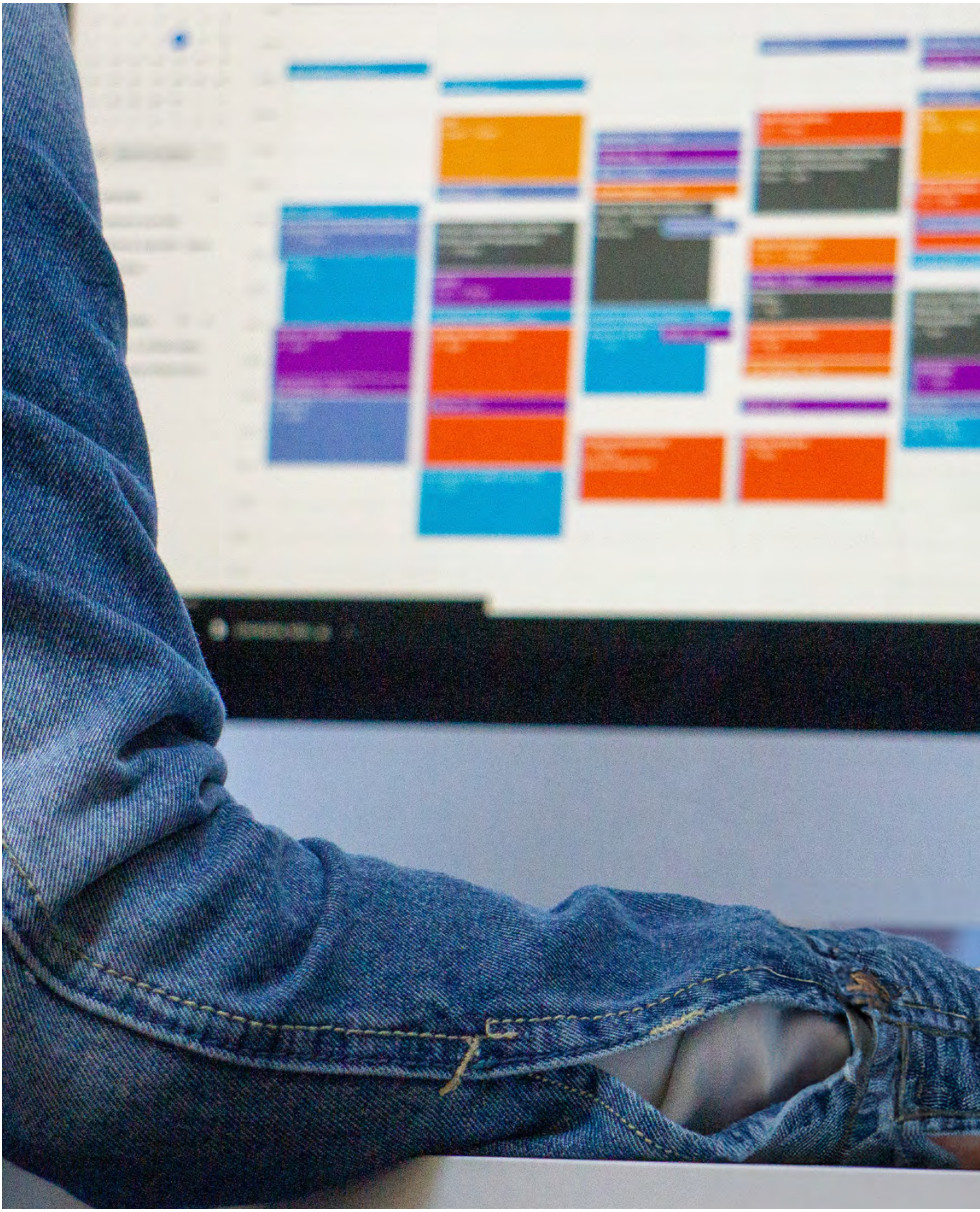
Author	Title
Hannes Kurzmann	Development of a planning aid for the identification of medium and long-term grid expansion projects in the low-voltage grid
Michelle Leopold	Analysis and evaluation of the status quo and the development potential of biogas plants in German agriculture
Samar Ouadhani	Systematic specification of new residential energy management control strategies
Emma Pensky	Analysing the effects of different energy procurement models and different topologies on the use of bidirectional charging
Mika Radler	Modeling of electricity consumption in the commercial, trade, and services (GHD) and household sectors considering efficiency improvements in Germany until 2030.
Anthea Rieseberg	Automation of an evaluation & analysis of measurement data from a field test with electric vehicles
Nils Rosebrock	Structure of a partial discharge measurement
Johannes Rothert	Development of a communication concept for distributed energy management using the smart meter infrastructure in Germany
Hannah Schröder	Stakeholder analysis for the charging infrastructure expansion
Kai Schulze	Simulative evaluation of the grid-serving use of flexibility for higher voltage levels
Alexander Wedemann	Analysis and discussion of incentives and guidelines for improving unblance through (home) battery storage
Laura Zalewski	Evaluation of charging infrastructure options for battery electric multiple units for Goslar and Bad Harzburg

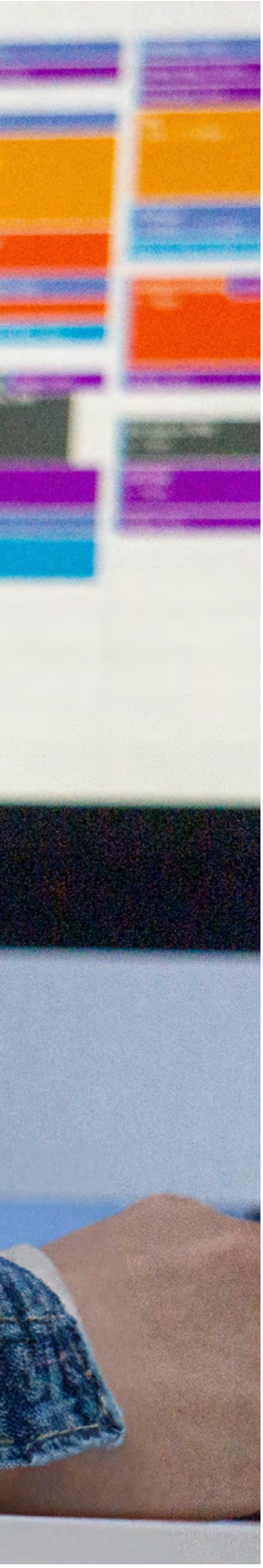
Master Thesis

Author	Title
Faraj Abd Alraheem	Investigation and evaluation of the metal vapor arc of a vacuum interrupter with different TMF contacts
Leonie Maria Brümmer	Development of a thermal building model with implementation in Python to analyze energy efficiency and heat demand, taking into account existing buildings in Germany
Eray Cinkaya	Analysis and implementation of grid forming concepts for HVDC systems
Yannic Cullmann	Laboratory testing of voltage stability and unbalance control for single-phase, two-phase and three-phase battery inverter systems
Felten Feldt	Simulation Studies needed for Planning and Specification of Offshore Wind HVDC Interconnectors
Merle Ferk	Conceptual design, model-based implementation and simulative evaluation of the application-oriented multi-use of domestic battery storage systems
Keno Giesselmann	Evaluation of grid-supporting and grid-sustaining charging approaches for electric vehicles based on measurement data from a commercial vehicle fleet
Nils Hendrik Grafelmann	Development of a test setup and performance of disconnection tests on cutout high-voltage fuses
Caroline Hampe	Development of operator models for German renewable energy communities in the area of conflict between economy, environment and social issues

Author	Title
Niklas Hardebusch	Performance analysis for online and offline algorithms in residential prosumer energy management
Ahmed Hassanin	Further development of a model for the optimal dimensioning of power engineering devices for residential buildings
Zhuoyao Huang	Development of sustainable charging strategies for electric vehicles for integration into the operating concept of a home energy management system
Jan Philip Jäger	Investigation, implementation and evaluation of various classification algorithms for LVDC selective protection
Maximilian Jantos	Detailed technical description and normalization possibilities of plants for exponential growth of RE generation, local use and production of green hydrogen for countries in North Africa
Anouar Jemai	Development of a testing-tool for communication scenarios in prosumer energy management systems
Tim Joswig	Development and integration of a charging strategy for a fleet based on local renewable energy in an energy management system
Henning König	Design and economic analysis of business models for wind turbines for hydrogen production and reconversion to electricity
Eric Krupp	Development and evaluation of different abstracted AEM electrolyzer models for dynamic grid stability investigations
Jianuo Li	Integration of different energy generation models to simulate charging strategies based on renewable generation”
Sebastian Lindemann	Investigation of amplification and compensation effects with regard to harmonics by integrating electric vehicles into an existing industrial network
Yasmin Loeper	Conceptualization of the possible participation of volatile generators in balancing power and balancing energy markets
Linus von Loh	Requirements definition and system design of a DC system in the Netflexum project using MBSE
Adrian Lux	Investigation and evaluation of the integration of emergency power systems into an industrial grid with included gas and steam power plant in the context of a blackout scenario
Edgar Martins Pires	Detailed technical description of concepts for exponential growth of RE generation and transformation of energy into tradable products for countries in North Africa
Mattias Meinert	Development of an optimization model to control charging processes for electric vehicles in districts
Marleen Möller	Shared energy use: local energy markets and P2P trading
Duc Anh Nguyen	Development of a dynamic battery storage model for transient grid stability studies
Friederike Paul	Exploratory data analysis of cross-voltage level and grid operator data sets
Zhiyan Peng	Method development for determining the condition of contaminated lithium-ion batteries
Marten Probst	Analysis of the effects of faults in HVDC systems
Daniel Redlich	Investigations to increase the electric strength of a vacuum interrupter with external field control rings
Peter-Matthias Reimers	Conceptual design, analysis and evaluation of charging infrastructure for battery electric multiple units for Goslar and Bad Harzburg

Author	Title
Nils Reinköster	Modeling and simulation of §14 a EnWG in the low-voltage grid
Kevin Schiemenz	Optical in-situ diagnosis of the electrode structure during the forming process
Victor Schnell	DC Fault Isolation in Power Systems on a Component Level
Julian Schwung	Laboratory investigation of the influence of grid-forming converters on industry-standard stand-alone grid detection methods of existing low-voltage systems and on their testing after a resonant circuit test
Jinyuan Si	Investigation into the influence of signal acquisition and processing on the determination of explosion pressures
Chenye Song	Thermal runaway investigations on lithium-ion batteries using electrochemical impedance spectroscopy
Christian Staudenmaier	Development of fallback scenarios for energy management systems
Daniel Swientek	Development of a model for the economic analysis of energy components, taking into account operator models in energy communities
Kim Maria Tigelaar	Creation of a transformation concept for the climate-neutral energy supply of a slaughterhouse
Jurek Türk	Development of a grid usage dependent reactive power supply for converter coupled renewable energy systems
Manuel Wagner	Investigation of an optimized PV system design through the use of on-load tap-changers to increase yield and improve the system's ability to provide power
Stefanie Walujski	Analysis and evaluation of the influence of highly dynamic frequency maintenance mechanisms on the future demand for instantaneous reserve
Ziang Wang	Electrochemical investigation of the fromation of lithium-ion batteries as a function of impurity additives
Fabian Witt	Development of a thermal model to simulate the heat demand of livestock housing in agriculture
Qianyu Wu	Grid Forming Wind Farm Converter Controllability Fault Ride Through Study with Participation of HVDC
Yushijie Xin	Creation of different pricing models and their effects on the charging periods of electric vehicles
Edgar Zeitler	Investigation of the dynamic stability and useful operating ranges of tap-change transformers when used in PV parks to increase yields
Zijian Zhao	Electrolyte changes during cyclic ageing of lithium-ion batteries
Huanni Zhu	Model-based development of PHiL experiments for DC systems





Chronology

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Rauscher, F., Zimmermann, V., Sauer, T., Engel, B.
Bereitstellung von Momentanreserve aus Mittel- und Niederspannungsnetzen
ENINNOV2022 — 17. SYMPOSIUM ENERGIEINNOVATION, GRAZ, AUSTRIA (ONLINE), 16.–18.02.2022

Ries, J., Essers, J., Hadlak, M., Reinhold, C.
Entwicklung einer Rapid Control Prototyping Platform für die Analyse von Energiemanagementstrategien auf Laborebene
ENINNOV2022 — 17. SYMPOSIUM ENERGIEINNOVATION, GRAZ, AUSTRIA (ONLINE), 16.–18.02.2022

Klabunde, F., Reinhold, C., Engel, B.
Regionsabhängige Energiesystemanalysen auf Basis einer datengesteuerten Verteilnetzmodellierung
ENINNOV2022 — 17. SYMPOSIUM ENERGIEINNOVATION, GRAZ, AUSTRIA (ONLINE), 16.–18.02.2022

Sauer, T., Tiedt, F., Rauscher, F., Engel, B.
Vergleich verschiedener Wechselrichterregelungen in Netzfehlersituationen im Grid Dynamics Laboratory
ENINNOV2022 — 17. SYMPOSIUM ENERGIEINNOVATION, GRAZ, AUSTRIA (ONLINE), 16.–18.02.2022

Jennert, T., Kurrat, M.
Diagnosis of cell properties by electrochemical impedance spectroscopy during formation
14. INTERNATIONALE FACHTAGUNG KRAFTWERK BATTERIE – ADVANCED BATTERY POWER", MÜNSTER, GERMANY, 28.–30.03.2022

Kopp, T., Bösche, D., Vieth, P., Anspach, F., Kurrat, M., Meyer, S.
Prüfungen von Hybridschaltern in dem neuartigen Hochleistungs-Gleichstromprüffeld DC.lab der TU Braunschweig
26. FACHTAGUNG ALBERT-KEIL-KONTAKTSEMINAR, KARLSRUHE, GERMANY, 30.03.–01.04.2022, S. 141–145. ISBN: 978-3-8007-5780-0

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Untersuchung der Anforderungen und modellgestützte Komponentenauslegung eines 3-kV-Hybridschaltgerätes in einem MVDC-Netz
26. FACHTAGUNG ALBERT-KEIL-KONTAKTSEMINAR, KARLSRUHE, GERMANY, 30.03.–01.04.2022, S. 146–153. ISBN: 978-3-8007-5780-0

Gartner, J., Xu, Z., Wussow, J., Engel, B.
Harmonics in industrial grids as a result of charging infrastructure in employee parking lots
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Garn, T., Vanselow, A., Biedermann, C., Moser, A., Engel, B.
Flicker Emission Of Electric Vehicle Charging In Low Voltage Grids
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Anspach, F., Peters, E., Bösche, D., Vieth, P., Kopp, T., Kurrat, M.
Electrical investigation of the time development of the recovery voltage of a closed model arrangement after current loads in the operating range of an LVDC hybrid switch
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Ferenz, S., Ofenloch, A., Vaca, F., Wagner, H., Werth, O., Breitner, M., Lehnhoff, S., Nieße, A.
An Open Digital Platform to Support Interdisciplinary Energy Research and Practice—Conceptualization
ENERGIES 2022, 15 (17), 6417, 02.09.2022, DOI: 10.3390/EN15176417

Flügel, K., Gentsch, D., Kurrat, M.
Investigations of Lightning Impuls Voltage on Vacuum Circuit Breakers and Comparison of Effects between Industry and Research
8TH ITG INTERNATIONAL VACUUM ELECTRONICS WORKSHOP, BAD HONNEF, GERMANY, 02.–03.09.2022

Klabunde, F., Wegkamp, C., Engel, B.
Provision of grid-serving flexibility by agricultural operations and households in rural power distribution grids
NEIS 2022 — CONFERENCE ON SUSTAINABLE ENERGY SUPPLY AND ENERGY STORAGE SYSTEMS, HAMBURG, GERMANY, 26.–27.09.2022, S. 208–214. ISBN: 978-3-8007-5983-5

Meyer, T., Gentsch, D., Kurrat, M.
Review of post-arc current measurements and simulation of test circuit interaction
CURRENT ZERO CLUB VACUUM CIRCLE, DÄTTWIL, SWITZERLAND, 27.09.2022

Wegkamp, C., Buchholz, S., Tiemann, P., Engel, B., Weyer, H., Nieße, A.
Specific Product Characteristics of System Services and a Discussion of the joint market-based Procurement in a Single Product
11TH INTERNATIONAL RUHR ENERGY CONFERENCE (INREC), ESSEN, GERMANY, 27.–28.09.2022

Ebbert, L., Di-Modica, G., Wussow, J., Engel, B.
Comparing different price models and their impact on the charging times of battery electric vehicles
6TH E-MOBILITY POWER SYSTEM INTEGRATION SYMPOSIUM, EMOB 2022, THE HAGUE, NETHERLANDS, 10.10.2022, DOI: 10.1049/ICP.2022.2723

Wagner, H., Peñaherrera V. F., Fayed, S., Werth, O., Eckhoff, S.
Co-simulation-based Analysis of the Grid Capacity for Electric Vehicles in Districts: the Case of Am Ölper Berge" in Lower Saxony
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Fayed, S., Peñaherrera V. F., Wagner, H., Rolink, J.
An Open Source Grid Observer for the Analysis of Power Flexibilities in Low Voltage Distribution Grid Simulations
10TH INTERNATIONAL CONFERENCE ON SMART GRID AND CLEAN ENERGY TECHNOLOGIES (ICSGCE), KUALA LUMPUR, MALAYSIA (ONLINE), 14. – 16.10.2022, DOI: 10.1109/ICSGCE55997.2022.9953716

Anspach, F., Vieth, P., Bösche, D., Kurrat, M.
Comissioning of a novel high power medium voltage DC laboratory with exemplary studies on an MVDC hybrid contactor
67TH IEEE HOLM CONFERENCE ON ELECTRICAL CONTACTS, TAMPA, USA, 23. – 26.10.2022, P-ISSN: 2158-9992

Jennert, T., Kurrat, M.
Effects of electrochemical impedance spectroscopy before and after formation
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Landrath, O., Kurrat, M.
Development of fast charging strategies for lithium-ion battery cells using an electro-thermal model approach
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Rollin, A., Kurrat, M.
Impact of Metal Oxalates on Lithium-Ion Batteries
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Schneider, A., Klabunde, F., Buck, L., Ohlhoff, M., Reis, L., Olvermann, M., Kauffeld, S., Engel, B., Glatzel, G., Schröder, B., Frerichs, L.
Drawing transformation pathways for making use of joint effects of food and energy production with biodiversity agriphotovoltaics and electrified agricultural machinery
JOURNAL OF ENVIRONMENTAL MANAGEMENT, VOLUME 335, 2023, 24.02.2023, H. 335, S. 1 – 10. DOI: 10.1016/J.JENVMAN.2023.117539

Gartner, J., Nothdurft, C., Engel, B.
Wechselwirkungen zwischen Oberschwingungsquellen aus dem Industrienetz und Elektrofahrzeugen
ATZ ELEKTRON 18, 26 – 32 (2023), 06.04.2023, DOI: 10.1007/S35658-022-1432-6

Jennert, T., Song, C., Kurrat, M.
Investigation of battery cells during thermal runaway using electrochemical impedance spectroscopy
15. INTERNATIONALE FACHTAGUNG KRAFTWERK BATTERIE – ADVANCED BATTERY POWER", AACHEN, GERMANY, 27. – 28.04.2023

Rollin, A., Gottschalk, J., Novák, P., Kurrat, M.
How Are Different Metal Oxalates Influencing Li-Ion-Batteries?
15. INTERNATIONALE FACHTAGUNG KRAFTWERK BATTERIE – ADVANCED BATTERY POWER", AACHEN, GERMANY, 26. – 28.04.2023

Schuster, M., Pape, M., Studt, J., Bollhorn, S., Engel, B.
Design of a Data Driven Reactive Power Forecasting for an Active Cross-Voltage Level Reactive Power Management
ETG-KONGRESS 2023 — DIE ENERGIEWENDE BESCHLEUNIGEN, KASSEL, GERMANY, 25. – 26.05.2023, S. 1 – 6. HTTPS://IEEEXPLORE.IEEE.ORG/DOCUMENT/10172984

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Phase-Precise Control of Electric Vehicles to Reduce Voltage Unbalance in Low-Voltage Grids
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Biedermann, C., Beutel, V., Beyrodt, J., Brand, M., Buchholz, S., Gerlach, J., Majumdar, N., Leveringhaus, T., Lotz, M., Raeiszadeh, A., Scheunert, A., Teimourzadeh Baboli, P., Tiemann, P. H., Wegkamp, C., Agert, C., Breitner, M. H., Engel, B., Geissendörfer, S., Hofmann, L., Könnemund, M., Kurrat, M., Lehnhoff, S., von Maydell, K., Nieße, A., Weyers, H.
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Rooftop Photovoltaic Systems in German Agriculture – An Analysis of the Status quo and Potential for the future
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Lotz, M. R., Könemund, M., Kurrat, M.
Adaption of Inverter-Based System Controls to Reduce the Negative Impact of Intermediate Infeed on Distance Protection Systems
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Korff, F., Köppe, H., Engel, B.
Techno-economic Estimation of Reactive Power Related Additional Losses In Wind Farms During Reactive Power Supply
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2023 IEEE ELECTRICAL INSULATION CONFERENCE (EIC 2023), QUEBEC, CANADA, 18.–21.06.2023, S. 1–4. DOI: 10.1109/EIC55835.2023.10177325

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Partial Discharge measuring of additive manufactured component with a defined cavity
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PAC WORLD 2023 — PROTECTION, AUTOMATION & CONTROL WORLD CONFERENCE, GLASGOW, UNITED KINGDOM, 26.–29.06.2023

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Overview of Test Methods for Electric Strength of Vacuum Interrupter using Lightning Impulse Voltage
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Computer-aided optical plasma postprocessing applied on model spark gaps
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Flügel, K., Meyer, T., Gentsch, D., Kurrat, M.
Partial Breakdown Detection in Vacuum Interrupter under Lightning Impulse Voltage
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Kahn, M., Tiedemann, L., Kurrat, M.
High Voltage Design of Additive Manufactured Dielectric Test Samples
23RD INTERNATIONAL SYMPOSIUM ON HIGH VOLTAGE ENGINEERING, GLASGOW, UNITED KINGDOM, 28.08.–01.09.2023

Zeng, F., Kopp, T., Bösche, D., Claaßen, L., Vieth, P., Terörde, M., Kurrat, M.
Investigation of DC circuit breaker with extinguishing chamber at reduced ambient pressure for an application in avionics
CONFERENCE ON SUSTAINABLE ENERGY SUPPLY AND ENERGY STORAGE SYSTEMS (NEIS), HAMBURG, GERMANY, 04.–05.09.2023

Grandel, M., Kübler, C., Niehs, E., Wachenfeld, V., Engel, B.
Prioritized EV Charging – Enhanced Smart Meter Gateway infrastructure enabling an event driven dynamic tariff
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Peters, E., Bösche, D., Kurrat, M.
Design of a triggerable ignition circuit for model spark gap diagnostics
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High-pressure plasma phenomena in spark gaps — a survey
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Field Test of a Battery Electric Logistics Fleet: Results from a Field Test and Comparison of Different Charging Strategies
7TH E-MOBILITY POWER SYSTEM INTEGRATION SYMPOSIUM, COPENHAGEN, DENMARK, 25.09.2023

Kübler, C., Niehs, E., Grandel, M., Engel, B.
Smart EV Charging with Event Driven Tariffs in the German Smart Meter Infrastructure
7TH E-MOBILITY POWER SYSTEM INTEGRATION SYMPOSIUM, COPENHAGEN, DENMARK, 25.09.2023

Sauer, T., Schulz, N., Engel, B.
Control Strategies of Electrolyzers to contibute Intertia an Fast Frequency Reserve in Context of a Megawatt-Scale Hydrogen Living-Lab
22ND WIND & SOLAR INTEGRATION WORKSHOP, COPENHAGEN, DENMARK, 26. – 28.09.2023

Wagner, H., Lüdecke, M., Scheunert, A., Wegkamp, C., Engel, B., Weyer, H.
Technical and Legal Analysis of the Grid-Serving Multi-Use of Battery Storage Systems for Prosumers
22ND WIND & SOLAR INTEGRATION WORKSHOP, COPENHAGEN, DENMARK, 26. – 28.09.2023

Winter, B. O., Schwung, J., Schulz, N., Engel, B.
Limitations of Current Norms to Predict Reliable Islanding Detection by Example of two Detection Methods for Grid-Forming Inverters
22ND WIND & SOLAR INTEGRATION WORKSHOP, COPENHAGEN, DENMARK, 26. – 28.09.2023

Türk, J., Schuster, M., Köppe, H., Engel, B.
Development approach of a volt-var control for inverter-coupled renewable energy plants using deep reinforcement learning
22ND WIND & SOLAR INTEGRATION WORKSHOP, COPENHAGEN, DENMARK, 26. – 28.09.2023

Eichner, S., Schuster, M., Köppe, H., Sass, F., Grab, R.
Development of a Pricing Model for the Reactive Power Supply via Statcom Capability of a real PV Power Plant
22ND WIND & SOLAR INTEGRATION WORKSHOP, COPENHAGEN, DENMARK, 26. – 28.09.2023

Köppe, H., Schuster, M., Engel, B.
Improving Power System Efficiency: A Case Study on optimized Reactive Power Management in High-Voltage Grids
22ND WIND & SOLAR INTEGRATION WORKSHOP, COPENHAGEN, DENMARK, 26. – 28.09.2023

Wegkamp, C., Ferk, M., Grobler, J., Engel, B.
Application of Residental Prosumer Flexibility for Frequency Control — Analysis and Simulative Inverstigation Considering Control Power and Inertia
22ND WIND & SOLAR INTEGRATION WORKSHOP, COPENHAGEN, DENMARK, 26. – 28.09.2023

Jennert, T., Spörhase, S., Kianfar, A., Essmann, S.
Effect of thermal runaway of lithium-ion batteries in a flameproof enclosure and simultaneous electrochemical impedance spectroscopy
4TH IBSW 2023 – INTERNATIONAL BATTERY SAFETY WORKSHOP, ULM, GERMANY, 28. – 29.09.2023

Zeng, F., Kopp, T., Bösche, D., Vieth, P., Kurrat, M.
Schalten von DC-Lichtbögen unter Umgebungsbedingungen der Luftfahrt
27. VDE-FACHTAGUNG ALBERT-KEIL-KONTAKTSEMINAR, KARLSRUHE, GERMANY, 27. – 29.09.2023

Vieth, P., Bösche, D., Anspach, F., Kurrat, M.
Investigation on the recovery behavior of the mechanical switching path of DC hybrid circuit breakers
68TH IEEE HOLM CONFERENCE ON ELECTRICAL CONTACTS, SEATTLE, USA, 08. – 11.10.2023

Heckmann, W., Reimann, T., Degner, T., Winter, B. O., Ohrem, S.
Das Runde muss ins Eckige — Momentanreserve durch netzbildende Stromrichter im Verteilnetz
NETZPRAXIS 62 (10-23), 13.10.2023, HTTPS://EMAGAZIN.NP-MAGAZIN.DE/DE/PROFILES/4223BF679ADA/EDITIONS/9D3CC35F8588CB0EF03C

Ndoh, E. T., Byeon, S., Lotz, M. R., Ehlers, S.
A Method to Enable Reduced Sensor Capacitor Voltage Estimation in Modular Multilevel Converters
4TH INTERNATIONAL CONFERENCE ON MODELLING AND OPTIMISATION OF SHIP ENERGY SYSTEMS (MOSES), DELFT, NETHERLANDS, 26. – 27.10.2023

Jennert, T., Gomez, M. R.
Comparison of Thermal Runaway Early Detection Using Different Electrical Measurement Methods
INTERNATIONAL BATTERY PRODUCTION CONFERENCE, BRAUNSCHWEIG, GERMANY, 7. – 9.11.2023

Noronha, F., Rollin, A., Sukanya, S., Wilhelm, R., Kurrat, M., Kwade, A.
From end-of-life batteries to high quality graphite — developing a recycling process focused on anodic materials
INTERNATIONAL BATTERY PRODUCTION CONFERENCE, BRAUNSCHWEIG, GERMANY, 07. – 09.11.2023

Events 2022

20.01.2022
Study Seminar Winter Semester 21/22
KURRAT

25.01.–27.01.2022
Conference Future Power Grids, Session Chair
ENGEL

11.02.2022
Ph.D. Examination Jan Bellin
KURRAT

15.02.2022
DFG
KURRAT

16.02.2022
Current Zero Club Plenary meeting
KURRAT

17.02.2022
B-IGSM: Plenary Meeting
KURRAT

24.02.2022
FNN Info Day on Unbalance in Low-Voltage Grids
ENGEL

25.02.2022
Ph.D. Examination Ying Su (PTB), second assessor
ENGEL

10.03.2022
Film Shooting NEEMO
ENGEL

24.03.2022
Bmwk: Advisory Board Meeting - Digitalisation Barometer 2021
ENGEL

25.03.2022
Inspection of Sustainable Energy Systems and Electromobility (NEEMO) by the Accreditation Institute
ENGEL, KURRAT

29.03.–30.03.2022
Battery- Conference
KURRAT

29.03.–31.03.2022
Retreat of the AG Energy Systems
ENGEL

04.04.2022
ZIEHL-Conference
KURRAT

21.04.–22.04.2022
EFZN Annual Meeting Hydrogen
ENGEL

06.05.2022
JHV VDE Foundation Erwin Marx
KURRAT

12.05.–13.05.2022
Symposium Safety and Approval of Electrical Railway Equipment
ENGEL

19.05.2022
5th Lower Saxony Solar Energy Forum, Lecture
ENGEL

20.05.2022
Support Group Meeting of the VDE Network Technology Network Operation Forum (FNN)
ENGEL

30.05.2022
Final Workshop of the University Development Initiative
KURRAT

09.06.2022
Consortium Meeting EU- Research Program ALPHEUS
ENGEL

16.06.2022
Graduate College / CirkularLIB
KURRAT

22.06.2022
ESYS 2022 Conference Energy Prices and Security of Supply
ENGEL

21.06.–23.06.2022
PV Symposium 2022, Session Leader
ENGEL

23.06.–24.06.2022
FNN-Workshop “Grid-Forming Inverters”, Lecture
ENGEL

27.06.2022
Award Ceremony FK 5
KURRAT

06.07.–07.07.2022
Final Conference BMWK Research Project Netzregelung 2.0, Moderation
ENGEL

18.07.–19.07.2022
Strategy Workshop Automotive Research Centre of Lower Saxony
ENGEL

24.07.2022
NFF-Workshop
KURRAT

28.07.2022
VDE High Voltage Technology Programme Committee Meeting
KURRAT

06.09.2022
Prof.- Summer Party
KURRAT

15.09.2022
Grid Forming Seminar for TenneT TSO GmbH
ENGEL

19.09.2022
Energy Symposium of the North German Conference of Science Ministers
ENGEL

20.09.2022
AG Energy Technologies Workshop
KURRAT

26.09.–27.09.2022
Final Conference BMWK Research Project U-Control
ENGEL

28.09.–29.09.2022
ETG GMA Network Control and System Management Conference
ENGEL

04.10.–06.10.2022
Conference of the Faculty of Electrical Engineering, Information Technology and Physics
ENGEL, KURRAT

12.10.2022
VDE FNN: netz.con 2022 - The Congress on the Climate Protection Network
ENGEL

13.10.2022
NFF- Annual General Meeting
KURRAT

10.10.–14.10.2022
Grid Integration Week, 2 Lectures, Session Leader
ENGEL

24.10.2022
First Semester Welcome EMOB
KURRAT

27.10.2022
ZDIN- Network Meeting 2022
ENGEL

04.11.2022
EITP- Graduation Ceremony
KURRAT

10.11.2022
Final Conference BMWK Research Project Q-Integral
ENGEL

08.11.–10.11.2022
VDE - High Voltage Days
KURRAT

17.11.2022
Prof@Turntables
ENGEL

21.11.2022
ETG Symposium Generation and Storage of Electrical Energy - Security of Supply in the Energy System of the Future, Moderation of Panel Discussion
ENGEL

22.11.–23.11.2022
Energy Days of Lower Saxony
ENGEL

01.12.2022
VDE Symposium Thuringia District Association, Lecture
ENGEL

13.12.2022
ETG Congress / Programme Committee
KURRAT

Ongoing
ETG Task Force Young Enthusiasts
ENGEL

Ongoing
VDE BS Advisory Board Meeting
KURRAT

Ongoing
ETG Board Meeting
ENGEL

Ongoing
EFZN board Meeting
ENGEL

Ongoing
FNN Expert Network Asymmetry
ENGEL

Ongoing
ETG Q2 Meeting/Program Committee
KURRAT

Ongoing
City of the Future - Board Meeting
KURRAT

Ongoing
BK Robust H/S-Systems
KURRAT

Ongoing
Brunswick Scientific Society – BWG
KURRAT

Ongoing
Meeting DKE/K124 (High-Voltage and High-Current Test Engineering)
KURRAT

Ongoing
PISC - Meeting
KURRAT

Ongoing
JRG Wiring Technologies Advisory Board Meeting
KURRAT

Ongoing
Advisory Board Meeting BMWK Roadmap System Stability
ENGEL

Events 2023

18.01.2023
VDE New Year's reception
ENGEL

23.01.2023
FNN Workshop on European Grid Codes
ENGEL

25.01.–26.01.2023
Conference on Future Power Grids
ENGEL

31.01.–01.02.2023
Appointments Committee for Energy Networks
KURRAT

02.02.–03.02.2023
Workshop EFZN Board
ENGEL

14.02.2023
PTB Stakeholder Hydrogen workshop, Lecture
ENGEL

16.02.2023
ZLE Presence Workshop
ENGEL

20.02.2023
VDE_BS Strategy Meeting Hanseatic Region
KURRAT

22.02.2023
Research Exchange Ilmenau
KURRAT

23.02.–24.02.2023
24th NFF Workshop
ENGEL

28.02.2023
Current Zero Club Meeting on Planning ads Future
KURRAT

28.02.–02.03.2023
PV Symposium 2023, Session Leader
ENGEL

08.03.2023
Kick-off meeting BMWK Research Project Q-REAL
ENGEL

14.03.2023
Regional Network Meeting for the Hanover Region and Southern Lower Saxony
ENGEL

16.03.–17.03.2023
Annual Meeting EFZN
ENGEL

23.03.2023
Ground-Breaking Ceremony for H2 Terminal
ENGEL

23.03.2023
MetroPolis Workshop
KURRAT

24.03.2023
Doctorate Marian Meyer, Second Assessor
ENGEL

28.03.2023
InZePro- Research Colloquium
KURRAT

28.03.2023
ETG-Q2
KURRAT

18.04.2023
BK Chemie Energy Storage
KURRAT

19.04.2023
ZDIN/ZLE Hanover Fair
ENGEL

20.04.2023
3rd Advisory Board Meeting Roadmap System Stability
ENGEL

21.04.2023
Brunswick Scientific Society - BWG - Annual Meeting/ Celebration
KURRAT

24.04.2023
Ph.D. Examination Dirk Bösche
KURRAT

26.04.2023
Presentation to Technical Consulting DB Netze
ENGEL

28.04.2023
Brunswick Scientific Society - BWG - Plenary Assembly
KURRAT

03.05.2023
Inauguration of Fraunhofer IEE/ 35th Anniversary
ENGEL

02.05.–03.05.2023
DKE-124 Meeting
KURRAT

04.05.2023
NFF - Board Meeting
ENGEL

05.05.2023
Summer Get-Together of the Professors
KURRAT

10.05.–11.05.2023
BNetzA/EFZN: 14th Göttingen Energy Conference, Greeting
ENGEL

23.05.2023
Kick-off BMWK Research Project Verteilnetz 2030plus Internal
ENGEL

25.05.–26.05.2023
ETG Congress 2023
ENGEL, KURRAT

07.06.2023

BLB- General Assembly 2023
KURRAT

14.06.2023
Ph.D. Examination Frederik Anspach
KURRAT

16.06.2023
Meeting of the VDE FNN Support Group
ENGEL

22.06.2023
Kick-off BMWK Research Project Verteilnetz 2030plus
ENGEL

26.06.2023
Lecture "New System Services from Photovoltaics and Battery Systems"
ENGEL

23.06.–01.07.2023
ISDEIV-Conference
KURRAT

05.07.2023
EFZN Research Workshop
ENGEL

07.07.2023
Electrical Engineering Faculty Day
ENGEL

10.07.2023
JRG-Wiring Technologies-Advisory Board Meeting
KURRAT

14.07.2023
VDE Hanseatic Day
KURRAT

14.07.2023
BK Thermodynamics
KURRAT

18.07.2023
Ph.D. Examination Robin Drees
KURRAT

20.07.2023
Institute Company Outing
ENGEL, KURRAT

21.08.–23.08.2023
AG Energy Technologies Workshop
KURRAT

28.08.2023
Final Project Meeting of the BMWK Research Project flexess
ENGEL

29.08.–31.08.2023
Retreat of the Energy Systems Working Group
ENGEL

11.09.2023
Gas Discharge 23
KURRAT

11.09.–12.09.2023
FNN Info Day System Requirements
ENGEL

18.09.2023
Kick-off BMWK Research Project Fuchstal leuchtet
ENGEL

19.09.2023
ZDIN Network Meeting 2023
ENGEL

21.09.2023
Energy Research Conference of the North German Conference of Science Ministers
ENGEL

21.09.–22.09.2023
elenia Symposium/Energy Seminar
ENGEL, KURRAT

25.09.–26.09.2023
NFF-Workshop
KURRAT

27.09.2023
Ph.D. Examination Benjamin Weber
KURRAT

25.09.–28.09.2023
Renewable Energy Grid Integration Week, Session Leaders
ENGEL

28.09.2023
VDE FNN Netzcamp
ENGEL

29.09.2023
Symposium on High-Voltage Technology
KURRAT

10.10.–11.10.2023
Conference of the Faculty of Electrical Engineering, Information Technology and Physics
ENGEL, KURRAT

12.10.2023
Presentation at the Workshop of the Federal Association of Local Rail Transport (BSN) on Infrastructure for Operation with Battery Electric Vehicles (BEMU)
ENGEL

12.10.2023
Ph.D. Examination L. Hanisch
KURRAT

16.10.–17.10.2023
NetFlexum Consortium Meeting
KURRAT

19.10.2023
Regional Network Meeting of the Citizens' Dialogue on the Electricity Grid
ENGEL

27.10.2023
Ph.D. Examination Florian Rauscher
ENGEL

02.11.2023
First Semester Welcome EMOB
KURRAT

03.11.2023
Graduation ceremony Faculty of Electrical Engineering, Information Technology, Physics
ENGEL

06.11.–08.11.2023
ETG Symposium on Flexible Generators, Consumers and Storage Systems
ENGEL

13.11.2023
NFF Doctoral Award Ceremony
ENGEL

16.11.2023
Prof@Turntables
ENGEL

20.11.–21.11.2023
15th Lower Saxony Energy Days
ENGEL

23.11.2023
Ph.D. Examination Stefanie Celan
ENGEL, KURRAT

25.11.–26.11.2023
ETG High-Voltage goes green
KURRAT

14.12.2023
Christmas Party Institute
ENGEL

Ongoing
ETG Task Force Young Enthusiasts
ENGEL

Ongoing
EFZN Board Meeting
ENGEL

Ongoing
ETG Congress Program Committee
KURRAT

Ongoing
VDE_BS Board and Advisory Board Meeting
KURRAT

Ongoing
City of the Future - Board meeting
KURRAT

Ongoing
PISC-Meeting
KURRAT

Ongoing
BK Electrochemistry
KURRAT

Ongoing
BK Photonic Systems and Technologies
KURRAT

Ongoing
Advisory Board Meeting BWMK Roadmap System Stability
ENGEL

Ongoing
EFZN Supervisory Board Meeting
ENGEL

Participation in self-administration 2022

University

MICHAEL KURRAT

- Dean's meeting
  20.01. | 10.02. |31.05.
- Deanery
  10.02. | 22.02. | 17.03. | 22.09. | 08.12.

BERND ENGEL

- Energy Advisory Board
  09.03.
- WG Sustainability
  11.01 | 20.01. | 17.02. | 17.03 | 21.04. | 12.05. | 16.06. | 07.07. | 25.08. | 22.09. | 02.11. | 12.12.

Faculty

MICHAEL KURRAT

- Subject Representative Meetings
  21.01. | 22.04. | 20.05.2 | 24.06. | 22.07. | 16.12.
- Faculty Council Meeting (FKR) / Special FKR
  21.03. | 25.04. | 23.05. | 27.06. | 15.08. | 19.09. | 10.10. | 21.11. | 19.12.
- Faculty Council Meeting (committees) Extraordinary
  03.02.
- Planning Board EITP
  14.01. | 18.03 | 16.05. | 10.06. | 30.09. | 02.12.
- Faculty Council EITP

BERND ENGEL

- Subject Representative Meetings
- Faculty Council Meeting
  24.01.
- Faculty Council EITP (Substitution)
- Study Commission
  ET/WIING-ET/NEEMO/ELSY/EMOB
  10.01. | 28.09. | 13.12.
- Examination Committee
  ET/EMOB/ELSY/NEEMO/QTEC

elenia Institute

MICHAEL KURRAT

- Executive Head of the Institute
- Institute Board (Managing Board)
  onogoing - monthly
- Managing Board Meeting elenia
  31.01. | 14.02. | 16.05. | 16.06. | 13.06. | 11.07. | 17.10 | 14.11. | 12.12.
- Plenary Meetings (Staff Assembly)
  ongoing - monthly
- Project Management Officeongoing – if required
- Team Leader Meeting WG Energy Technologies, ongoing - monthly
- Novice Group (Doctoral Student Seminar), ongoing - monthly
- Mentoring Meeting
  12.01 | 31.05. | 06.07. | 14.11.
- Mentoring meeting
  once per semester
- Student Colloquium
  ongoing - weekly
- First Semester Welcome
  24.10.

BERND ENGEL

- Institute Board (Managing Board)
  ongoing -monthly
- Managing Board Meeting elenia
  31.01. | 14.02. | 16.05. | 16.06. | 13.06. | 11.07. | 17.10 | 14.11. | 12.12.
- Plenary Meetings (Staff Assembly)
  ongoing -monthly
- Project Management Office
  ongoing – if required
- Team Leader Meeting WG Energy Systems, ongoing - monthly
- Mentoring Meeting
- Mentoring Group
  once per semester
- Student Colloquium
  ongoing - weekly

Participation in self-administration 2023

University

BERND ENGEL

- Energy Advisory Board
  27.04. | 06.12.
- WG Sustainability
  23.01. | 20.02. | 12.04. | 13.06. | 01.11.

Faculty

MICHAEL KURRAT

- Faculty Council EITP
- Subject Representative Meetings
  20.01. | 14.04. | 16.06. | 22.09. | 20.10. | 17.11 | 15.12.
- Subject Representative Meetings-Teaching
  12.07.
- Faculty Council Meeting
  23.01 | 02.02. | 20.03. | 17.04. | 15.05. | 19.06. | 24.07. | 23.10. | 20.11. | 18.12.
- Planning Board EITP
  10.02. | 10.03. | 07.07.

BERND ENGEL

- Faculty Council EITP (Substitution)
- Subject Representative Meetings
  20.01. | 16.06. | 12.07. | 18.07. | 22.09.
- Faculty Council Meeting
  24.07.
- Study Commission
  ET/WIING-ET/NEEMO/ELSY/EMOB
  22.02. | 08.05.
- Examination Committee
  ET/EMOB/ELSY/NEEMO/QTEC

elenia Institute

MICHAEL KURRAT

- Executive Head of the Institute
  until April 2023
- Institute Board (Managing Board)
  onoging -monthly
- Managing Board Meeting elenia
  24.01. | 21.02. | 20.03. | 24.04. | 25.05. | 19.06 | 24.07. | 20.09 | 23.10 | 13.11. | 11.12.
- Plenary Meetings (Staff Assembly)
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- Project Management Office
  ongoing – if required
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  ongoing - monthly
- Novice Group (Doctoral Student Seminar)
  ongoing - monthly
- Mentor Meeting
  30.01. | 24.05. | 17.07.
- Mentor Group
  once per semester
- Student Colloquium
  ongoing - weekly

BERND ENGEL

- Executive Head of the Institute
  since April 2023
- Institute Board (Managing Board)
  onoging -monthly
- Managing Board Meeting elenia
  24.01. | 21.02. | 20.03. | 24.04. | 25.05. | 19.06 | 24.07. | 20.09 | 23.10 | 13.11. | 11.12.
- Plenary Meetings (Staff Assembly)
  ongoing -monthly
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  ongoing – if required
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- Mentor Meeting
- Mentor Group
  once per semester
- Student Colloquium
  ongoing - weekly

Imprint

elenia Institute for High Voltage Technology and Power Systems

Schleinitzstraße 23
38106 Braunschweig
Phone +49 531 391-7700
Telefax +49 531 391-8106

elenia@tu-braunschweig.de
www.tu-braunschweig.de/elenia

Editorial team: Merten Schuster, Johanna Grobler, Nelly Schulz
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elenia Institute for High Voltage Technology
and Power Systems

Schleinitzstraße 23
38106 Braunschweig
Phone +49 531 391-7700
Telefax +49 531 391-8106

elenia@tu-braunschweig.de
www.tu-braunschweig.de/elenia