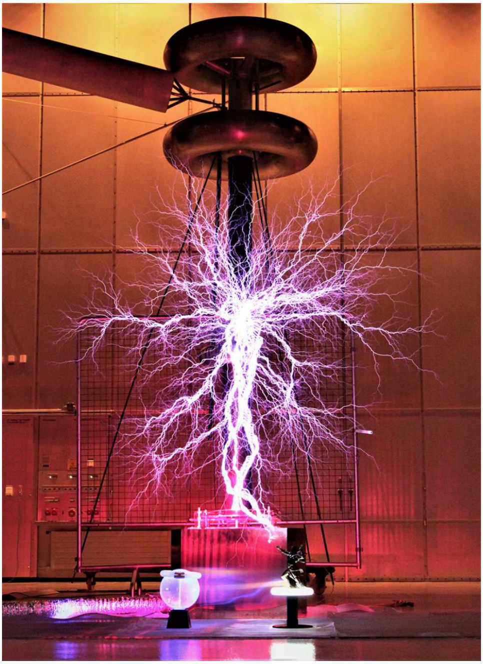
Power Systems and High Voltage Laboratories

Annual Report 2018



High Voltage Laboratory

Power Systems Laboratory

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Annual Report 2018

Issued by
Power Systems and High Voltage Laboratories
(Institut für elektrische Energieübertragung und Hochspannungstechnik)

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Front Cover: Spark(l)ing sound: The symbolic power of musical Tesla transformers; First Prize of D-ITET research photo competition, R. Faerber

Back Cover: Construction of optimal first zone characteristic of distance protection.

Preface

Dear colleagues and friends of the laboratory!

It is our pleasure to present the annual report of the Power Systems and High Voltage Laboratories for 2018. It has been a busy year for both groups. The accomplished work has been presented at a variety of international conferences and in a number of journals. Six PhD students have completed their PhD theses. We congratulate (in order of defense dates): Andreas Ritter, Malte Tschentscher, Pascal Haefliger, Dmitry Shchetinin, Pascal Buehlmann and Alice Chachereau for the successful defence of their theses. We have further welcomed 8 new PhD students and 3 new postdoctoral researchers.
With respect to teaching we have newly taken over the lecture on "Networks and Circuits I" for first semester electrical engineering students. It was a demanding task, but also very rewarding to see the enthusiasm and engagement of our new group of bachelor students.
In 2018, the Power Systems Laboratory went on an excursion to Geneva packed with many technical visits but also some team building activities. We got to see the inside of the nuclear power plant Mühleberg, visited the startup DepSys, CERN and more and had fun river rafting.
As every year, we would like to thank our collaborators and industry partners for their valuable input and our external lecturers for their efforts in offering our students interesting insights into a broad range of topics. And of course, we also would like to thank all of the members of both our groups for their continuous efforts and dedication to their research but also for making EEH a pleasant place to work at.
ETH Zurich has committed to an open access policy and all publications and doctoral theses can be found via our homepage on ETH research collection. More details, updates, and news can be found on our homepage: www.eeh.ee.ethz.ch.

G. Hug C. M. Franck

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1. Organisation

1.1 Power Systems Laboratory

Head:	Prof. Dr. Gabriela Hug
Secretary:	Judith Eberle
Scientific Staff:	Conleigh Byers (September 2018 -) Jun Xing (Jack) Chin Nadezhda Davydova Dr. Stefanos Delikaraoglou Andrew Hamann (- May 2018) Xuejiao Han Adrian Hauswirth Aleksandar Jovicic Stavros Karagiannopoulos Dr. Evangelos Kardakos (- March 2018) Dr. Deep Kiran (November 2018 -) Uros Markovic Conor O'Malley Elena Raycheva (August 2018 -) Dmitry Shchetinin (- December 2018) Dr. Gustavo Valverde (- July 2018) Johanna Vorwerk (November 2018 -) Thierry Zufferey
Technical Staff:	Claudia Stucki, System Engineer (- January 2018)
External Lecturers:	Dr. Hubert Abgottspon, HES-SO, Valais-Wallis Dr. Rainer Bacher, Bacher Energie, Baden Dr. Martin Densing, PSI, Villigen Dr. sc. ETH Gaudenz Koeppel, Axpo, Baden Dr. sc. techn. Dieter Reichelt, Axpo, Baden Dr. Andreas Ulbig, Adaptricity, Baden
Ext. PhD Student:	Michael Haendel

Scientific Associates:	Prof. em. Dr. Göran Andersson Prof. em. Dr. Hans Glavitsch Dr. Evangelos Vrettos (Lawrence Berkeley National Lab)
Academic Guests:	PhD Student Ramana Avula, KTH Royal Institute of Technology, Stockholm, Sweden (- January 2018) Prof. Duncan Callaway, UC Berkeley, Berkeley, USA (January - July 2018)

1.2 High Voltage Laboratory

Head:	Prof. Dr. Christian M. Franck
Secretary:	Karin Sonderegger Zaky
Scientific Staff:	Pascal Bleuler Pascal Bühlmann (-Nov 2018) Lorenz Bort Alise Chachereau Pascal Devaud (Apr 2018-) Eda Egüz (Sep 2018-) Raphael Färber Pascal Häfliger (-Sep 2018) Soeren C. Hedtke Andreas Hösl Florian Küchler (Nov 2018-) Dr. Bernhard Lehmeyer (Oct 2018-) Henrik Menne Juriy Pachin Dr. Mostafa Refaey (Jun 2018-) Andreas Ritter (-May 2018) Tim Schultz Malte Tschentscher (-Jul 2018) Daniel Wackernagel (May 2018-) Tianyu Wei (Sep 2018-)
Technical Staff:	Fabian Mächler, Automation Engineer Hans-Jürg Weber, Senior Technician
Academic Guest:	Xian Wang, Aalborg Uni, Denmark Jan-Mar 2018 Chunmeng Xu, Georgia Tech, USA Mai-July 2018
External Lecturer:	Dr. Werner Hofbauer, ABB Switzerland Ltd Dr. Christian Schaffner, ESC Zurich Prof. Dr. Jasmin Smajic, HSR Dr. Ueli Straumann, ABB Switzerland Ltd Dr. Marija Zima, ABB Switzerland Ltd
Scientific Associates:	Prof. em. Dr. Klaus Fröhlich

2. Teaching

The lectures and laboratory classes listed in the following section are part of the standard curriculum of the Department of Information Technology and Electrical Engineering and are organized and conducted by the staff of the Power Systems and High Voltage Laboratories.

2.1 Lectures

Introduction to Electric Power Transmission: System & Technology 6 ECTS points

Lecturer(s): G. Hug and C. M. Franck

Abstract: Introduction to theory and technology of electric power systems.
Objective: At the end of this lecture, the student will be able to describe the structure of electric power systems, name the most important components and describe what they are needed for, apply models for transformers and lines, explain the technology of power lines and switchgear, calculate stationary power flows and other basic parameters in simple power systems.
Contents: The topics discussed include the structure of electric power systems, transformer and power line models, analysis of and power flow calculation in basic systems, symmetrical and unsymmetrical three-phase systems, transient current and voltage processes, technology and principle of electric power systems.

Networks and Circuits I 4 ECTS points

Lecturer(s): C. M. Franck

Abstract: First semester course introducing the fundamentals of electrical engineering.
Objective: This course introduces the students into the basics of electric circuits, the underlying physical phenomena and required mathematical methods. Voltage, current and properties of basic elements of electric circuits, i.e. capacitors, resistors and inductors should be understood in relation to electric and magnetic fields. Furthermore, the students should be able to mathematically describe, analyze and finally design technical realizations of circuit elements. Students should also be familiar with the calculation of

voltage and current distributions of DC circuits.
Contents: Electrostatic field; Stationary electric current flow; Basic electric circuits; current conduction mechanisms; time variant electromagnetic field.

Power System Analysis 6 ECTS points

Lecturer(s): G. Hug

Abstract: The focus of this course is on analysis tools such as load flow, fault and stability analysis.
Objective: The goal of this course is understanding the stationary and dynamic problems in electrical power systems and the application of analysis tools in steady and dynamic states.
Contents: The course includes the development of stationary models of the electrical network, their mathematical representation and special characteristics and solution methods of large linear and non-linear systems of equations related to electrical power grids. Approaches such as the Newton-Raphson algorithm applied to power flow equations, superposition technique for short-circuit analysis, equal area criterion and nose curve analysis are discussed as well as power flow computation techniques for distribution grids.

Technology of Electric Power System Components 6 ECTS points

Lecturer(s): C.M. Franck and other lecturers

Abstract: Basics of the technology of important components in electric power transmission and distribution systems (primary technology).
Objective: At the end of this course, the students can name the primary components of electric power systems and explain where and why they are used. For the most important components, the students can explain the working principle in detail and calculate and derive key parameters.
Contents: Basic physical and engineering aspects for transmission and distribution of electric power. Limiting boundary conditions are not only electrical parameters, but also mechanical, thermal, chemical, environmental and economical aspects.
The lecture covers the most important traditional components, but also new trends and the dimensioning of components with computer simulations. Parts of the lecture will be held by external experts in the field and there will be two excursions, one to a utility and one to an industrial company.

High Voltage Engineering I: Experimental Techniques 6 ECTS points

Lecturer(s): C.M. Franck and H. J. Weber

Abstract: This lecture is an introduction to experimental and measurement techniques. The course is designed with practical relevance in mind and comprises several laboratory modules where the students perform, evaluate and document experiments. The taught topics are of relevance for almost all electrical engineering disciplines, in this course they are taught on the example of high-voltage engineering.
Objective: At the end of this lecture, the students will be able to: i) perform basic practical laboratory experiments and record data, in particular with an oscilloscope, ii) take a meaningful Lab Notebook, write a clear measurement evaluation protocol, and can estimate the accuracy and precision of the evaluated data, iii) can explain the main reasons for electromagnetic interference and propose measures to avoid or reduce these interferences, and iv) Explain and use different methods to generate and measure high voltages and calculate basic relevant relations

High Voltage Engineering II: Insulation Technology 6 ECTS points

Lecturer(s): C.M. Franck and U. Straumann

Abstract: Understanding of the fundamental phenomena and principles connected with the occurrence of extensive electric field strengths. This knowledge is applied to the dimensioning of equipment of electric power systems. Methods of computer-modeling in use today are presented and applied within the framework of the exercises.
Objective: The students know the fundamental phenomena and principles connected with the occurrence of extensive electric field strengths. They comprehend the different mechanisms leading to the failure of insulation systems and are able to apply failure criteria on the dimensioning of high voltage components. They have the ability to identify of weak spots in insulation systems and to name possibilities for improvement. Further they know the different insulation systems and their dimensioning in practice.

Case Studies
Energy Systems and Technology: Part 1 — 2 ECTS points

Lecturer(s): Ch. Schaffner and C.M. Franck

Abstract: This course will allow the students to get an interdisciplinary overview of the Energy topic. It will explore the challenges to build a sustainable energy system for the future. This will be done through the means of case studies that the students have to work on. These case studies will be provided by industry partners.
Objective: The students will understand the different aspects involved in designing solutions for a sustainable future energy system. They will have experience in collaborating in interdisciplinary teams. They will have an understanding on how industry is approaching new solutions.

Optimization in Energy Systems — 6 ECTS points

Lecturer(s): G. Hug, M. Densing, H. Abgottspon

Abstract: The course covers various aspects of optimization with a focus on applications to energy networks and scheduling of hydro power. Throughout the course, concepts from optimization theory are introduced followed by practical applications of the discussed approaches.
Objective: After this class, the students should have a good handle on how to approach a research question which involves optimization and implement and solve the resulting optimization problem by choosing appropriate tools.
Contents: The course covers various aspects of optimization with a focus on applications to energy networks. Throughout the course, concepts from optimization theory are introduced followed by practical applications of the discussed approaches. The applications are focused on 1) the Optimal Power Flow problem which is formulated and solved to find optimal device settings in the electric power grid and 2) the scheduling problem of hydro power plants which in many countries, including Switzerland, dominate the electric power generation. On the theoretical side, the formulation and solving of unconstrained and constrained optimization problems, multi-time step optimization, stochastic optimization including probabilistic constraints and decomposed optimization (Lagrangian and Benders decomposition) are discussed.

Power System Dynamics, Control and Operation 6 ECTS points

Lecturer(s): G. Hug, A. Ulbig

Abstract: Introduction and discussion into the dynamical properties of the electric power grid and relevant monitoring and operating tools.
Objective: The objectives of the course are to understand and be able to apply the dynamic modeling of power systems, to compute and discuss the actions of generators based on frequency control, to describe the workings of a synchronous machine and the implications on the grid, to describe and apply state estimation procedures, to discuss the IT infrastructure and protection algorithms in power systems.
Contents: The course starts with the introduction of general operational procedures and the discussion of state estimation which is an important tool to observe the state of the grid. The course is then dedicated to the modeling and studying of the dynamical properties of the electric power grid. Frequency control which ensures the generation/load balance in real time is the basis for real-time control and is presented in depth. For the analysis of how the system detects and reacts dynamically in fault situations, protection and dynamic models for synchronous machines are introduced.

Liberalized Electric Power Systems and Smart Grids 6 ECTS points

Lecturer(s): R. Bacher

Abstract: Discussion of the paths from monopolies towards liberalized electric power markets with the grid as natural monopoly. After going through detailed mainly transmission grid constrained market models, SmartGrids models and approaches are introduced for the future distribution grid.
Objective: Understanding both: the legal and physical framework for the efficient regulation of transmission systems, understanding the theory of mathematical optimization models and algorithms for a secure and economic operation of power systems, gaining experience with the implementation and computation of non-linear constrained optimization problems in Matlab.
Contents: The following topics are discussed: Legal conditions for the regulation and operation of electric power systems (CH, EU); modelling physical laws, objectives and constraints of electric power systems at transmission and smart distribution level; optimization as mathematical tool to achieve maximum society profits and considering at the same time grid based constraints and incentives towards distributed / renewable energy resources; various electricity market models, their advantages and disadvan-

tages; SmartGrids: The new energy system and compatibility issues with traditional market models and regulation.

Power Market I - Portfolio and Risk Management 6 ECTS points

Lecturer(s): D. Reichelt and G. Koeppel

Abstract: Portfolio and risk management in the electrical power business, Pan-European power market and trading, futures and forward contracts, hedging, options and derivatives, performance indicators for the risk management, modelling of physical assets, cross-border trading, ancillary services, balancing power market, Swiss market model.
Objective: Knowledge on the worldwide liberalisation of electricity markets, pan-European power trading and the role of power exchanges. Understanding financial products (derivatives) based on power. Management of a portfolio containing physical production, contracts and derivatives. Evaluating trading and hedging strategies. Apply methods and tools of risk management.
Contents: The content includes the introduction of the pan-European power market and trading mechanisms; the modelling and organisation of markets and services; providing the background for portfolio and risk management; introduction of financial tools in energy markets.

Power Market II - Modelling and Strat. Positioning 6 ECTS points

Lecturer(s): D. Reichelt and G. Koeppel

Abstract: Continuation of Power Market I with in-depth discussions of more details in energy markets and financial products.
Objective: Knowing the main derivatives applied in the electricity business, understanding and evaluating hedging strategies, having a basic understanding of the optimization of large, complex hydro power plants, of capacity markets and of quota systems, knowing the discounted cash-flow method and real options to assess the value of power plants.
Contents: The course includes two main parts. The first part is dedicated to option pricing, Black-Scholes, sensitivity analysis (”greeks”), modelling of power market prices, binominal trees, advanced modelling (mean reversion), derivatives on electricity market prices: swaps, caps and floors, swaptions, spread options, ”exotic” options, hedging of an option portfolio, financial modelling of power plants, evaluation of power plants, contracts and grids using future cash-flows an risk, discounted cash flow, real options. The second part focuses on strategic positioning including initial position of utilities

in a dynamic environment, expected market development, SWOT analysis, strategic positioning, strategic options and examples of selected European utilities, case studies.

International Business Management for Engineers 3 ECTS points

Lecturer(s): W. Hofbauer

Abstract: Globalization of markets increases global competition and requires enterprises to continuously improve their performance to sustainably survive. Engineers substantially contribute to the success of an enterprise provided they understand and follow fundamental international market forces, economic basics and operational business management.
Objective The goal of the lecture is to get a basic understanding of international market mechanisms and their consequences for a successful enterprise. Students will learn by practical examples how to analyze international markets, competition as well as customer needs and how they convert into a successful portfolio an enterprise offers to the global market.

Multiphysics Simulations for Power Systems 3 ECTS points

Lecturer(s): J. Smajic

Abstract: The goals of this course are a) understanding the fundamentals of the electromagnetic, thermal, mechanical, and coupled field simulations and b) performing effective simulations of primary equipment of electric power systems.The course is understood complementary to 227-0537-00L ”Technology of Electric Power System Components”, but can also be taken separately. *Objective:*The student should learn the fundamentals of the electromagnetic, thermal, mechanical, and coupled fields simulations necessary for modern product development and research based on virtual prototyping. She / he should also learn the theoretical background of the finite element method (FEM) and its application to low- and high-frequency electromagnetic field simulation problems. The practical exercises of the course should be done by using one of the commercially available field simulation software (Infolytica, ANSYS, and / or COMSOL). After completing the course the student should be able to properly and efficiently use the software to simulate practical design problems and to understand and interpret the obtained results.

2.2 Student Excursions

As part of some lectures also student excursions have been organized and are listed here (sorted by date):

Technology of Electric Power System Components
Surge Arresters
ABB Switzerland Ltd
Wettingen, Switzerland
29 March 2018

Power Markets II
Axpo Etzelwerk AG and Centralschweizerische Kraftwerke (CKW)
Altendorf/Emmen and Luzern, Switzerland
28 - 29 March 2018

Technology of Electric Power System Components
Power Test Laboratory
ABB Switzerland Ltd
Baden, Switzerland
12 April 2018

Power System Dynamics, Control and Operation
EKZ Battery
Dietikon, Switzerland
16 April 2018

Power System Dynamics, Control and Operation
Control Center
Swissgrid
Laufenburg, Switzerland
22 May 2018

Technology of Electric Power System Components
Transformers
Pfiffner Instruments Ltd
Hirschthal, Switzerland
31 May 2018

High Voltage Engineering 2: Insulation Technology
GE Grid
Oberentfelden, Switzerland
8 November 2018

Power Markets I
Axpo Trading and Dispatch Centre
Baden, Switzerland
20 November 2018

Introduction to Electric Power Transmission: System & Technology
EWZ Substation Sempersteig
Zurich, Switzerland
21 November 2018

Power System Analysis
Axpo - Power plant Eglisau-Glattfelden
Zweidlen, Switzerland
5 December 2018

High Voltage Engineering 2: Insulation Technology
ABB Micafil
Zurich, Switzerland
6 December 2018

2.3 Seminars

In addition to the lectures, Bachelor students also have to complete some practical training, projects and seminars (P&S) during their first two years. In the third year the students have to carry out a number of several laboratory experiments (Fachpraktikum). The following P&S and FP courses are offered at the EEH.

P&S: Econ. and Techn. Principles of a Sustain. Energy Supply
(Wirtsch. und techn. Aspekte einer nachh. Energieversorgung)

P&S: Spark(l)ing Sound: Construction of a audiomodulated Tesla-Coil
(Spark(l)ing sound: Bau einer audiomodulierten Teslaspule)

HS1: Breakdown Experiments
(Durchschlagsverhalten von Elektrodenanordnungen bis 200 kV)

HS3: High-Temperature Superconductors
(Hochtemperatur-Supraleiter)

HS5: Electrical Safety
(Berührungsschutz und Gefahren durch Körperströme)

2.4 Semester Projects

Master students are required to complete one or two semester projects (depending on their Master program, i.e. ITET or MEST). The projects are supervised by a professor of the Department. Most projects are carried out under the guidance of, and in close contact with, a PhD student of the supervising professor. Each semester project should take about half of a student's time during one semester, i.e. about 280 hours. The project includes an oral presentation and a written report, and it is graded. The following is a list of semester projects that have been completed at EEH in the past year. Some of the PSL project reports can be found on the website.

2.4.1 System Oriented Semester Projects

Stefan Agovski
Synthesis of reactive power profiles for consumers in a distribution grid
Supervisors: Thierry Zufferey, Nicolas Stocker (Adaptricity)

Matthieu Ansart
The impact of uncertainty in load forecast on the performance of privacy protection algorithms
Supervisor: Jun Xing Chin

Michael Chow
Sharing storage recourses using tradable financial/physical rights
Supervisor: Stefanos Delikaraoglou

Zhongda Chu
Adaptive provision of virtual inertia on a transmission system level
Supervisor: Uros Markovic

Joël Dunant
Investigation of forecasting techniques in distribution grids
Supervisors: Thierry Zufferey, Conor O'Malley

Roman Engeler
Long-term energy forecasting of smart metered customers in a distribution grid
Supervisor: Thierry Zufferey

Chouaib Fennan
Creation of a generic test case for combined simulations of medium and low voltage networks
Supervisor: Gustavo Valverde

Nicolas Früh
Interval-based adaptive intertia and damping control of a virtual synchronous machine
Supervisor: Uros Markovic

Baiwei Guo
Model-free optimal control in active
Supervisor: Stavros Karagiannopoulos

Simon Hobi
Comparison of a synchronous machine and a matching DC-AC converter model
Supervisors: Uros Markovic, Taouba Jouini (IfA)

Tara Katamay-Smith
Capacity expansion of the Mid-Columbia hydropower system
Supervisors: Andrew Hamann, Xuejiao Han

Jaël Keller
Traveling Wave Protection for Distribution Grids with Renewable Energy Sources
Supervisor: Nadezhda Davydova

Boody Nasef
Small-signal modeling and stability analysis of a virtual induction machine
Supervisor: Uros Markovic

Matthieu Paturet
Unit commitment problem with inclusion of inertia constraints
Supervisors: Uros Markovic, Stefanos Delikaraoglou

Ridas Rimkus
Generation expansion planning with natural gas considerations
Supervisors: Conor O'Malley, Stefanos Delikaraoglou

Florian Scherrer
Optimization of multi-energy networks
Supervisors: Conor O'Malley, Stefanos Delikaraoglou

Etta Shyti
Optimal Power Flow Formulations in Modern Distribution Grids
Supervisor: Stavros Karagiannopoulos

Birkir Snaer Sigfusson
Classification of disturbances on power lines
Supervisor: Nadezhda Davydova

Ognjen Stanojev
Interactions between the grid-forming and grid-following VSC control techniques
Supervisor: Uros Markovic

Baudouin Vandenbussche
Optimal placement of grid-forming converters in a 100% PE-based power system
Supervisors: Uros Markovic, Dmitry Shchetinin

Ashwin Venkatraman
Least absolute value state estimation
Supervisor: Dmitry Shchetinin

Johanna Vorwerk
Small-signal analysis of power systems with no rotational inertia
Supervisor: Uros Markovic

Daniel Weber
Modeling and simulation of flexible loads for control of distribution networks
Supervisor: Gustavo Valverde

Jialun Zhang
Impact of varying time delays on stability of inertia-less power systems
Supervisor: Uros Markovic

2.4.2 Technology Oriented Semester Projects

Arnaud Bertoni
Automation of Circuit Breaker Benchmark Tests
Supervisor: Tim Schultz

Verena Häberle
Analysis and Optimization of Current Injection Circuits for Hybrid HVDC Circuit Breakers, Part I
Supervisor: Tim Schultz

Julia Glaus
Analysis and Optimization of Current Injection Circuits for Hybrid HVDC Circuit Breakers, Part II
Supervisor: Tim Schultz

André Eggli
Implementation of an Automated Current Source Control System
Supervisor: Henrik Menne

Stganojev Ognjen
Economical and Technical Benefit of a Hybrid HVAC/HVDC Line
Supervisor: Sören Hedtke

Michael Schubiger
Evaluation of new Gas Candidates for Electrical Insulation
Supervisor: Andreas Hösl

Melissa Artiglia
Modification of a Breakdown Experiment for Insulating Gases
Supervisor: Juriy Pachin

Manuela Luther
Evaluation of Long-Termn Outdoor HVAC/HVDC Corona Test
Supervisor: Sören Hedtke

Ruben Stadler
Setting up an Lightning Impulse Breakdown Experiment for Insulation
Supervisor: Juriy Pachin

2.5 Master Projects

The Master Programme concludes with a Master Project that lasts six months full time. The project is supervised by a professor of the Department or by a professor formally associated with the Department. The project includes an oral presentation and a written report (the Master Thesis), and it is graded. The following is a list of Master projects that have been completed at EEH in the past year. Some of the PSL project reports can be found on the website.

2.5.1 System Oriented Master Projects

Stefanie Aebi
Optimizing Voltages in Transmission Grids under Input Uncertainty
Supervisors: Stavros Karagiannopoulos, Roger Wiget (Swissgrid)

Martin Baltzinger
Applications of community detection in power systems
Supervisor: Dmitry Shchetinin

Iason-Ioannis Chontzopoulos
Very Short-term Probabilistic Demand Forecasting at High Aggregation Level for the Mitigation of Balancing Costs
Supervisors: Thierry Zufferey, Gaudenz Koeppel (Axpo)

Zhongda Chu
LQR-Based Adaptive Virtual Synchronous Machine for Power Systems with High Inverter Penetration
Supervisor: Uros Markovic

Carmen Exner
Implementation of a predictive maintenance engine for power cables
Supervisors: Thierry Zufferey, Damiano Toffanin (Adaptricity)

Xingliang Fang
Valuation of Energy Flexibility Solutions in Different Power Market Regimes
Supervisor: Jun Xing Chin, Donnacha Daly (Landis+Gyr)

Jan Gimpel-Henning
Low-voltage grid overloads due to the diffusion of E-vehicles and solar photovoltaics
Supervisor: Xuejiao Han

Iraklis Katsolas
Supply curve forecasting in the Italian power market
Supervisors: Conor O'Malley, Thierry Zufferey, Christian Berclaz (Axpo)

Hannes Knapp
Optimal control strategy for energy hub at NEST
Supervisors: Conor O'Malley, Philipp Heer (Empa)

Christos Konstantinopoulos
Integration of PV units in the primary and secondary control ancillary services in Switzerland
Supervisors: Saverio Bolognani (IFA), Dominic Gross (kompl. Regelsyst), Avramiotis Iason (Swissgrid)

Alice Lépouzé
Design of an automatic forecasting engine for real-time state estimation in distribution grids
Supervisor: Thierry Zufferey

David Rodriguez Flores
Robust converter control design under varying time delays
Supervisor: Uros Markovic

Benjamin Schaule
Disaggregation of smart meter measurement data into specific load components
Supervisors: Thierry Zufferey, Stephan Koch (Adaptricity)

Haoyang Zhang
Distribution grid state estimation based on smart meter data
Supervisor: Thierry Zufferey

2.5.2 Technology Oriented Master Projects

Daniel Wackernagel
FPGA Controller Development for Pulsed Current Source
Supervisor: Henrik Menne

Aldo Ferdinand Tobler
Sine Voltage Modulation for Improved Power Transmission Capacity
Supervisor: Prof. Christian Franck

David Graber
Setting up and Controlling a Gas Discharge Experiment
Supervisor: Juriy Pachin

Martina Stadelmann
Corona Measurement on an Outdoor Hybrid AC/DC Test Line
Supervisors: Sören Hedtke

Miriam Vonesch
Gas Circuit Breaker Arc Voltage Under Different Flow Conditions
Supervisors: Lorenz Bort

Emil Walser
Interruption Limits of Mechanical Circuit Breakers in Current Injection Topologies
Supervisors: Tim Schultz

Timotheus Stiefel
Development of high current contacts for an Ultra Fast Disconnector for HVDC Circuit Breakers
Supervisors: Henrik Menne

Emiliano Trodini
Modelling the Electrical Signal in Spark Discharge Generators for Electrode Ablation Control
Supervisors: Profs. Richardson and Schmidt-Ott, TU Delft

Johanna Vorwerk
Effect of Electric Field on Droplets Impacting Surfaces with Different Wettabilities
Supervisors: Pascal T. Bleuler

3. Completed PhD Theses

Disconnector Switching in HVAC and Future HVDC GIS

Candidate:	Andreas Ritter
Thesis:	ETH No. 25060
Date of oral exam:	23 March 2018
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. sc. ETH Lukas Graber, Georgia Tech, USA

Abstract While bus-transfer switching by disconnector is a common operation performed in many existing HVac substation worldwide, there exists a notable lack of research concerning the underlying process, especially for gas insulated switchgear (GIS). Furthermore, the advent of multi-terminal HVdc (MTdc) grids warrants an investigation of the dc switching capabilities of such disconnectors. To address both ac and dc test cases, a non-standard bus-transfer loop setup capable of emulating a wide range of GIS substations was built. Through extensive testing, using an LC-oscillating current source to drive this setup, an arc voltage function as well as an extinction criterion linking recovery voltage and predicted arc voltage at current zero were found for ac bus-transfer. With these findings, simulative predictions of disconnector performance for varying applications and as a response to changes in the disconnector design were performed.The theoretical feasibility of bus-transfer in dc was shown using these same simulation algorithms, which was followed by a test series confirming the applicability of both arc voltage function and the extinction criterion, thus validating that existing disconnector can be used for bus-transfer in future HVdc GIS. From the subsequent simulations it was evident that the most effective method of reducing arcing time while increasing resilience against recovery voltages caused by excessive current harmonics was an accelerated arc voltage function. This hypothesis was subsequently verified by employing a commercial mixed technology switchgear (MTS) HVac disconnector using a spring-loaded electrode assembly in the dc test setup. In a custom-built disconnector testbed, reduction of arcing contact erosion was successfully demonstrated using magnetic arc driving by means of an array of permanent magnets. In simulation, the combination of fast contact separation and magnetic arc driving showed promise for disconnector switching in future HVdc GIS not limited to bus-transfer.

Conduction and Interface Phenomena in Gas-Insulated DC Systems

Candidate:	Malte Tschentscher
Thesis:	ETH No. 25106
Date of oral exam:	31 May 2018
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. Jinliang He, Tsinghua University, CHN

Abstract WA detailed understanding of the charge generation and transport in gaseous insulation forms the basis for modeling numerous problems in high-voltage engineering. Some examples for processes relevant to the dimensioning of gas-insulated devices are the surface-charging phenomena at insulator surfaces, prediction of initiatory electron provisions for partial discharges in small voids, estimation of statistical time lags for breakdown inception in gaseous insulation, etc. Here, the intensity and continuity of the charge provision strongly influence the operating states of the devices and, owing to their impact on the mean energy input from the discharges, the long-term performance and aging behavior of the insulation. Over the years, researchers have made enormous progress using continuous ion-current measurements or surface-charging experiments with model spacers downscaled from gas-insulated components. Whereas the low sensitivity of the former method limits its measurement range, the latter method is time consuming and demands comprehensive modeling.

To overcome the limitations of the classical current-measurement techniques, this thesis introduces a new measurement approach that enables studying spatially resolved currents in the sub-femtoampere range. Low-conductive polymeric interfaces function as information storage, which accumulate the conduction and charge provision processes from solid or gaseous domains and interfaces. Using Al2O3-filled epoxy resin for solids and sulfur hexafluoride (SF_6) for gaseous insulation, new fundamental insights on the processes are presented to determine the dimensioning of gas-insulated devices.

Low-field charge provision and transport processes serve as the basis for the simulation of surface-charge decay under no-load conditions, modeling of initial electron provisions for partial discharges in small volumes, and explanation of statistical time lags for breakdown inception in gaseous insulations. The established theories assume that charge generation from natural ionization is the main source of charge carriers, which defines the current

flowing through the gaseous insulation in DC devices. In this thesis, the ion-pair generation from natural ionization in a gas was demonstrated to be significantly influenced by the surrounding solid materials and therefore scales with the insulation volume. This charge generation was assumed to be independent of the applied electric field in cases where the electric field is sufficiently below the onset of microdischarges at the interfaces. Enhanced currents that were measured in a limited range of low electric fields revealed further conduction phenomena, which could be explained by electrophoretic conduction.

Charge generation at the interfaces of gas-insulated devices is mostly studied from a macroscopic point of view. Integral current measurements are among the common methods of determining the average inception field strengths and intensities of microdischarges. However, because of the lack of spatial resolution and measurement sensitivity, these experiments do not provide deeper insights on the microscopic processes. Spatially resolved analyses of charge-generation processes in technically rough aluminum electrodes and insulating interfaces reveal a highly inhomogeneous charge generation from microdischarges. The analysis of the charge generation from a macroscopic perspective has been demonstrated to possibly underestimate the local charge generation by up to three orders of magnitude. From the results, microdischarges are expected to be highly relevant for the dimensioning of gas-insulated devices.

The influence of humidity on the electric strength and conduction phenomena in gas-insulated devices has been discussed for many decades. In the framework of this thesis, a highly precise humidity control circuit has been developed to analyze the significance of humidity in the range applicable to operating gas-insulated devices. Whereas humidity is determined to have no influence on low-field ion currents through gaseous insulation, an increase in humidity significantly enhances the intensity of microdischarges at the interfaces and potentially influences the dimensioning of gas-insulated devices.

Electric strength of N2, O2, CO2, Ar mixtures based on swarm and breakdown experiments

Candidate: Pascal Haefliger
Thesis: ETH No. 25446
Date of oral exam: 29 October 2018
Examiner: Prof. Dr. Christian M. Franck
Co-examiner(s): Prof. Abderrahmane Haddad, Cardiff University, UK

Abstract In gas insulated equipment, sulfur hexafluoride (SF_6) is the predominantly used insulation gas due to its superior electrical properties for insulation and switching applications compared to other gases. The drawback of SF_6 is the high global warming potential which led to the research of replacement gases or gas mixtures.

Amongst other possible alternative gases or mixtures, atmospheric gas mixtures (N_2, O_2, CO_2 and Ar) are considered as replacementof SF_6 as insulation gas in medium voltage and probably even high voltage applications in this thesis. The homogeneous electric field strength of mixtures was investigated based on swarm experiments, namely pulsed Townsend experiments (PT). To assess the electric strength of mixtures, two methods are used; the critical reduced electric field ((E/N)crit) and the streamer criterion. The obtained electric strength from swarm experiments is then verified by homogeneous field breakdown measurements.

In detail, N_2-O_2 mixtures at the mixing ratio of air and admixtures of Ar and CO_2 are analyzed, as these additives are claimed to increase the breakdown strength compared to synthetic air alone. At low pressures (2-8 kPa), measured PT displacement currents for these mixtures are very similar. Hence, from this measurements derived breakdown strength based on (E/N)crit shows no meaningful difference between air mixture and the mixtures with additional Ar or CO_2 content. Nevertheless, swarm measurements in these mixtures at elevated pressures (10-100 kPa) show a strong influence of detachment and ion conversion processes. Thus, measured currents could only be evaluated with an extended kinetic model incorporating detachment and ion conversion. Some of the resulting rates showed a non-linear pressure dependence. Due to the additional kinetic processes, a new definition of an effective rate is necessary to account for the influence of detachment and ion conversion processes. As a result, the obtained eff and derived (E/N) crit were pressure dependent, leading to a pressure dependent electric strength

of air mixtures based on swarm results considering (E/N) crit alone. Interestingly, the main influence of detachment and ion conversion on eff obtained by the extended model is dominant below (E/N)crit. In addition, for higher pressures measured in the air mixture, eff around (E/N)crit even tends to the eff from low pressure measurements only incorporating attachment and ionization. Accordingly, the pressure dependent influence on the electric strength calculated with the streamer criterion disappears and therefore confirms Paschen-law conform breakdown measurements in air. As a conclusion, it is justified to use low pressure swarm measurements to derive breakdown voltages in air mixtures and N_2-O_2 mixtures in the understanding that this approach might not be applicable in every case of detaching gases.
In the present measurements, Ar did not increase the breakdown strength of synthetic air whereas CO_2 admixtures slightly increased its breakdown strength. When comparing all measured mixtures, it becomes apparent that atmospheric gas mixtures containing O_2 show a higher electric strength than without O_2. Optimum mixtures with an electric strength higher than the individual components were found dependent on the used method, swarm or breakdown. As the methods sensitivity is smaller than the difference in the results (for N_2-O_2 mixtures between a content of 60-80% of O_2), it already indicates the limited possible increase of the electric strength of these mixtures when compared to O2 only. Overall, it was found that an addition of 5% CO_2 increases the breakdown strength of N_2-O_2 mixtures. For technical applications, mixtures with a low O_2 content but similar or higher breakdown strength than pure O2 can be of interest. Accordingly, ternary mixtures of N_2-O_2-CO_2 with additions of 40-60 % O_2 and 5 % CO_2 are proposed as optimal mixtures. To clarify the impact of these proposed mixtures, the breakdown voltage compared to air was increased at maximum 8 % for a content of 60 % O_2, 5 % CO_2 and 35 % N_2. The presented PT experiment is considered as a reliable, efficient and experimental condition independent technique to asses the intrinsic electric strength of gases and gas mixturesWith .

Optimization of Power System Operation: Approximations, Relaxations, and Decomposition

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Thesis:	ETH No. 25598
Date of oral exam:	12 November 2018
Examiner:	Prof. Dr. Gabriela Hug
Co-examiner(s):	Dr. Daniel Molzahn, Georgia Tech, USA / Prof. Dr. Spyridon Chatzivasileiadis, Technical University of Denmark, Denmark

Abstract With higher penetration of renewable generation and market liberalization, operating points of electric power systems become increasingly variable and less predictable. To ensure economically efficient and secure operation of such systems, fast and robust optimization algorithms are required. Despite considerable research efforts, the development of these algorithms remains a challenge due to the nonlinearity and high dimensionality of system models. This dissertation focuses on the optimal power flow (OPF) problem, which is at the heart of techniques used in power system operation and planning. As this problem is non-convex and highly nonlinear, modern solvers cannot always find its locally optimal or even feasible point. To address this issue, an approximation of the OPF problem is proposed that helps reduce its complexity without compromising the solution quality. Moreover, the obtained solution is guaranteed to be physically meaningful. Next, this work presents several computationally efficient techniques for strengthening convex relaxations of the OPF problem. A tighter relaxation helps provide a better estimate of a globally optimal solution of the original problem and recover a physically meaningful operating point. Lastly, this work presents several approaches to incorporating risk-based security indices in the OPF problem. To reduce the computational burden of solving the resulting problems, decomposition algorithms are employed. The proposed techniques were tested on grids of various sizes. The results demonstrate that these techniques can potentially help improve optimization tools used in power system operation.

Electrothermal and Mechanical Phenomena of Overhead Line Conductors near Tension Clamps

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Thesis:	ETH No. 25517
Date of oral exam:	20 November 2018
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. Edoardo Mazza, D-MAVT, ETHZ / Dr.-Ing. habil. Konstantin Papailiou, Pfisterer Internat. AG, Switzerland

Abstract Ampacity based solutions are necessary for increasing operational flexibility, efficiency, and reliability of the existing transmission grid. This could be achieved by operating overhead line conductors close to their maximum allowable temperature over longer time periods.
Therefore, the thermal and mechanical behaviors of an All Aluminum Alloy Conductor (AAAC) at a wedge tension clamp, where elevated mechanical stresses are expected, are presented in this thesis.
An analytic approximation of the thermal transition length as well as a finite element model to determine the conductor temperature profiles in the thermal transition zone were developed. The model is verified by measuring the temperature distribution and the underlying physical phenomena. It can be concluded that the solid aluminum wedge tension clamp is decreasing the heating due to the enlarged electrically conductive cross-section and is increasing the convective and emissive cooling by its enlarged surface area. Thus, the clamp is significantly lowering the conductor temperature.
The mechanical influence of the clamp was investigated with experiments based on x-ray and optical methods as well as with a finite element model. It was observed that the inner layers slip towards the free-span since all tensile force is transferred by friction from the conductor to the clamp through the outermost conductor layer. Furthermore, not all wires on the same layer are clamped equally as the clamp compresses the conductor from two sides only.
This work can lead to improved clamp design. Furthermore, combining the presented results with the creep characteristics of the conductor would allow to improve conductor lifetime predictions.

Electron an ion kinetics in fluorinated gases for electrical insulation

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Thesis:	ETH No. 25657
Date of oral exam:	10 December 2018
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. Nickolay L. Aleksandrov, Moscow Institute of Physics, Russia

Abstract Electron and ion transport coefficients, reaction rate coefficients, and collisional cross sections are fundamental quantities for describing low temperature plasmas. They are used to model a wide variety of domains and applications, such as semiconductor plasma processing, gaseous dielectrics, plasma medicine, gaseous particle detectors, astrophysics, and environmental plasmas. The measurement or calculation of these fundamental quantities is thus of major importance for the development of the above-mentioned applications.

This thesis presents measurements of the transport coefficients and reaction rate coefficients of electrons and ions in different fluorinated gases. The specific motivation for these measurements is the search for an alternative to SF_6 as an electrical insulation medium. Sulphur hexafluoride (SF_6) is an excellent insulator thanks to its ability to capture free electrons, its chemical stability and its volatility, which makes the use of high pressures possible. However, it is a potent greenhouse gas, and its use is therefore strongly regulated. The European Union regulation No. 517 of 2014 foresees a ban on the use of SF_6 as soon as a cost-effective alternative is available. There is therefore a strong interest from electrical equipment manufacturers in finding an alternative - or proving the absence of an alternative - in order to be well-positioned on the market. For this purpose, it is necessary to characterize the properties of new fluorinated gases which could serve as SF_6-alternatives.

Since most fluorinated gases are not as volatile as SF_6, SF_6 will be most likely replaced by a gas mixture and not by a pure gas. Such a gas mixture would contain a few percent of fluorinated gas mixed in a highly volatile carrier gas, such as N_2, CO_2, O_2, or a mixture of these. For this reason, this work focuses on gas mixtures between fluorinated gases and either N_2 or CO_2 as carrier gases. The reaction rate coefficients and transport coefficients of electrons and ions are obtained by measuring the current induced

to electrodes by electron avalanches in these gas mixtures, with a pulsed Townsend experiment.

The main scientific contributions of this thesis are the following. First of all, two problematic aspects of the pulsed Townsend experiments are identified and remedied: the need to distinguish the current induced by the electron avalanche from the capacitive recharging current of the electrodes, and the need to ensure a low charge density of the electron avalanche, so that the space charge electric field is negligible compared to the externally applied field.

Secondly, analytic models and tools for the analysis, interpretation and inter-comparison of measurements are developed. In particular, a new model for calculating the ionization and attachment rate coefficients is obtained.

Thirdly, the reaction rate coefficients and transport coefficients are measured in eight fluorinated gases: octafluorooxolane (c-C_4F_8O), octafluorobutene (2-C_4F_8), hexafluoropropylene oxide (C_3F_6O), (1E)- 1,3,3,3-tetra- fluoropropene ($C_3H_2F_4$), trifluoromethylsulphur hexafluoride (SF_5CF_3), heptafluoropropane (C_3HF_7), heptafluoroisobutyronitrile (C_4F_7N) and heptafluoroisopropyl trifluoromethyl ketone ($C_5F_{10}O$), and their mixtures with N_2 and CO_2. In order to make the obtained results publicly available, an online database "ETHZ" is opened on the platform of the Plasma Data Exchange Project LXcat. For some of the investigated gases, the total electron attachment cross section is estimated from the measured attachment rate coefficients using a linear inversion method. The obtained electron attachment cross sections are compared with those measured in electron beam experiments with ion mass spectrometry.

Finally, the properties of these gases and gas mixtures are compared in regard to their performance for electrical insulation. The electron attachment cross sections of the gases are compared, and set in relation with the synergism observed in gas mixtures. The dependence of the results on the gas pressure and the consequences for high pressure applications are discussed.

https://www.overleaf.com/project/5c35c1636009b4425e351a7e

4. Research Activities

4.1 High Voltage Gaseous Insulation

Since a few years, the search for alternative and more eco-friendly insulation systems is becoming stronger than ever. Still, today sulfur hexafluoride (SF_6) is predominently used in high-voltage gas insulated equipment (GIS), as it combines a uniquely high electric strength with long term stability and easy handling. However, since it has become clear that SF_6 is one of the most potent greenhouse gases (global warming potential 23500), several attempts have been made to find minimize or eliminate its use.

One the one hand, alternative (but strongly electron attaching) insulation gases are investigated that (in mixtures with background gases) can replace SF_6 as insulation and switching medium and keep the principle insulation arrangement similar. On the other hand, the switching is done in vacuum circuit breakers and synthetic air or liquid or solid insulation can be used for those parts that need to be insulated.

Our group has developed a procedure to systematically identify and quantify novel molecular gases with low global warming potential for application in high and medium voltage insulation as gas mixtures. The procedure contains three steps: In a first step, quantum chemical simulation methods are used to identify new molecules. Since our first publication, several follow-up correlation studies have been build on this work and applied by other groups. The swarm parameters of these pre-selected molecules in mixtures with buffer gases are then quantified, using two newly set-up Pulsed Townsend experiments. The setups operate with a high degree of automation to enable systematic evaluation of gas mixtures not to miss possible synergistic effects. Electron swarm parameters such as drift velocity, effective ionisation rate and diffusion time constant are derived. Finally, the measured swarm parameters need to be translated into breakdown voltage strengths of different electrode arrangements and different applied voltage wave shapes. For this, a model of the the streamer to leader transition is used. Selective comparison of these predictions with actual breakdown tests are performed for validation.

Besides the above described research topics, our group was also partner (together with ecofys) in a study for the German Federal Ministry for Environment, Nature Conservation, Building and Nuclear Safety (BMUB) that aims to explore alternatives to SF6 in electrical equipment, their suitability for use, advantages and limits as well as their environmental impact.

In addition, a new working group (Cigre D1.67) has started with the task to describe methods for identifying new insulating gases and gas mixtures and investigate and summarize the dielectric properties and the practical insulation performance of new non-SF6 insulating gases and gas mixtures for gas-insulated systems. It will coordinate an international round-robin test with around 15 participating laboratories to compare the electric strength of novel insulation gas mixtures. Prof. Franck was elected the convenor of this working group.

Partnership: *ABB Schweiz AG (Corporate Research), General Electric Switzerland GmbH, Pfiffner Instrument Transformers Ltd, Siemens AG (Corporate Technology)*

Researchers: *Pascal Häfliger, Alise Chachereau, Andreas Hösl, Juriy Pachin, Eda Egüz*

Publications In this research area, the following publications have been published in 2018:

M. Zawadzki, A. Chachereau, J. Kocisek, C. M. Franck, J. Fedor, "Electron attachment to hexafluoropropylene oxide (HFPO)"
We probe the electron attachment in hexafluoropropylene oxide, C_3F_6O, a gas widely used in plasma technologies. We determine the absolute electron attachment cross section using two completely different experimental approaches:
(i) a crossed-beam experiment at single collision conditions (local pressures of 5» 104 mbar) and (ii) a pulsed Townsend experiment at pressures of 20 - 100 mbar.
In the later method, the cross sections are unfolded from the electron attachment rate coefficients. The cross sections derived independently by the two methods are in very good agreement. We additionally discuss the dissociative electron attachment fragmentation patterns and their role in the radical production in industrial HFPO plasmas.
J Phys Chem (2018)

A. Chachereau, C. M. Franck, "Electrical Insulation properties of the perfluoroketone $C_5F_{10}0$"
The electrical insulation properties of pure $C_5F_{10}O$ and of $C_5F_{10}O/N_2$ and $C_5F_{10}O/CO_2$ mixtures are investigated in a pulsed Townsend setup. The electron rate and transport coefficients and the density-reduced critical electric field of these mixtures are obtained, and a synergy effect is observed in in $C_5F_{10}O/N_2$ and $C_5F_{10}O/CO_2$ mixtures. The total electron attachment cross section of $C_5F_{10}O$ is estimated based on the attachment rate to

$C_5F_{10}O$ in diluted $C_5F_{10}O/N_2$ and $C_5F_{10}O/CO_2$ mixtures.
Journal of Physics D: Applied Physics, **51**, 33 (2018)

Andreas Hösl, Juriy Pachin, Alise Chachereau, C. M. Franck, "Perfluoro-1,3-dioxolane and Perfluoro-oxetane: promising gases for electrical insulation"
Perfluorinated cyclic ethers represent an interesting class of molecules to use as dielectric gases for electrical insulation. Measurements of the two compounds 4,4,5,5-Tetrachloro-2,2-difluoro-1,3-dioxolane (c-$C_3Cl_4F_2O_2$, CAS 87075-01-2) and Octafluoro-1,4-dioxane (c-$C_4F_8O_2$, CAS 32981-22-9) in a Pulsed Townsend Experiment are presented, their ionization and attachment rate coefficients are obtained and their electron attachment cross sections are estimated. Both gases have a high critical electric field strength of about 3.5 and 1.3 times the one of SF_6, respectively, which is presumably due to very high electron attachment cross sections in the range from $2-4$ eV. In particular, for c-$C_3Cl_4F_2O_2$the values appear to be very close to the S-wave scattering limit around 3 eV. Based on these results, we recommend the two analogous compounds Perfluoro-1,3-dioxolane (c-$C_3F_6O_2$, CAS 21297-65-4) and Perfluoro-oxetane (c-C_3F_6O, CAS 425-82-1) for further research for the use as insulation and refrigerant gases, since they are chemically comparable, presumably environmentally friendly, and have high vapor pressures.
Journal of Physics D: Applied Physics **52**, 055203 (2018)

P. Häfliger, A. Hösl, C. M. Franck, "Experimentally derived rate coefficients for electron ionization, attachment and detachment as well as ion conversion in pure O2 and N2-O2 mixtures"
We obtain rate coefficients for mixtures of O_2 and N_2 as well as pure O_2, by fitting pulsed Townsend measurements over a large pressure range from 3 kPa to 100 kPa in a density-reduced electric field range from 40 to 110 Td (1 Td = 10^{-21} Vm^2). The applied model includes ionization, dissociative attachment to O^- and non-dissociative attachment to O_2^-, O^- and O_2^- detachment, as well as charge transfer and ion conversion from O^- to O_2^- and O_3^-. The results are compared to Bolsig+ and MAGBOLTZ simulations and experimental data, where available. The key novelty is the simultaneously obtained rate coefficients from a single Pulsed Townsend experiment including several ion processes over the whole N_2-O_2 mixing range.
Journal of Physics D: Applied Physics **51**, 355201 (2018)

A. Chachereau, A. Hösl, C. M. Franck, "Electrical insulation properties of the perfluoronitrile C_4F_7N "
The electrical insulation properties of pure C_4F_7N and of C_4F_7N /N_2 and

C_4F_7N /CO_2 mixtures are investigated in a pulsed Townsend setup. The electron rate and transport coefficients and the density-reduced critical electric field of these mixtures are obtained, and a synergy effect is observed in C_4F_7N /N_2 and C_4F_7N /CO_2 mixtures. The total electron attachment cross section of C_4F_7N is estimated based on the attachment rate to C_4F_7N in diluted C_4F_7N /N_2 , C_4F_7N /CO_2 and C_4F_7N /O_2 /CO_2 mixtures. Measurements in pure C_4F_7N at pressures of a few hundred pascal show that ion kinetics play a major role in C_4F_7N discharges and that further modelling is required to assess the electric strength of C_4F_7N at high pressures.
Journal of Physics D: Applied Physics **51**, 495201 (2018)

4.2 Switching in HVDC Systems

The need for switchgear for use in future multi-terminal HVDC grids is widely established today. Numerous working groups are dealing with this topic and try to address the world-wide trend in increasing requirements for electric power transmission capacitiy. In terms of switching HVDC currents, research world-wide used to be primarily focused on fault-currents and their interruption by means of circuit-breakers. However, during normal operation of any substation, numerous switching cases of non-fault currents exist. Our research topics cover the range from small-current switching up to full fault current interruption.

Key experimental facility is a flexible pulsed current source that can be freely programmed to any arbitrary current shape up to 3 kA and 3 kV. We are in the phase of modernizing the existing source: increasing the capability to > 20 kA and 10 kV and designing an new FPGA-controller for operation. For this, two new temporary employees have been hired.

Up to now, several HVDC circuit breakers (CB) topologies have been proposed. One of them is based on an LC-resonance circuit in parallel to a mechanical gas circuit breaker. This concept is already used in MRTSs (metal return transfer switches) which can commutate the normal load current from the earth electrode line at a converter station to another parallel line. These resonance breakers strongly rely on the fact that the arc in the mechanical breaker has a negative dU/dI-behaviour, i.e. the voltage drop across the breaker has to decrease if the current through the breaker increases. Making use of our flexible pulsed current source by applying complex test current shapes to different designs of an interruption chamber, the physical effects that lead to the negative dU/dI-behaviour can be identified and quantified. Parameters that are investigated here are the nozzle shapes and material, blow gas pressure, and the type of gas.

Hybrid HVDC CB aim to combine the low on-state losses of mechanical switching devices with the fast switching times of semiconductor devices. Many of todays proposed topologies make use of an ultra-fast, but arcless, mechanical switching device. Our research investigates from scratch arrangements that can potentially outperform todays realisation in particular with respect to switching time. In turn, very few of todays proposed topologies exploit the ulitmate strengths of the used arc-based mechanical and semiconductor switching devices. The interaction of arcs in mechanical devices with semiconductor switches is thus of particular interest and is investigated. The results of this work will be used as a basis to judge the potential of existing hybrid circuit breaker concepts, point out optimisation potential and may lead to the introduction of new topologies.

Small-current switching requirements for HVDC disconnectors have been determined and investigated. Using the international standards and the research performed on traditional AC disconnectors as a starting point, calculations and simulations were conducted to find typical cases of application in future HVDC substations. Potential modifications and redesign suggestions arising from these investigations are made and implemented into future switch designs.

Partnership: *ABB Schweiz AG, ABB Schweiz (Corporate Research), SCCER-Furies*

Researchers: *Andreas Ritter, Lorenz Bort, Tim Schultz, Henrik Menne, Daniel Wackernagel, Tianyu Wei, Pascal Devaud*

Publications In this research area, the following publications have been published in 2018:

H. Menne, C. M. Franck, "Contact resistance measurement on contacts for an Ultra Fast Disconnector"
The growing need of an HVDC grid requires the development of HVDC circuit breakers. One possible topology is the hybrid HVDC CB. The mechanical Ultra Fast Disconnector determines its performance. The UFD has to separate the contacts within a few milliseconds and provide a low loss current path. To achieve this goal, the development is split into different tasks; one task contains the development and testing of high current contacts. To test such contacts, a test stand was built which allows measuring the contact resistance and heat distribution of the contacts. With this test stand it is possible to test a number of different contact shapes and experimentally verify their performance. The first measurements could be carried out and the results are promising.
VDE Hochspannungskonferenz Berlin (2018)

E. Kontos, T. Schultz, L. Mackay, L. M. Ramirez-Elizondo, C. M. Franck, P. Bauer, "Multiline Breaker for HVdc Applications"
This paper presents a breaker arrangement concept, the multiline breaker (MLB), for the protection of multiterminal high voltage dc (MTdc) networks. Based on the design of a hybrid breaker, the MLB is an economically attractive solution for the protection of multiple dc lines in nodal connection using a single main breaker path. By using commutation units, the MLB directs the fault current through the main breaker in a unidirectional way, irrespective of the fault location. Hence, this study presents the design

requirements for the MLB, regarding both hardware and control, and evaluates its operation within a grid. For this reason, a four-terminal half-bridge multilevel modular converters-based MTdc grid in radial configuration was used and pole-to-ground dc fault conditions were investigated. The dc fault response of the grid with one MLB at the central node is compared to the respective response of the grid when one hybrid breaker is employed at each dc line. The simulations show that the MLB is feasible and that the overall MTdc grid fault response for the two protection systems is very similar. As a result, the design advantages of the MLB make it a promising solution for the dc fault isolation in MTdc grids.
IEEE Transactions on Power Delivery **33(3)** (2018)

L.S.J. Bort, C.M. Franck, "Arc discharges, HVDC interrupters, Gas blast circuit breakers, AC circuit breakers"
DC switchgear using gas circuit breakers in parallel to a LC-resonant path is used for decades already. This "passive oscillation" topology relies on negative damping of the oscillating current, made possible by the fact that the voltage drop over the CB decreases with increasing current. This concept is cheap and reliable, since it does not require any active components besides the mechanical breaker. However, the achievable breaking times and maximum current amplitude that can be interrupted highly depend on the u(i) characteristic of the axially blown arc inside the breaker. Improvements to the breaking chamber could move the maximal breakable current to higher values, and reduce the time to CZ. Analyzing which parameters influence the arc voltage is crucial for this optimization. Knowing which axial segments contribute how much to the total arc voltage enables a deeper understanding and possibilities to improve performance. Direct measurements of voltage inside the nozzle of a CB is not feasible, therefore an indirect method was developed. The contact positions in a model circuit breaker were varied systematically, and by evaluating the u(i) curves of 13 different configurations, the voltage drop of eight segments of 2 length was calculated. It is shown that most of the voltage drops over the converging nozzle part, where gas density and acceleration is high. These segments also exhibit beneficial behavior, with du/di being negative. The method was validated by comparing the extracted results with suitable direct measurements.
IEEE Transactions on Plasma Science, **47(1)** (2018)

A. Ritter, C. M. Franck, "Prediction of Bus-Transfer Switching in Future HVDC Substations"
Prior research has characterized bus-transfer switching capabilities of disconnectors commonly found in ac gas insulated switchgear (GIS) by means of a limit performance prediction. A large number of dc bus-transfer tests

was conducted on a modified bus-transfer test setup in order to study the applicability of these findings for the use of disconnectors in future HVdc substations. It was found that the ac extinction criterion based solely on the instantaneous recovery voltage and the expected arc voltage at current zero is also valid for dc bustransfer switching. However, due to the high frequency harmonics inherent to HVdc power transmission, the process of reaching the initial current zero and the extinction of the switching arc at current zero have been discovered to be independent to a certain degree. For negligible harmonic content of the switching current, arcing times below 20 ms have been predicted for reasonable sizes of substations and realistic dc current magnitudes, which is certainly within the capabilities of existing ac disconnectors. The previously devised limit performance prediction can be applied to gauge influences of different harmonic current contents and small modifications to the disconnector in simulation by applying the reignition criterion at the initial and all subsequent current zeros. Ultimately, however, exact knowledge of frequency and magnitude of the harmonic currents is needed in order to perform accurate predictions.
IEEE Transactions on Power Delivery **33(3)** (2018)

A. Ritter, U. Straumann, C. M.Franck, "Improving GIS Disconnectors for Future HVDC Applications"
The use of standard HVac disconnectors for bus-transfer switching in future HVdc gas-insulated switchgear (GIS) has been demonstrated successfully in past research through simulation and testing. Prolonged arcing times through reignitions caused by high frequency harmonics as well as the proposed extension of GIS disconnector switching cases, however, create an HVdc-specific demand for more advanced disconnector concepts capable of withstanding higher switching stresses and increased recovery voltages. A spring-loaded disconnector designed for use in HVac mixed technology switchgear was found to shorten the time to first current zero through an accelerated increase of the arcing voltage compared to standard disconnectors. Despite its increased switching performance, the reignition characteristics of this fast-acting disconnector were found to largely follow the previously established extinction criterion, which enables further simulation of similar technologies for HVdc applications. To additionally combat the issue of contamination of HVdc GIS by electrode erosion products, a prototype disconnector was improved using permanent magnets to evoke arc rotation. Erosion tests in air have shown an effective reduction of electrode erosion for long arcing times at currents typical for disconnector switching, whereas bus-transfer tests revealed promising enhancements of the reignition behavior.
IEEE Transactions on Power Delivery **34(1)** (2019)

4.3 Future Overhead Power Transmission Lines

The ultimate wish of any transmission and distribution system operator is to find ways of quickly adding transmission capacity to its network when needed. Today, this process takes very long time due to regulatory processes and public objections that often end in legal processes. There are two principle ways that system planners can take: 1) increasing the transmission capacity of existing infrastructure without any constructional changes, or 2) an improved stakeholder involvement process which increases the acceptance of projects.

Projects in this first area research the possibility of increasing the transmission capacity of existing line without (or with minimum) constructional changes.

One idea is to convert existing multi-circuit AC transmission towers to hybrid AC/DC systems (AC and DC on the same tower). The goal is to maximise the power transmission capacity of existing infrastructure (the conversion of one circuit from AC to DC), but to keep the easy access and tap-off from AC systems. Critical technical questions related to such a conversion include the impact on the electric fields and ion currents at the ground level, the DC current coupling into the AC phases, and the resulting corona generated noise. Another idea is to work on the lines current rating. The transmission capacity (or ampacity) of OHLs is determined by limits on the maximum conductor temperature. Historically, system operators base their ampacity calculations on conservative assumptions of the weather and conductor conditions, leading to static thermal line ratings.

Dynamic Thermal Line Rating (DTLR) provides more flexibility to the transmission capacity of the network by making more realistic estimations of the current capacity of the lines since it is based on accurate weather and conductor conditions. This ensures that the line limits are not exceeded at any time and can also lead to an average increase in the transmission capacity. Due to the higher ampacities of a DTLR scheme, the OHLs may be operated closer to their real thermal and operational limits. Our research determines the thermal and mechanical limits of the OHLs, with particular focus on the behaviour close to the clamps.

In collaboration with partners, the public acceptance of these new technical solutions is investigated and acceptance critical constraints are influencing the technical optimisation procedures. A detailed study has shown that a key factor for public acceptance of new technical solutions are advance open information. In general the acceptance can be very high, but it is also quite sensitive if potential negative effects are not considered. A technical optimization is done to certainly eliminate negative effects, at the expense of lowering the capacity increase.

Partnership: *ABB, Amprion, Axpo, CCEM, EPRI, KWO, Pfisterer Sefag, RWTH Aachen (IfHT), Swisselectric Research, Swissgrid, Tennet, TransnetBW, Climate Policy Group (ETHZ), Institute of Political Science (University Bern), Laboratoire des systèmes électriques distribués (EPFL)*

Researchers: *Pascal B. Bühlmann, C. Sören Hedtke, Pascal T. Bleuler, B. Lehmeyer*

Publications In this research area, the following publications have been published in 2018:

S. Hedtke, M. Pfeiffer, C. M. Franck, "HVDC & hybrid HVAC/HVDC overhead line conversion: An acceptance case study"
The demand for electric power is continuously growing and an increasing share of it is generated using remote renewable energy sources. Thus, more long-distance transmission capacity is required, but public acceptance for the construction of new lines is generally very low. By converting existing AC transmission lines to DC or hybrid AC/DC lines, the transmission capacity could be significantly increased without altering the visual appearance. This could avoid construction delays due to public objection as the acceptance for a tower conversion is assumed to be higher. However, corona effects are likely to increase due to the implementation on existing geometry with fixed clearances. This study critically investigates the assumption of higher acceptance for a hybrid tower conversion. It is shown, that the general acceptance of a hybrid line is positive, especially when confronted with the alternative of a new overhead line. However, acceptance for the new technology has shown to be very volatile and especially sensitive to uncertainties with regard to the impact on humans. Therefore, a conservative approach for the tower design is advised to avoid public annoyance and diffuse fears. In order to reduce the impact on humans as far as possible and hence create an acceptance basis, a simulation study is conducted to optimize hybrid tower environmental effects beyond regulatory limits. A compaction of the AC system is envisioned to reduce the magnetic field below the levels of the conventional tower. The compacted phase spacing is optimized as a compromise between audible noise and magnetic field. Based on the compacted geometry, the ion currents and DC fields at ground are simulated. According to existing prediction models for the perception of electric fields, e.g. through head hair sensation, the ground level fields and ions are barely sensitive.

CIGRE Session Paris (2018)

S. Hedtke, M. Pfeiffer, M. Gobeli, R. Bräunlich, C. M. Franck, "Setup of an outdoor hybrid AC / DC test line for corona measurements"
While the installed capacity of remote renewables is increasing around the globe, the construction of new transmission lines is often delayed due to public opposition. Therefore many operators evaluate the option of an uprating of existing corridors. A conversion of existing tower infrastructure to hybrid AC/DC lines allows a significant capacity increase without low visual impact. Possible negative effects such as corona audible noise and electromagnetic fields will be a main factor for the acceptance and hence success of this conversion. However, only few experimental studies have been presented with regard to the corona effects of hybrid lines. Therefore, ETH and FKH have constructed an outdoor test line which allows to study these effects under realistic conditions. The Däniken test line allows to measure the corona performance of a hybrid section of 35m length for typical conductor bundles and operating surface gradients. The ground clearance, the AC-DC separation distance and the voltages can be varied in order to study different ratios of coupling between both sides. The safety system and voltage control is designed to be able to run autonomously for several days in order to capture long-time trends in changing weather and pollution conditions. Existing sensor concepts were upgraded in order to cope with harsh environmental conditions such as heavy rain, as these are often the worst case for corona effects.
VDE High Voltage Congress (2018)

P. Bühlmann, C. M. Franck, "Temperature Profiles of All-Aluminum-Alloy Conductors near Wedge Tension Clamps"
Conductor temperatures at the wedge tension clamp are significantly lower than in the free-span. In this paper, the reasons for the lower temperatures due to the clamp are investigated. The increased convective and emissive cooling power as well as the decreased power losses at the clamp are causing the lower conductor temperatures. A numerical model is developed and described, which enables to accurately predict axial and radial temperature profiles of the conductor inside and close to the clamp. Experimental measurements of electric resistance, magnetic flux and temperature are used to verify the presented model. This developed numerical tool uses adapted material characteristics that allow to model the conductor as a simplified bulk cylinder. The tool can be adapted to other clamps and applications to analyze and optimize them.

CIGRE Science and Engineering **10**, pp. 66-76 (2018)

4.4 High Voltage Solid Insulation

Power electronic devices are increasingly used also in medium and high voltage applications such as HVDC transmission systems, FACTS devices, or motor drives, and research for use in future applications such as solid state transformers or wireless charging for electric vehicles is ongoing. As a result, the insulation system is no longer stressed only with power frequency voltages, but also DC and mixed-frequency voltage stress. Research is needed to achieve the same reliable and long-term performance also under these new conditions.

4.4.1 Mixed-Frequency Medium-Voltage Stress

Voltage waveforms generated with the aid of solid state switches introduce a new form of insulation stress as compared to the conventional 50 Hz sinusoidal waveforms. Their high slew rates have been shown to lead to enhanced partial discharge activity and corresponding accelerated ageing of wire insulation in inverter-fed induction motors as well as reduced breakdown voltages of oil-impregnated paper insulation. However, apart from enhanced dielectric heating due to higher harmonics, the effects of mixed-frequency voltages on insulation materials below partial discharge inception are to a large extent unknown. It is the goal of this project to contribute to a more detailed understanding of the impacts of mixed-frequency stress on insulation materials under such conditions in order to establish dimensioning guidelines for reliable insulation concepts of, e.g., the medium-frequency transformer winding insulation of medium voltage solid-state transformers.

4.4.2 High Voltage DC Stress

The main challenge in gas-insulated HVDC equipment is to control the surface charging of the solid-gas interfaces to prevent field enhancements in case of voltage polarity reversals or transient overvoltages. A large number of processes have to be considered when analysing surface charge accumulation and surface charge decay of polymer-gas interfaces: different charge origins, charge species, charge mobilities, and polarisation-processes. Furthermore, the determination of the dominant processes is rather challenging since all parameters show different time, temperature, pressure, humidity, and field dependencies. The processes are investigated in detail using spatially-resolved analysis accessible with surface potential scans. These novel and highly sensitive measurements enable a to investigate the involved processes to a level that has previously been hidden in measurement noise. This way, a new understanding of the charging processes and their magnitude is achieved. The findings can then be used to establish dimensioning guidelines for gas-insulated HVDC components in order to construct efficiently and reliably gas-insulated HVDC systems as a key element of the future energy network.

Partnership: *ABB Schweiz AG, Elantas (Altana), SCCER Furies, Power Electronic Systems Laboratory (ETHZ)*

Researchers: *Raphael B. Färber, Malte Tschentscher, Mostafa Refaey, Florian Küchler*

The following publications have been published in 2018:

R. Färber, C. M. Franck, "Modular High-Precision Dielectric Spectrometer for Quantifying the Aging Dynamics in (Sub-)Picofarad Polymeric Specimens"
A custom-made modular high-precision dielectric spectrometer for quantifying aging-induced molecular changes in (sub-)picofarad polymeric samples is presented. Validation and characterization of the setup's performance is obtained by quantifying the change in the dielectric response of an epoxy polymer following the exposure to thermal, hygrothermal and ultraviolet radiation stress. It is shown that the observed changes in the dielectric spectra can be resolved with a relative precision better than $5 \cdot 10^{-5}$ *and are in line with previous studies employing commercial instruments on samples of higher capacitance. This setup is intended to serve as a blueprint for a sensitive and extensible (because modular) measurement tool for studying the pre-breakdown dynamics in low-capacitance recessed or disc-shaped specimens as used, e.g., in high-voltage insulation testing.*
IEEE Transaction on Dielectrics and Electrical Insulation, **25(3)** (2018)

M. Tschentscher, C. M. Franck, "Conduction Processes in Gas-Insulated HVDC Equipment: From Saturated Ion Currents to Micro-Discharges"
Charge generation in gas-insulated high-voltage direct current (HVDC) equipment has been investigated since surface charge accumulation was detected as the main challenge to insulation coordination. Over the years, researchers have made enormous progress using continuous ion current measurements or surface charging experiments with model spacers downscaled from gas-insulated components. Whereas the low sensitivity of the former method limits its measurement range, the latter method is timeconsuming and demands comprehensive modeling. In this paper, more than 3,000 hours of surface charge measurements are presented, covering the full range of charge generation processes from ion currents owing to natural ionization to the inception of micro-discharges. In accordance with gas-insulated equipment, Al_2O_2*-filled epoxy resin was used for the solids, and sulfur hexafluoride (*SF_6*) was used for the gaseous insulation. It has been demonstrated that*

the ion pair generation from natural ionization in the gas is significantly influenced by the surrounding solid materials, and therefore, scales with the insulation volume. From the onset of micro-discharges, sharp and locally limited charge patterns are formed, as surface conductivity does not appear to influence the investigated charge distributions. Whereas the primary charge dissipation from surface areas centered at the distribution could be explained in terms of the gas volume size, the discharge currents could not be reproduced with common ion-current models. At low electric fields, the observed charge decay indicates the presence of low-field conduction processes that cannot be explained by charge generation from natural ionization in the gas.
IEEE Transactions on Dielectrics and Electrical Insulation, **25(4)** (2018)

M. Tschentscher, C. M. Franck, "A critical re-examination on conduction processes in gas-insulated DC devices at low electric fields"
The established theories behind low-field ion-drift currents assume that the charge generation from natural ionization is the main source of the charge-carriers, and that it defines the current flowing through the insulation gas in gas-insulated direct current (DC) devices. This charge generation is assumed to be independent of the applied electric field in the cases where the electric field is sufficiently below the onset of microdischarges at the interfaces. However, the results of a few previous studies have suggested the presence of a field-dependent current contribution from some conduction processes, which might significantly accelerate the decay of the surface charges distributed on the insulator surfaces. In this paper, an extensive study on low-field charge transport is presented, and the influences of the insulation volume, electric field, and gas pressure on low-field charge transport are discussed. In accordance with the common structure employed in gas-insulated devices, Al_2O_3*-filled epoxy resin is used in the solid parts of the device and sulfur hexafluoride (*SF_6*) is used for gaseous insulation. At electric fields of approximately 1800 V/m, a gas current that is up to 30 times higher, when compared to the conduction currents caused by the charge generation from natural ionization, is observed. This enhanced current reveals a further conduction process acting in a limited range of low electric fields and is characterized to be independent of the applied voltage polarity. With an increase in the gas pressure, the current amplitude is found to increase linearly and higher electric field is required to reach its maximum. At electric fields below 200 V/m, the conduction current reverses its pressure dependency and increases with decreasing gas pressure. The reported findings strongly indicate that the enhanced low-field charge transport in gasinsulated devices may be owing to electrophoretic conduction.*

IEEE Transactions on Dielectrics and Electrical Insulation, textbf25(4) (2018)

M. Tschentscher, C. M. Franck, "Microscopic charge provision at interfaces of gas-insulated (HVDC/HVAC) systems"
Charge generation at the interfaces of gas-insulated switchgear or gas-insulated lines is mostly studied from a macroscopic point of view. Integral current measurements are a common method to determine the average inception field strengths and intensities of micro discharges. However, because of the lack of spatial resolution and measurement sensitivity, these experiments do not provide deeper insights on the microscopic processes. By applying surface potential measurement techniques, studying the charge generation of single interface protrusions and drawing conclusions relative to their spatial distribution have become possible. This paper presents a spatially resolved analysis of charge-generation processes at rough aluminum electrodes and insulating interfaces. The results reveal a highly inhomogeneous charge generation at the interfaces even for electric fields below 6 kV/mm. Analyzing the charge generation from a macroscopic perspective has been demonstrated to possibly underestimate the local charge generation by up to three orders of magnitude. Using sulfur hexafluoride (SF_6) as the insulation gas at 0.45 MPa and Al_2O_3-filled epoxy resin insulators, the inception field strength for charge generation at the insulating interface is measured to be 3 kV/mm. For a technical insulation system that includes both a rough aluminum electrode and an insulating interface, significant discharge intensities are observed at a 5-kV/mm electric field. From these results, micro discharges are expected to be highly relevant for dimensioning of gas-insulated devices.
IEEE Transactions on Dielectrics and Electrical Insulation, textbf25(4) (2018)

4.5 Optimal Power Flow and System Operation

Optimization is an important tool in electric power systems to make best use of all assets in the system. However, due to the nonlinear physical dependencies the resulting Optimal Power Flow problem is non-convex. Hence, despite this being a long-standing problem, research is still highly active in developing efficient algorithms to accurately solve these problems. Convexification of the non-convex constraints has received significant attention in recent years as a potential solution approach. The overall goal is to approximate the problem with convex approximations for which global solutions can be found. In order to recover the actual solution the relaxations should be as tight as possible and it should lead to a problem structure that can be solved efficiently.

Usually there is a clear distinction made between scheduling and real-time operation. Schedules are made for time resolutions of one hour down to 5 minutes (depending on the specific market) in a forward looking fashion that is inherently based on optimization whereas real-time operation activates resources that have been set aside as reserves. In the latter case, only the reservation is optimized but not the activation. Online optimization, i.e. the derivation of controllers that track the optimal solution of the problem, have the potential to enable merging real-time operation with optimization thereby improving operational and economic performance of the electric power grid.

Another optimization problem is involved in the process of state estimation. The traditional formulation is non-linear and an iterative approach is usually used to solve it. The increased penetration of phasor measurement units which provide very accurate measurements of voltage and current phasors has lead to research that studies how to efficiently integrate these measurements into the state estimation formulation. It is possible to derive a state estimation formulation that is based on representing the power system and its measurements as a set of coupled electric circuits and that shows significantly improved computational properties.

When striving towards a more sustainable energy system, it should not be forgotten that the the electric energy system is also coupled to other energy systems such as the gas or the heating system. The modelling of the interconnections between these systems and the optimal coordination of these systems provides mutual benefits. An important aspect thereby is the consideration of the highly different time scales in these systems which may mean that the transients in a slower system (such as the gas system) can have significant impacts on systems that act at faster time scales (such as the electric system). Additionally, the markets for these individual energy carriers have their own sets of rules that need to be taken into account when designing such coordination.

But even if just focusing on the electric power system, the interrelations between the economics, policy making and physical system are quite complex and requires detailed modelling in order to study and lay out paths towards sustainable energy systems. Consequently, the development of a simulation platform supports a wide range of other research but necessitates research in its own. This allows studying how the system will or should be planned and operated in the future including answering questions such as how capacity expansion for the provision of required flexibility can be efficiently done or what impact plug-in electric vehicles will have onto the system.

Research in all of the above topics was and is carried out at the Power Systems Laboratory by the following researchers in collaboration with a number of partners and within specific larger research projects:

Researchers: *Stefanos Delikaraoglou, Xuejiao Han, Michael Haendel, Adrian Hauswirth, Aleksandar Jovicic, Evangelos Kardakos, Conor O'Malley, Dmitry Shchetinin*

Partnership: *ETH Control Laboratory, Fraunhofer Gesellschaft, Neplan, Universita della Svizzera Italiana, ETH Energy Science Center, ETH Research Center for Energy Networks, ETH Center of Economic Research, ETH Reliability and Risk Engineering Lab, Swissgrid, Ernst Basler + Partner, Carnegie Mellon University*

Externally Funded Research Projects:
ESORIMUS - Efficient Simulation and Optimization for Reliable Intercoupled Multi-Energy Carrier Systems: The objective of this project is to develop and integrate a novel software module in the power systems simulation software NEPLAN that enables the simulation and optimization of coupled multi-energy carrier systems. This includes deriving the mathematical models of the coupled systems with a special focus on integrating a holistic security formulation for the overall system and devising algorithms for the efficient solution of the resulting problems for large scale systems.
Funded by the Bundesamt für Energie, in collaboration with Neplan and Universita della Svizzera Italiana.

Nexus - The role of flexibility providers in shaping the future energy system: The project analyses the mutual influences of large scale centralized and small scale decentralized flexibility providers in light of a transition to an

energy sector with a high RES share in 2050. The main focus is on how, in a market setup that honours flexibility as a market product, these different flexibility technologies will be deployed (through investment incentives) and how they influence the whole energy system as well as how they influence each other. This project is part of an initiative of the Energy Science Center to develop an integrated modelling platform for assessing future energy systems. This Nexus Modelling Platform aims to provide a comprehensive technical and economic assessment tool of current and future energy systems.
Funded by the Bundesamt für Energie, in collaboration with ETH Energy Science Center, ETH Research Center for Energy Networks, ETH Center of Economic Research, ETH Reliability and Risk Engineering Lab, Swissgrid, Ernst Basler + Partner

The Role of Gas and the Gas Infrastructure within the Future Energy System - a Techno-Economic Assessment: This project aims at a quantitative techno-economic-assessment of the utilisation of interdependencies between various energy infrastructures (electricity, gas, and heating) at municipal level in the supply area of Wasserwerke Zug (WWZ) and the assessment of the ability especially of gas networks in providing the additional operational fexibility for electrical power system to avoid costly network expansions at the distribution level.
Funded by the Bundesamt für Energie, lead by ETH Research Center for Energy Networks, in collaboration with TEP Energy, VSG, Wasserwerke Zug

Publications In this research area, the following publications have been published in 2018:

A. Jovicic, M. Jereminov, L. Pileggi, G. Hug, "An Equivalent Circuit Formulation for Power System State Estimation including PMUs"
In this paper, a novel formulation for the power system state estimation is proposed, based on the recently introduced equivalent split-circuit formulation of the power flow problem. The formulation models the conventional and time synchronized measurements simultaneously and contains a significantly lower level of nonlinearity compared to the available hybrid state estimators. The appropriate circuit models are derived for different types of measurements and integrated into the existing circuit framework for the power flow problem. A constrained optimization problem is then formulated to estimate the states of the system in rectangular coordinates, while satisfying the circuit equations and bounds on the measurement data. To further prove the concept and validate the accuracy of the proposed formulation, several test

cases are solved and the results are presented and discussed.
North American Power Symposium, September 9-11, 2018, Fargo, ND (2018)

D. Shchetinin, T. Tinoco De Rubira, G. Hug, "On the Construction of Linear Approximations of Line Flow Constraints for AC Optimal Power Flow"
The AC optimal power flow problem is a non-convex optimization problem that is difficult to solve quickly and reliably for large-scale grids. While various approximations have been proposed, they may lead to physically meaningless solutions. This paper presents a computationally efficient algorithm for constructing accurate linear approximations of line flow constraints. These approximations reduce the complexity of the optimization problem while ensuring that the solution is physically meaningful and has a high quality. The algorithm is based on an in-depth analysis of the feasible set of the line flow constraint. Numerical experiments are performed on ten large-scale systems using three nonlinear programming solvers. Obtained results indicate that the proposed formulation helps improve the solvers' reliability and reduce the computation time for hard large-scale problems. At the same time, the developed algorithm provides high quality approximations of the line flow constraints.
IEEE Transactions on Power Systems (Early Access) (2018)

X. Han, E. G. Kardakos, G. Hug, "Offering Strategy of a Price-maker PV Power Plant: Multi-stage Stochastic Programming With Probabilistic Constraints"
This paper presents a stochastic bi-level model to derive optimal offering strategies for an aggregated photovoltaic (PV) power plant, who participates as a price-maker in both day-ahead and intraday markets, and a deviator in the balancing market. The upper-level represents the profit maximization of the PV power plant, while the two lower-levels represent the market clearing of the day-ahead and the intraday market, respectively. The problem considered is stochastic and subject to different levels of uncertainties. Uncertainties concerning rivals offers are modeled using scenarios, while the PV output uncertainty is taken into consideration by formulating probabilistic constraints. The stochastic bi-level optimization problem is then solved by being transformed into a mixed-integer linear programming model using the Karush-Kuhn-Tucker optimality conditions and the strong duality theory. A case study based on the data from a modified Swiss system demonstrates the effectiveness of the proposed model.
20th Power Systems Computation Conference (PSCC 2018), June 11-15,

Dublin, Ireland (2018)

M. Haendel, G. Hug, "Analysis of Electric Vehicle Charging Behavior in Low-Voltage Grids Using a Receding Horizon Control Strategy"
Electric vehicles (EV) are becoming increasingly popular due to the need for a greater contribution of the transport sector to climate protection. Their integration into the system, however, poses both challenges and opportunities. This paper takes a closer look at the behavior of EVs in a setting influenced by electricity market prices and network restrictions. Our focus is a market model that includes network constraints in order to derive a market driven control strategy for EVs that also observes all grid constraints. A price signal from the market is used to control the charging behavior with a receding horizon approach and considering network restrictions. A case study examines the possible effects of the control strategy on the system. The main result is that EVs are very flexible in shifting their demand for the considered low-voltage grid. However, high photovoltaics feed-in, especially in the summer months, can lead to high network loads that EVs cannot always completely compensate.
International Conference on Smart Energy Systems and Technologies (SEST) 10-12 September, 2018, University of Sevilla, Sevilla, Spain (2018)

A. Hauswirth, I. Subotić, S. Bolognani, G. Hug, F. Dörfler, "Time-varying projected dynamical systems with applications to feedback optimization of power systems"
This paper is concerned with the study of continuous-time, non-smooth dynamical systems which arise in the context of time-varying non-convex optimization problems, as for example the feedback-based optimization of power systems. We generalize the notion of projected dynamical systems to time-varying, possibly non-regular, domains and derive conditions for the existence of so-called Krasovskii solutions. The key insight is that for trajectories to exist, informally, the time-varying domain can only contract at a bounded rate whereas it may expand discontinuously. This condition is met, in particular, by feasible sets delimited via piecewise differentiable functions under appropriate constraint qualifications. To illustrate the necessity and usefulness of such a general framework, we consider a simple yet insightful power system example, and we discuss the implications of the proposed conditions for the design of feedback optimization schemes.
2018 IEEE Conference on Decision and Control (CDC), 3258-3263, Miami, FL, USA, Dec. 2018 (2018)

A. Hauswirth, S. Menta, S. Bolognani, G. Hug, F. Dörfler, "Stability of Dynamic Feedback Optimization with Applications to Power Systems"

We consider the problem of optimizing the steady state of a dynamical system in closed loop. Conventionally, the design of feedback optimization control laws assumes that the system is stationary. However, in reality, the dynamics of the (slow) iterative optimization routines can interfere with the (fast) system dynamics. We provide a study of the stability and convergence of these feedback optimization setups in closed loop with the underlying plant, via a custom-tailored singular perturbation analysis result. Our study is particularly geared towards applications in power systems and the question whether recently developed online optimization schemes can be deployed without jeopardizing dynamic system stability.
56th Annual Allerton Conference on Communication, Control, and Computing, Monticello, IL, USA, Oct. 2018 (2018)

A. Hauswirth, S. Bolognani, G. Hug, F. Dörfler, "Generic Existence of Unique Lagrange Multipliers in AC Optimal Power Flow"
Solutions to nonlinear, nonconvex optimization problems can fail to satisfy the Karush-Kuhn-Tucker (KKT) optimality conditions even when they are optimal. This is due to the fact that unless constraint qualifications (CQs) are satisfied, Lagrange multipliers may fail to exist. Even if the KKT conditions are applicable, the multipliers may not be unique. These possibilities also affect AC optimal power flow (OPF) problems which are routinely solved in power systems planning, scheduling and operations. The complex structure-in particular the presence of the nonlinear power flow equations which naturally exhibit a structural degeneracy-make any attempt to establish CQs for the entire class of problems very challenging. In this letter, we resort to tools from differential topology to show that for AC OPF problems in various contexts the linear independence constraint qualification is satisfied almost certainly, thus effectively obviating the usual assumption on CQs. Consequently, for any local optimizer there generically exists a unique set of multipliers that satisfy the KKT conditions.
IEEE Control Systems Letters, Volume 2, Issue 4, Oct. 2018 (2018)

A. Venzke, L. Halilbasic, U. Markovic, G. Hug, and S. Chatzivasileiadis, "Convex Relaxations of Chance Constrained AC Optimal Power Flow"
High penetration of renewable energy sources and the increasing share of stochastic loads require the explicit representation of uncertainty in tools such as the optimal power flow (OPF). Current approaches follow either a linearized approach or an iterative approximation of nonlinearities. This paper proposes a semidefinite relaxation of a chance-constrained AC-OPF, which is able to provide guarantees for global optimality. Using a piecewise affine policy, we can ensure tractability, accurately model large power devi-

ations, and determine suitable corrective control policies for active power, reactive power, and voltage. We state a tractable formulation for two types of uncertainty sets. Using a scenario-based approach and making no prior assumptions about the probability distribution of the forecast errors, we obtain a robust formulation for a rectangular uncertainty set. Alternatively, assuming a Gaussian distribution of the forecast errors, we propose an analytical reformulation of the chance constraints suitable for semidefinite programming. We demonstrate the performance of our approach on the IEEE 24 and 118 bus system using realistic day-ahead forecast data and obtain tight near-global optimality guarantees.
IEEE Trans. Power Syst., vol. 33, no. 3, pp. 28292841, May 2018 (2018)

C. O'Malley, L. Roald, D. Kourounis, O. Schenk, G. Hug, "Security Assessment in Gas-Electric Networks"
In many parts of the world, electricity systems are experiencing an increasing amount of gas-fired generation being installed due to its cheap fuel. The flexibility offered by gas generators is considered to be beneficial for electric grids, particularly in the face of increasing renewable generation. However, gas generators are often problematic for the gas network, as they induce large, rapid changes in the demand. The objective of this paper is to investigate the interaction between electrical and gas networks, and how security criteria for gas system operations implicitly impact the operation of the electric grid. Special attention is paid to the incorporation of the gas system dynamics, which have profound impact on the security assessment. To facilitate the assessment, the paper proposes an analysis framework which considers i) preventive security assessment for the gas system, ii) determination of remedial actions and gas load shedding after a contingency occurs, and iii) the impact of the load shedding on the electric grid, given different operating rules for the gas system. A case study shows that the preventive security assessment is beneficial both for the gas and electric grid, and that the security criterion used to determine the required gas system remedial actions impacts the cost of the electric grid.
20th Power Systems Computation Conference (PSCC 2018), June 11-15, Dublin, Ireland (2018)

C. O'Malley, Conor, D. Kourounis, G. Hug, O. Schenk, "Finite volume methods for transient modeling of gas pipelines"
Given the increasing importance of multi-energy carrier system modeling, this paper focuses on modeling the dynamics that occur in natural gas transmission lines. In high-pressure pipelines, these dynamics are governed by a set of hyperbolic partial differential equations. Dissipative finite volume discretization schemes are proposed that honor the discrete maximum prin-

ciple. The convergence of the proposed discretization schemes is investigated and compared with existing methods suggested in the literature for natural gas transmission such as the implicit cell-centered method. High order time discretization methods are also tested and their suitability with respect to the maximum principle is discussed.
2018 IEEE International Energy Conference (ENERGYCON), Limassol, Cyprus (2018)

S. Delikaraoglou, P. Pinson, "Optimal allocation of HVDC interconnections for exchange of energy and reserve capacity services"
The increasing shares of stochastic renewables bring higher uncertainty in power system operation and underline the need for optimal utilization of flexibility. However, the European market structure that separates energy and reserve capacity trading is prone to inefficient utilization of flexible assets, such as the HVDC interconnections, since their capacity has to be ex-ante allocated between these services. Stochastic programming models that co-optimize day-ahead energy schedules with reserve procurement and dispatch, provide endogenously the optimal transmission allocation in terms of minimum expected system cost. However, this perfect temporal coordination of trading floors cannot be attained in practice under the existing market design. To this end, we propose a decision-support tool that enables an implicit temporal coupling of the different trading floors using as control parameters the inter-regional transmission capacity allocation between energy and reserves and the area reserve requirements. The proposed method is formulated as a stochastic bilevel program and cast as mixed-integer linear programming problem, which can be efficiently solved using a Benders decomposition approach that improves computational tractability. This model bears the anticipativity features of a transmission allocation model based on a pure stochastic programming formulation, while being compatible with the current market structure. Our analysis shows that the proposed mechanism reduces the expected system cost and thus can facilitate the large-scale integration of intermittent renewables.
Energy Systems, pp.1-41. DOI https://doi.org/10.1007/s12667-018-0288-6 (2018)

V. Dvorkin, S. Delikaraoglou, and J. M. Morales, "Setting reserve requirements to approximate the efficiency of the stochastic dispatch"
This paper deals with the problem of clearing sequential electricity markets under uncertainty. We consider the European approach, where reserves are traded separately from energy to meet exogenous reserve requirements. Recently proposed stochastic dispatch models that co-optimize these services provide the most efficient solution in terms of expected operating costs by

computing reserve needs endogenously. However, these models are incompatible with existing market designs. This paper proposes a new method to compute reserve requirements that bring the outcome of sequential markets closer to the stochastic energy and reserves co-optimization in terms of cost efficiency. Our method is based on a stochastic bilevel program that implicitly improves the inter-temporal coordination of energy and reserve markets, but remains compatible with the European market design. We use two standard IEEE reliability test cases to illustrate the benefit of intelligently setting operating reserves in single and multiple reserve control zones.
IEEE Transactions on Power Systems 34.2 (2019): 1524-1536 (2018)

N. Viafora, S. Delikaraoglou, P. Pinson and J. Holboll, "Chance-Constrained Optimal Power Flow with Non-Parametric Probability Distributions of Dynamic Line Ratings"
Compared to Seasonal Line Rating (SLR), Dynamic Line Rating (DLR) allows for higher power flows on overhead transmission lines, depending on the actual weather conditions. Nevertheless, the potential of DLR has to be traded off against the additional uncertainty associated with varying ratings. This paper proposes a DC-Optimal Power Flow (DCOPF) algorithm that accounts for DLR uncertainty by means of Chance-Constraints (CC). The goal is to determine the optimal day-ahead dispatch taking the cost of reserve procurement into account. The novelty of the proposed paper is twofold: non-parametric probability distributions of DLR are considered and wind power forecasts errors are included as well in the optimization problem. Our results highlight the benefits of DLR in wind-dominated power systems, assuming typical risk aversion levels in the line rating estimation.
Medpower 2018, Dubrovnik, Croatia (2018)

A. Kargarian, J. Mohammadi, J. Guo, S. Chakrabarti, M. Barati, G. Hug, S. Kar, R. Baldick, "Toward Distributed/Decentralized DC Optimal Power Flow Implementation in Future Electric Power Systems"
This paper reviews distributed/decentralized algorithms to solve the optimal power flow (OPF) problem in electric power systems. Six decomposition coordination algorithms are studied, including analytical target cascading, optimality condition decomposition, alternating direction method of multipliers, auxiliary problem principle, consensus+innovations, and proximal message passing. The basic concept, the general formulation, the application for DC-OPF, and the solution methodology for each algorithm are presented. We apply these six decomposition coordination algorithms on a test system, and discuss their key features and simulation results.

IEEE Transactions on Smart Grid, Vol. 9, No. 4, pp. 2574 - 2594 (2018)

J. Guo, G. Hug, O. Tonguz, "On the Role of Communications Plane in Distributed Optimization of Power Systems"
Distributed optimization methods have been widely studied in recent years as they could be instrumental in optimizing the operation of future power systems. Compared to the centralized approach, communications will have greater impact on distributed methods as their performance depends heavily on the information exchange among multiple control entities. However, it is not clear what communications infrastructures and technologies should be adopted for distributed methods in practice. To investigate this issue and bridge the gap between the power system communications research community and the distributed optimization research community, this paper models the communications infrastructures and schemes required by distributed methods using the OPNET modeler. The capabilities and limitations of centralized and distributed communications infrastructures are investigated in terms of communications delays incurred and their impact on the convergence of two distributed algorithms, namely, Alternating Direction Method of Multipliers (ADMM) and Optimality Condition Decomposition (OCD) for solving the AC Optimal Power Flow problem in the IEEE 118-bus system and in the large-scale Polish power system. Our simulation results show that the existing communications plane in power systems might not be able to support widely used distributed optimization techniques (such as ADMM and OCD), which is a major finding. In addition, our results indicate that the connectivity requirements of distributed optimization necessitate a mesh network architecture with additional communications links among substations.
IEEE Transactions on Industrial Informatics, Vol. 14, No. 7, pp. 2903 - 2913 (2018)

A. Pandey, M. Jereminov, M. Wagner, G. Hug, L. Pileggi, "Robust Convergence of Power Flow Using TX Stepping Method with Equivalent Circuit Formulation"
Robust solving of critical large power flow cases (with 50k or greater buses) forms the backbone of planning and operation of any large connected power grid. At present, reliable convergence with applications of existing power flow tools to large power systems is contingent upon a good initial guess for the system state. To enable robust convergence for large scale systems starting with an arbitrary initial guess, we extend our equivalent circuit formulation for power flow analysis to include a novel continuation method based on transmission line ('Tx') stepping. While various continuation methods have been proposed for use with the traditional 'PQV' power flow formulation,

these methods have either failed to completely solve the problem or have resulted in convergence to a low voltage solution. The proposed Tx Stepping method in this paper demonstrates robust convergence to the high voltage solution from an arbitrary initial guess. Example systems, including 75k+ bus test cases representing different loading and operating conditions for Eastern Interconnection of the U.S. power grid, are solved from arbitrary initial guesses.

20th Power Systems Computation Conference (PSCC 2018), June 11-15, Dublin, Ireland (2018)

4.6 Power System Dynamics and Control

The electric power system is a large scale dynamical system that due to the continuous load changes is never in a steady state. However, it is crucial to ensure that the system always stays stable even in case of disturbances. The inertia provided by synchronous machines naturally slows down the overall reaction of the system to generation and load imbalances. But with the increased levels of renewable generation, the level of inertia decreases which on the other hand increases the speed at which frequency deteriorates. This is due to the fact that the newly added renewable generation resources use power electronics to connect to the grid.

Even though the inverter-based generation resources do not provide natural inertia to the system, an advantage of these resources is that the power electronics allow for an implementation of a variety of different control approaches. This also includes control designs that provide synthetic inertia. A complicating fact however is that any reaction by the resource needs to be established using measurements and a form of decision making which brings up the question of the impact of the delays in such signal processing on the control performance. Low inertia systems are clearly a topic of large interest in the years to come as solutions are sought to accommodate a large amount of renewable generation resources.

Renewable generation resources also have influence on the reaction of the system in case of faults and can lead to bi-directional flows even in distribution systems. Existing protection systems might not be able to reliably and securely handle some of the arising situations, requiring the design of new protection systems. This includes protection systems based on entirely new approaches but also a better utilisation and design of existing concepts for fault detection and identification.

Research in all of the above topics is carried out at the Power Systems Laboratory by the following researchers in collaboration with a number of partners and within specific larger research projects:

Researchers: *Nadezhda Davydova, Uros Markovic, Johanna Vorwerk*

Partnership: *ETH Control Laboratory, University of Leeds, RTE, University College of Dublin, Université Lille, Lawrence Berkeley National Lab*

Externally Funded Research Projects:
MIGRATE - Massive InteGRATion of power Electronic devices: The increasing penetration of power electronic components in the HVAC transmission networks gradually changes the way TSOs operate the transmission

system: system operations and control, together with the changes in protection schemes and the impact on the quality of the delivered power, need to be revisited together with the associated grid codes, this within the framework guidelines which are being adopted at EU level. Since the physical properties and limitations of converters are very different from the ones of synchronous generators, an evolution of todays control strategies is highly probable. The objective of this project is to develop and validate innovative, technology-based solutions in view of managing the pan-European electricity system experiencing a proliferation of power electronic devices involved in connecting generation and consumption sites.
Funded by Horizon 2020, within WP2 in collaboration with ETH Control Laboratory, RTE, University College of Dublin, Université Lille.

Publications In this research area, the following publications have been published in 2018:

R. Ofir, U. Markovic, P. Aristidou, G. Hug, "Droop vs. Virtual Inertia: Comparison from the Perspective of Converter Operation Mode"
Virtual Inertia Emulation (VIE) and traditional Active Power Droop Control (APDC) are among the most common approaches for regulating the active power output of inverter-based generators. Furthermore, it has been shown that, under certain conditions, these two methods can be equivalent. However, neither those studies, nor the analyses of different dynamical properties between the two control schemes, have investigated the impact of the converter operation mode. This paper explores the subject by investigating the two control approaches under such conditions, and determining when this assumption does not hold. Using time-domain simulations with a detailed Voltage Source Converter model, we compare VIE and APDC qualitatively and reformulate the respective conditions for equivalence.
IEEE International Energy Conference (ENERGYCON), Jun 2018, Limassol, Cyprus (2018)

L. Srinivasan, U. Markovic, M. G. Vayá, and G. Hug, "Provision of Frequency Control by a BESS in Combination with Flexible Units"
The inherent energy constraints of a Battery Energy Storage System (BESS) limit its ability to participate extensively in frequency reserve markets. This limitation can be addressed by operating the battery alongside distributed, controllable loads and generators in the form of a Virtual Power Plant (VPP). In this paper, a detailed MPC approach was developed to simulate the operation and cost of a VPP combined with a BESS providing primary and secondary frequency reserve. Unit types including photovoltaic arrays,

hydropower, combined heat and power and controllable loads were modeled. Two case studies are presented to validate the model, examining the technical and economic feasibility of a VPP under various operating scenarios, with different battery configurations. A techno-economic optimum is determined. Additionally, the relative value of different unit types is quantified.
IEEE International Energy Conference (ENERGYCON), Jun 2018, Limassol, Cyprus (2018)

U. Markovic, Z. Chu, P. Aristidou, G. Hug, "Fast Frequency Control Scheme through Adaptive Virtual Inertia Emulation"
This paper presents a novel virtual inertia controller for converters in power systems with high share of renewable resources. By combining the analytical study of system dynamics and a Linear-Quadratic Regulator (LQR)-based optimization technique, the optimal state feedback gain is determined, adapting the emulated inertia con- stant according to the frequency disturbance in the system. The optimality is achieved through trade-off between the critical frequency limits and the required control effort, i.e. utilization of the internal energy storage. The proposed controller is integrated into a state-of-the-art converter control scheme and verified through EMT simulations. The results show a significant improvement in the frequency response compared to an open- loop system, while also preserving significantly more DC-side energy than a non-adaptive controller.
ISGT Asia 2018, Singapore, Singapore (2018)

U. Markovic, O. Stanojev, P. Aristidou, G. Hug, "Partial Grid Forming Concept for 100% Inverter-Based Transmission Systems"
With the current trends in renewable energy integration, the concept of a 100% inverter-based power system is becoming more of a reality. However, the existing Voltage Source Converter (VSC) control schemes for such systems focus mostly on the operation of low-voltage microgrids, which have different requirements from the transmission system perspective. This paper proposes a new classification of VSC control strategies depending on their mode of operation. Then, the concept of partial grid forming VSC is introduced and it is shown that a system with zero rotational inertia can operate without a dedicated grid-forming VSC unit, but rather with partial forming of key system characteristics distributed across different VSC units. The performance of this approach is tested on detailed VSC models developed in both MATLAB Simulink and virtual Hardware-In-the-Loop (vHIL) platforms. Furthermore, an investigation towards necessary converter and network criteria for providing a stable system under the proposed control concepts is presented.

General Meeting Aug. 2018, Portland, United States (2018)

U. Markovic, J. Vorwerk, P. Aristidou, G.Hug, "Stability Analysis of Converter Control Modes in Low-Inertia Power Systems"
This paper deals with the small-signal stability analysis of converter control modes in low-inertia power systems. For this purpose, a detailed differential-algebraic equation model of the voltage source converter and its control scheme is developed. Both grid-forming and grid-feeding concepts have been considered, as well as different active power controllers based on traditional droop and virtual inertia emulation. An eigenvalue analysis of the linearized state-space system is conducted and the performance of different control configurations is compared. Furthermore, various bifurcation studies have been completed and conclusions on stability margins have been drawn with respect to control sensitivity and robustness.
2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), Oct 2018 (2018)

U. Markovic, Z. Chu, P. Aristidou, and G. Hug, "LQR-Based Adaptive Virtual Synchronous Machine for Power Systems with High Inverter Penetration"
This paper presents a novel virtual synchronous machine controller for converters in power systems with a high share of renewable resources. Using an LQR-based optimization technique, the optimal state feedback gain is determined to adaptively adjust the emulated inertia and damping constants according to the frequency disturbance in the system, while simultaneously preserving a trade-off between the critical frequency limits and the required control effort. Two control designs are presented and compared against the open-loop model. The proposed controllers are integrated into a state-of-the-art converter control scheme and verified through EMT simulations.
IEEE Trans. Sustainable Energy, Early Access (2018)

N. Davydova, D. Shchetinin and G. Hug, "Optimization of First Zone Boundary of Adaptive Distance Protection for Flexible Transmission Lines"
Traditionally, the tripping boundaries of distance protection zones are based predominantly on engineering experience and can be overly conservative, which reduces the reach of these zones. The installation of series compensation devices further reduces the protection zones, which is undesirable for a number of reasons. Despite research efforts to address this problem, developing a protection algorithm that constructs the first zone boundary containing only all separable internal faults remains a challenging task. This paper presents a new optimization-based algorithm for constructing the tripping boundary of the first protection zone for transmission lines with series com-

pensation devices. The obtained boundary encloses all internal line faults that can be separated from external ones and is valid for a predefined range of values of the compensation device reactance around its current operating point. The simulation results demonstrate that the proposed algorithm improves the reach of the first protection zone and is computationally efficient.
20th Power Systems Computation Conference (PSCC 2018), June 11-15, Dublin, Ireland, pp. 1-7 (2018)

N. Davydova, G. Hug, "Travelling Wave Protection with Disturbance Classification for Distribution Grids with Distributed Generation"
The high penetration of distributed generation in distribution grids and the development of microgrids may cause the malfunctioning of the conventional distribution level protection systems. Despite multiple works dedicated to addressing this problem, the development of reliable, high-speed, and cost-efficient protection systems for active grids remains a topical issue. This study proposes a protection system for medium voltage lines that relies entirely on the analytical description of travelling wave transients. This protection uses only local high-frequency current measurements and power-frequency voltage measurements, which potentially makes it a low-cost yet reliable solution. The protection system operates securely by not tripping healthy lines in case of disturbances that do not lead to any faults. The proposed protection is tested on the IEEE 34-bus distribution system with distributed generation.
The 14th International Conference on Developments in Power System Protection (DPSP 2018), pp.830-835: Institution of Engineering and Technology (IET) (2018)

F. Milano, F. Dörfler, G. Hug, D. Hill, G. Verbic, "Foundations and Challenges of Low-Inertia Systems"
The electric power system is currently undergoing a period of unprecedented changes. Environmental and sustainability concerns lead to replacement of a significant share of conventional fossil fuel-based power plants with renewable energy resources. This transition involves the major challenge of substituting synchronous machines and their well-known dynamics and controllers with power electronics-interfaced generation whose regulation and interaction with the rest of the system is yet to be fully understood. In this article, we review the challenges of such low-inertia power systems, and survey the solutions that have been put forward thus far. We strive to concisely summarize the laid-out scientific foundations as well as the practical experiences of industrial and academic demonstration projects. We touch upon the topics of power system stability, modeling, and control, and we particularly focus

on the role of frequency, inertia, as well as control of power converters and from the demand-side.
20th Power Systems Computation Conference (PSCC 2018), June 11-15, Dublin, Ireland (2018)

4.7 Distribution System Applications

Photovoltaic and wind generation resources are expected to make up most of the renewable generation targets. As these resources will be connected mostly at the lower voltage levels, a major focus in the transition to a sustainable power system lies on the distribution system. This is further emphasised by the fact that demand side management and distributed storage devices are viewed as flexible resources that can balance some of the variability and intermittency of the renewable generation. The coordination of all of these resources is enabled by the deployment of increased levels of sensing communication and control technologies.

Regulations in Switzerland dictate that 80% of existing smart meters need to be replaced by smart meters by 2027. These devices enable a nearly real-time communication with the consumers and measurement of its consumption but also pose the risk of endangering the privacy of the consumer. Potential means to provide privacy protection include the usage of a storage device to alter the actual consumption and operating it such that the consumer benefits from enhanced privacy but can also take advantage of optimising the consumption with regards to costs.

The trend is that more and more data will be available also for the distribution system. This, in theory, enables a more transparent operation of the lower voltage levels. But data can be faulty as well as missing, particularly in case of partial penetration with smart meters. Learning algorithms can therefor be used to fill the gaps and create reasonable profiles even for non-metered nodes as well as making predictions for the next hour or longer.

The overall goal is to operate the distribution system more safely and efficiently. The question however arises who will make the decisions on how to operate all of these distributed resources. Options range from a completely centralised to distributed or even decentralised decision making. While decentralised approaches are significantly more scalable, it is harder to achieve optimal usage of the available resources. A central question thereby is also how distribution and transmission system operators should coordinate with each other. It starts with how distributed resources could and should bid into the electricity markets considering their uncertain outputs but then also how resources are activated in real time.

Research in all of the above topics is carried out at the Power Systems Laboratory by the following researchers in collaboration with a number of partners and within specific larger research projects:

Researchers: *Jack Chin, Xuejiao Han, Stavros Karagiannopoulos, Evan-*

gelos Kardakos, Gustavo Valverde, Thierry Zufferey

Partnership: *Adaptricity, ABB, Ernst Basler + Partner, Imperial College, KTH, Inria, ETH Energy Science Center, ETH Research Center for Energy Networks, ETH Center of Economic Research, ETH Reliability and Risk Engineering Lab, TU Dortmund, TU Eindhoven, Enexis*

Externally Funded Research Projects:
COPES - Consumer Centric Privacy in Smart Energy Grids: The main research objective of COPES is to develop new technologies to protect consumer privacy, while not sacrificing the smartness, i.e., advanced control and monitoring functionalities. The core idea is to overlay the original consumption pattern with additional physical consumption or generation, thereby hiding the consumer privacy sensitive consumption. The means to achieve this include the usage of storage, small scale distributed generation and/or elastic energy consumptions. Hence, COPES proposes and develops a new approach to alter the physical energy flow, instead of purely relying on encryption of meter readings. Since storage resources can also be used to minimize the electricity bill or increase the integration of renewables, trade-offs between these objectives and privacy will be studied and combined into a holistic privacy guaranteeing house energy management system.
Funded by SNF (CHIST-ERA), in collaboration with Imperial College, KTH, and Inria.

SCCER FURIES (description only of PSL part): It is expected that distributed generation and storage technologies as well as demand response will become significantly more prevalent in the future electric power system. The consequence is that the TSOs and DSOs will need to jointly handle a large number of distributed controllable entities and concurrently have to deal with a high level of complexity of ongoing processes during both normal and emergency operation. Hence, the goal is to provide the concepts and computational frameworks to enable a reliable and efficient operation of modern electric power grids. This includes approaches to assign the responsibilities of managing the grid to the various players across the different levels in the grid (from DSOs to TSO and potentially new players) and how to coordinate these players locally as well as hierarchically.
Funded by the Bundesamt für Energie, in collaboration with Universita della Svizzera Italiana (for this part)

Planning and Operation of Distribution Grids in Future Electric Power Grids: The electric power system is transitioning from a structure with bulk

power plants and inflexible loads to increased penetration of distributed resources, i.e. distributed generation (mostly renewable and non-dispatchable), flexible loads participating in demand response and distributed storage devices. This changing infrastructure needs to be reflected in how the electric power system is planned and operated. Aside from passive measures such as transformer and distribution line upgrades, active measures including shifting of load and adapted control of distributed generation and storage should be valid means in the planning process of distribution grids. In this case, however, it is important that the planning and operation process go hand in hand because how the devices will be operated has impact on how the grid should be planned and vice versa. The scope of this project is to devise planning and operational procedures which take this interdependency into account and account for the high uncertainty in distributed generation and participation of consumer in load control.
Funded by ABB as part of a larger collaboration with ETH

Publications In this research area, the following publications have been published in 2018:

S. Karagiannopoulos, P. Aristidou, L. Roald, and G. Hug, "A Centralised Control Method for Tackling Unbalances in Active Distribution Grids"
Traditional distribution network operators are gradually being transformed to system operators, using modern technologies to ensure a secure and efficient operation in a rapidly changing and uncertain environment. One of their most challenging tasks is to tackle the unbalanced operation of low-voltage networks, traditionally caused by unequal loading and structural asymmetries, and exacerbated by the increased penetration of single-phase distributed energy resources. This paper proposes a centralized operation scheme based on a multi period optimal power flow algorithm used to compute optimal set-points of the controllable distributed energy resources located in the system. The algorithm reduces the operational cost while satisfying the appropriate security and power quality constraints. Furthermore, the computational tractability of the algorithm and the incremental cost of tackling imbalances in the network are addressed. Finally, the performance of the proposed method is tested on an unbalanced low-voltage distribution network.
20th Power Systems Computation Conference (PSCC 2018), June 11-15, Dublin, Ireland (2018)

F. Bellizio, S. Karagiannopoulos, P. Aristidou, and G. Hug, "Optimized local control schemes for active distribution grids using machine

learning techniques ”
Modern distribution system operators are facing a changing scenery due to the increasing penetration of distributed energy resources, introducing new challenges to system operation. In order to ensure secure system operation at a low cost, centralized and decentralized operational schemes are used to optimally dispatch these units. This paper proposes a decentralized, real-time, operation scheme for the optimal dispatch of distributed energy resources in the absence of extensive monitoring and communication infrastructure. This scheme uses an offline, centralized, optimal operation algorithm, with historical information, to generate a training dataset consisting of various operating conditions and corresponding distributed energy resources optimal decisions. Then, this dataset is used to design the individual local controllers for each unit with the use of machine learning techniques. The performance of the proposed method is tested on a low-voltage distribution network and is compared against centralized and existing decentralized methods.
IEEE PES General Meeting, 5-10 Aug. 2018, Portland, USA (2018)

J. Gallmann, S. Karagiannopoulos, M. Gonzalez Vaya and G.Hug, “On Frequency Control Provision with a Microgrid containing Battery Energy Storage Systems and Renewable Energy Sources”
The main benefit of operating a distribution grid as a microgrid (MG) is the additional security of supply due to its local electricity generation and islanding possibility. In this work, we investigate the technical ability and the economic viability of a MG with renewable generation to provide also frequency control (FC) to upper voltage levels as an additional source of revenue in grid-connected mode. To compensate for the variable generation of renewable energy sources and facilitate opportunities to bid in FC markets, we include a battery energy storage system (BESS). In order to determine the potential of the MG in the different FC markets, the problem is formulated as a multi-period optimal power flow with a rolling horizon of 24 hours. In order to evaluate the business case for such a system, we carry out an ex-post analysis in which we include the investment cost of a BESS and determine the life cycle benefits using the revenue streams calculated by the proposed optimization scheme.
Cired 2018, Aug. 2018, Ljubljana Slovenia (2018)

G. Valverde, T. Zufferey, S. Karagiannopoulos, and G. Hug, “Estimation of voltage sensitivities to power injections using smart meter data”
The rollout of smart metering infrastructure brings new opportunities to better monitor and model low voltage systems. This paper presents a novel methodology to estimate the sensitivities of voltages to power injections using smart meter data. Unlike previous works, this paper focuses on how

some highly correlated active and reactive power measurements affect the estimated parameters. Moreover, a clustering-based algorithm is proposed as a viable alternative when the number of unknown parameters needs to be reduced, without compromising the accuracy of the estimations. Power flow calculations of the IEEE European test system are performed to simulate the smart meter information. The tests demonstrate the robustness of the proposed algorithms with noisy and correlated measurements.
ENERGYCON 2018, 3-7 June 2018, Limassol, Cyprus (2018)

J. X. Chin, G. Giaconi, T. Tinoco De Rubira, D. Gündüz and G. Hug, "Considering Time Correlation in the Estimation of Privacy Loss for Consumers with Smart Meters"
Global electricity smart meter roll-out has brought about serious privacy risks for consumers. The masking of consumer consumption using rechargeable batteries has been studied as a means of protecting consumer privacy. One metric used to measure the effectiveness of such approaches is the empirical mutual information (MI), whose computation requires the estimation of both consumer load and grid-visible load distributions. These distributions have previously been modelled as independent and identically distributed (i.i.d.), or as stationary first-order Markov processes for simplicity. However, consumer load statistics are time-varying in nature, and have inherent intertemporal dependencies. Consequently, the empirical MI based on the stationarity assumption lacks accuracy, resulting in the risk of underestimating the information leakage. In this paper, we propose using features to characterise the change in consumer demand, modelling them as feature-dependent first-order Markov processes to better approximate the actual privacy-loss. Results indicate that this approach is more accurate than i.i.d. models, and in certain cases may be a better empirical estimate of MI compared to stationary first-order Markov models.
20th Power Systems Computation Conference (PSCC 2018), June 11-15, Dublin, Ireland (2018)

T. Zufferey, D. Toffanin, D. Toprak, A. Ulbig, G. Hug, "Generating Stochastic Residential Load Profiles from Smart Meter Data for an Optimal Power Matching at an Aggregate Level"
This paper presents an adaptive approach for modelling residential load profiles based on Markov chains that inherently accounts for seasonality. This approach is compared to a traditional approach where short-term seasonality is explicitly modelled in the transition matrix. A detailed evaluation of over 250 days of smart meter data from a few hundred households shows how the proposed approach outperforms the traditional approach in preserving the statistical properties of individual loads while minimizing the error

between the aggregated load and the actual aggregated load data. Substantial improvements are achieved by means of a logistic regression model that learns the Markov transition probabilities and better captures seasonality on a medium-to long-term basis. Furthermore, a method based on least squares regression is proposed for allocating synthetic profiles to households without smart meters. Combined with aggregate power matching, the adaptive approach for load profile generation allows for a precise distribution grid state estimation based on partial smart meter data.
20th Power Systems Computation Conference (PSCC 2018), June 11-15, Dublin, Ireland (2018)

J. Mohammadi, G. Hug, S. Kar, “A Fully Distributed Cooperative Charging Approach for Plug-In Electric Vehicles”
The flexibility of plug-in electric vehicles (PEVs) in shifting their charging schedules can be utilized to reduce charging costs. Given the ever-increasing adoption of PEVs and their geographical spread, coordinated charging schedules could be enabled by distributed algorithms. Here, we propose a fully distributed solution for PEVs cooperative charging (PEV-CC) problem. The PEV-CC minimizes the charging costs for a PEV fleet whilst considering limitations of PEVs and charging infrastructure. The PEV-CC is a convex multi-time step problem and a receding horizon is employed to integrate feedback into the decision-making process. Driving uncertainties are accounted for by considering multiple driving scenarios for individual PEVs. Our distributed iterative procedure achieves a distributed solution of the underlying convex optimization problem through local computations and limited communication. The algorithm is designed to reach an agreement on a price signal among PEVs over the course of iterations, while local PEV constraints are enforced at each iteration. Therefore, each iteration yields a feasible solution for the PEV-CC problem. The performance of our proposed algorithm is evaluated on a fleet of PEVs as a test case.
IEEE Transactions on Smart Grid, Vol. 9, No. 4, pp. 3507 - 3518 (2018)

N. Pilatte, P. Aristidou, G. Hug, “TDNetGen: An Open-Source, Parametrizable, Large-Scale, Transmission, and Distribution Test System”
In this paper, an open-source MATLAB toolbox is presented that is able to generate synthetic, combined transmission, and distribution network models. These can be used to analyse the interactions between transmission and multiple distribution systems, such as the provision of ancillary services by active distribution grids, the co-optimization of planning and operation, the development of emergency control and protection schemes spanning over different voltage levels, the analysis of combined market aspects, etc. The generated test-system models are highly customizable, providing the user with

the flexibility to easily choose the desired characteristics, such as the level of renewable energy penetration, the size of the final system, etc.
IEEE Systems Journal, Early Access (2018)

Ch. Wu, G. Hug, S. Kar, "Smart Inverter for Voltage Regulation: Physical and Market Implementation"
Lack of efficient coordination schemes between photovoltaic (PV) panels may result in voltage stability issues. In this paper, we exploit the power control potential enabled by the PV inverters for voltage regulation. There are considerable obstacles to design a viable coordination scheme. Physically, the power flow equations lead to a highly nonconvex constraint set. With respect to the market implementation, voltage regulation is predominately conducted by the system operator, and voltage regulation related products rarely exist. We cast the voltage regulation as a nonconvex optimization problem, and devise an analytical framework to show that based on a linearized model, one can design a gradient descent-based distributed scheme, which, when implemented in the nonconvex branch flow model, will converge to a local minimum exponentially fast. Additionally, we design a compensation scheme which incentivizes the PV panel owners to provide voltage regulation. The compensation naturally leads to a game between all the PV panel owners. By design, the equilibria coincide with the global minimizers to the social planner problem. Simulation results confirm the convergence rate of the control actions in practice.
IEEE Transactions on Power Systems, Vol. 33, No. 6, pp. 6181 - 6192 (2018)

5. Awards and Honours

Prof. Dr. Christian Franck
Golden Owl Award 2018 for Exceptional Teaching, VSETH Zurich, Switzerland
July 2018

Michael Händel
Best Paper Award
International Conference on Smart Energy Systems and Technologies
September 2018

Prof. em. Klaus Froehlich
Cigré Medal 2018, Cigré, Paris, France
October 2018

Dr. sc. ETH Malte Tschentscher
ETG Literaturpreis for Publication, ETG/VDE Group, Germany
October 2018

Aleksandar Jovicic
Best Paper Award - Second Prize in the Power Systems Communications and Cyber-security track at NAPS 2018, USA
October 2018

Dr. sc. ETH Andreas Ritter
ETH Medal for Outstanding Doctoral Thesis, ETHZ, Zurich, Switzerland
December 2018

6. Infrastructure

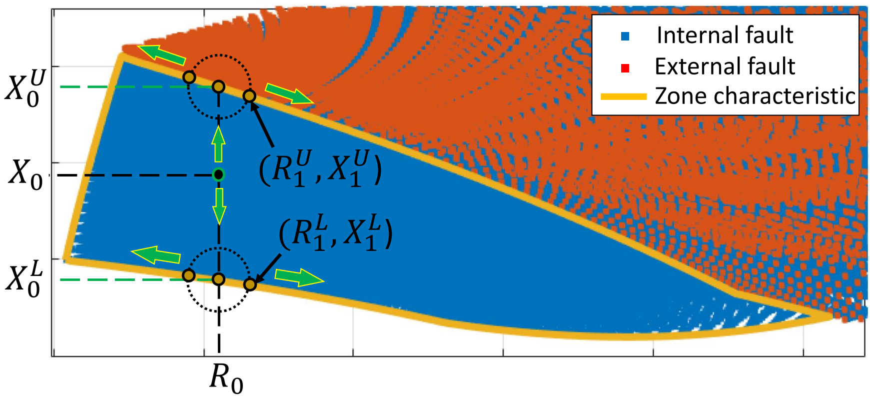
At the institute we have the following main test facilities available for research, teaching and measurements with the following dimensions and characteristics.

- Main high voltage laboratory (see Fig. 6.1): 22 m length, 21 m width, 9.3 m height
- Secondary high voltage laboratory: 21 m length, 11 m width, 10 m height
- several Faraday cages: 4.5 m length, 4 m width, 2.4 m height
- Impulse testing
  - Lightning Impulse: 1500 kV, 80 kJ
  - Switching Impulse: 1500 kV, 80 kJ
- AC Testing
  - (dry, short time) 800 kV/400 kVA; 50 Hz
  - (dry, permanent): 400 kV/200 kVA, 15 Hz – 200 Hz
  - (SF_6-encapuslated, short time): 750 kV/60 kVA, 50 Hz
- DC Testing (dry): 800 kV, 5 mA (permanent)
- Partial discharge up to 800 kV, 50 Hz
- C-tanδ testing up to: 600 kV, 50 Hz
- Mobile test systems (construction kit)
  - Lightning Impulse: 280 kV, 0.5 kJ
  - AC Testing: 200 kV, 5 kVA (permanent)
  - DC Testing: 280 kV, 10 mA (permanent)

Accredited calibration laboratory SCS 0081 Our calibration laboratory for electrical quantities in the field of high voltage, capacitance and apparent charge completed numerous orders in the course of the year. The primary tasks were the calibration of complete impulse, AC and DC high voltage measuring systems under operating conditions in the customers' laboratories. In addition PD calibrators, impulse peak voltmeters and C-$\tan\delta$ measuring systems have been calibrated.

Accredited testing laboratory STS 0181 Our laboratory for the testing of electrical properties of components for electric energy supply performed a wide variety of tests according to international standards as well as following laboratory-developed test procedures.

Figure 6.1: Picture of main high voltage laboratory.



Internal fault
External fault
Zone characteristic
X_0^U
X_0
X_0^L
(R_1^U, X_1^U)
(R_1^L, X_1^L)
R_0