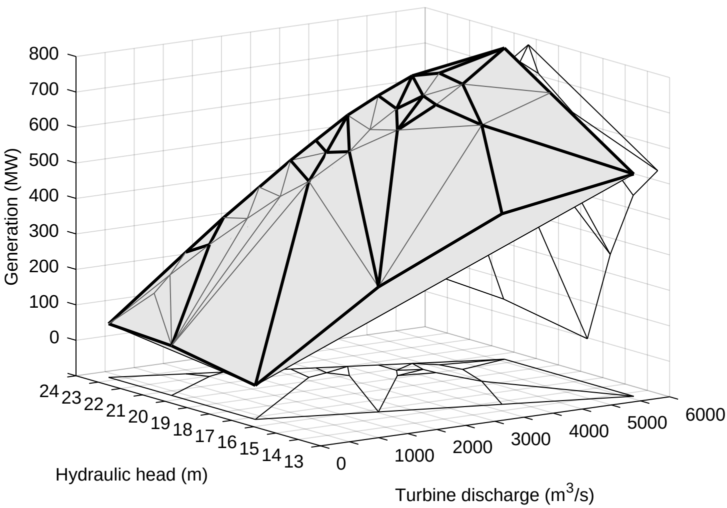
Power Systems and High Voltage Laboratories

Annual Report 2017



HVL High Voltage Laboratory

PSL Power Systems Laboratory

ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Annual Report 2017

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

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Front Cover: Hydropower generation function for Wells Dam, Washington, USA

Back Cover: Group picture of D.A.CH. symposium in front of a tree cut and split by lightning.

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 2017. The year was full of intense work on various projects and teaching activities, but also gratifying with respect to obtained research results and the excellent students that graduated. The research results are presented on numerous conferences and in a substantial number of peer-reviewed international journals. Around 40 students have carried out their group, semester or master thesis in our group. We are happy to welcome 5 new colleagues in our team and we congratulate the following five doctoral students to their successfully defended theses (in alphabetical order): Philipp Fortenbacher, Andrew Hamann, Olivier Megel, Martin Pfeiffer, and Mohamed Rabie.
In 2017, the HVL team travelled to Darmstadt, Germany, for the third high-voltage D.A.CH. symposium. This series is funded by the Swiss "SUK doctoral programme" and aims to improve the quality and attractiveness of doctoral training and the career perspectives of doctoral students. The content is organised by the doctoral students and scientific exchange happens in form of oral and poster presentations. We're looking forward to welcoming the groups of Darmstadt ("D") and Graz ("A") in Zurich ("CH") in summer 2018.
We are thankful to all researchers, staff and external lecturers for their enthusiastic and highly competent work. The pleasure of working in this team and the high quality of our work is your achievement.
Last but not least, we thank all our collaborators and partners from the power industry, universities and other research institutions for the continued support and cooperation in numerous research projects. The input and support from these partners is crucial for the success of our labs. We look forward to continued cooperation in the future.
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

Contents

1. Organisation

1.1 Power Systems Laboratory

Head:	Prof. Dr. Gabriela Hug
Secretary:	Judith Eberle
Scientific Staff:	MSc Jun Xing (Jack) Chin MSc Nadezhda Davydova Dr. Stefanos Delikaraoglou (September 2017 -) M.Sc. El.Eng. Philipp Fortenbacher (- March 2017) MSc Andrew Hamann MSc Xuejiao Han MSc ETH Adrian Hauswirth MSc Aleksandar Jovicic (Januar 2017 -) MSc ETH Stavros Karagiannopoulos Dr. Evangelos Kardakos MSc ETH Uros Markovic MSc EPF Olivier Mégel (- September 2017) MSc Conor O'Malley MSc Dmitry Shchetinin Dr. Tomas Tinoco De Rubira (- July 2017) Dr. Gustavo Valverde (July 2017 -) MSc ETH Thierry Zufferey
Technical Staff:	Claudia Stucki, System Engineer
External Lecturers:	Dr. Rainer Bacher, Bacher Energie, Baden Dr. sc. ETH Gaudenz Koeppel, Axpo, Baden Dr. sc. techn. Dieter Reichelt, Axpo, Baden
Ext. PhD Student:	MSc Michael Haendel

Scientific Associates:

Prof. em. Dr. Göran Andersson
Prof. em. Dr. Hans Glavitsch
Dr. Francesco Ferrucci (Spin-Off: Adaptricity)
Dr. sc. ETH Stephan Koch (Spin-Off: Adaptricity)
Dr. sc. ETH Andreas Ulbig (Spin-Off: Adaptricity)

Academic Guests:

PhD Student Florian Thams (DTU Electrical Engineering, Denmark, January - May 2017)

PhD Student Ramana Avula, (KTH Royal Institute of Technology, Stockholm, Sweden, November 2017 -)

1.2 High Voltage Laboratory

Head:	Prof. Dr. rer. nat. Christian M. Franck
Secretary:	Karin Sonderegger Zaky
Scientific Staff:	MSc ETH Pascal Bleuler (Oct 2017 -) MSc ETH Lorenz Bort MSc ETH Pascal B. Buehlmann MSc Alise Chachereau MSc EPFL Raphael Faerber MSc ETH Pascal Häfliger MSc TU Darmstadt Soeren C. Hedtke MSc Physics Andreas Hösl MSc TU Darmstadt Henrik Menne (April 2017 -) MSc TUM Juriy Pachin MSc ETH Martin D. Pfeiffer (- Dez 2017) Mag.rer.nat. Mohamed Rabie (- Oct 2017) MSc ETH Andreas Ritter MSc RWTH Tim Schultz MSc RWTH Malte Tschentscher
Technical Staff:	Fabian Mächler, Automation Engineer Claudia Stucki, System Engineer El.-Ing. FH Hans-Jürg Weber, Senior Technician
External Lecturer:	Dr. tech. Werner Hofbauer, ABB Switzerland Ltd Dr. sc. ETH Ueli Straumann, ABB Switzerland Ltd Prof. Dr. Jasmin Smajic, HSR
Scientific Associates:	Prof. Dr.-techn. em. Klaus Fröhlich
Academic Guests:	PhD Student Pengfei Xu (Tsinghua University, PRC, - Aug 2017)

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, HVDC and FACTS.

High Voltage 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 high-voltage equipment. Methods of computer-modeling in use today are presented and applied within a workshop in 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.

Power System Analysis 6 ECTS points
Modellierung und Analyse elektrischer Netze
Lecturer(s): G. Hug

Abstract: 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.

Energy System Analysis 4 ECTS points

Modellierung und Analyse elektrischer Energiesysteme
Lecturer(s): G. Hug and other lecturers

Abstract: Introduction to the methods and tools for analysis of energy systems.
Objective: The aim of the course is to give an overview over the methods and tools for analysing energy systems from different view points. Environmental aspects are included as well as economic considerations. Different sectors of society are treated, such as electric power, buildings, and transportation.
Contents: The course gives an introduction to methods and tools for analysis of energy consumption, energy production and energy flows. Both larger systems, e.g. countries, and smaller systems, e.g. industries, homes, vehicles, are studied. The tools and methods are applied to various problems. Different conventions of energy statistics used are discussed and energy systems models for developing scenarios of future energy consumption and production are introduced. Bottom-up and Top-Down approaches are addressed including their features and applications.

Power System Dynamics and Control 6 ECTS points
Systemdynamik und Leittechnik in der elek. Energieversorgung
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 disadvantages; SmartGrids: The new energy system and compatibility issues with traditional market models and regulation.

Power Market I - Portfolio and Risk Management 6 ECTS points
Strommarkt 1 - Portfolio und Risk Management
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
Strommarkt 2 - Modellierung und strateg. Positionierung
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
23 March 2017

Power System Dynamics
EKZ Battery System
Dietikon, Switzerland
24 April 2017

Power Market II
Axpo Tegra Biosmass Power Plant and Linth Limmern Pumped Storage Plant
Domar/Ems and Tierfehd, Switzerland
25-26 April 2017

High Voltage Engineering
GE Grid Switzerland GmbH
Oberentfelden, Switzerland
28 April 2017

Technology of Electric Power System Components
Transformers
Pfiffner Instruments Ltd
Hirschthal, Switzerland
4 May 2017

Power System Dynamics
Swissgrid Control Center
Laufenburg, Switzerland
23 May 2017

High Voltage Engineering
ABB Micafil
Zurich, Altstetten, Switzerland
26 May 2017

Technology of Electric Power System Components
Power Test Laboratory
ABB Switzerland Ltd
Baden, Switzerland
1 June 2017

Introduction to Electric Power Transmission: System & Technology
EWZ Substation Sempersteig
Zurich, Switzerland
10 November 2017

Power Market I
Axpo Trading and Dispatch Centre
Baden, Switzerland
14 November 2017

Power System Analysis
Axpo Power Plant Eglisau-Glattfelden
Rheinsfelden, Switzerland
13 December 2017

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 250 to 300 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. The project reports can be found on our website.

2.4.1 System Oriented Semester Projects

Stefanie Aebi
Optimal Power Flow Calculation for Unbalanced Distribution Grids
Supervisor: Stavros Karagiannopoulos

Martin Baltzinger
Performance Analysis and Validation of Optimal Power Flow Solvers of New Open-Source Software Stack
Supervisor: Tomas Tinoco De Rubira

Filippo Ferrando
Optimal Dispatch and Offering Strategies of a Wind Power Plant in a Multi-Market Environment
Supervisors: Evangelos Kardakos, Xuejiao Han

Anya Heider
Qualitative and Quantitative Assessment of Power System Flexibility
Supervisors: Evangelos Kardakos, Xuejiao Han, Michael Haendel

David Kayanan
Comparing the performance of VSC power control techniques
Supervisor: Uros Markovic

Iraklis Katsolas
Impact of Individual System Components on Overall Reliability
Supervisor: Stavros Karagiannopoulos

Alicer Lépouzé
Probabilistic Approach in Time-Series Simulation of Power Flows
Supervisors: Andreas Ulbig, Thierry Zufferey

David Rodriguez
Integration of a Dynamic Model for Stratified Electric Water Heaters into DPG.sim
Supervisors: Stephan Koch, Thierry Zufferey

Moritz Staub / Miriam Vonesch
The Grid Game - A Power Systems Education Tool
Supervisor: Adrian Hauswirth

Aldo Tobler
Nonlinear Optimization in Electric Power Systems with Uncertainty: Understanding the Impact of Uncertainty on the Feasible Space
Supervisors: Line Roald, Daniel Molzahn (Argone)

2.4.2 Technology Oriented Semester Projects

Joé Goelff
Limit Performance Evaluation of Mechanical Gas Circuit Breakers in HVDC Applications
Supervisor: Tim Schultz

Federica Bellizio
Construction of a humidity control system for HVDC insulation tests
Supervisor: Malte Tschentscher

Cindy Karina
Breakdown experiments in N2-O2- mixtures
Supervisor: Pascal Häfliger

Felix Hoffmann
Implementation of a Signal Acquisition System for High-Voltage Dielectric Spectroscopy
Supervisor: Raphael Färber

Kevin Lengauer
Gas modeling for strongly detaching gases in C4F7N and O2
Supervisor: Andreas Hösl

Jäel Keller
Measurements of the electron swarm parameters of C4F7N
Supervisor: Alise Chachereau

Brooke Spreen
Investigation of discharge inception on W7-X superconductor joint insulation
Supervisor: Christian M. Franck

John-Levi Nyberg
Lightning Impulse Breakdown Tests
Supervisor: Pascal Häfliger

Corentin Rouault
Clamp Geometry Optimization
Supervisor: Pascal Bühlmann

Daniel Wackernagel
Assembly and Testing of an Audio-Modulated Solid-State Tesla Transformer
Supervisor: Raphael Färber

Yvo Caduff
Assessing hybrid AC-DC lines in the Swiss Energy System
Supervisor: Sören C. Hedtke

Xiang Li
FEA of the wedge-clamp mechanism of AAAC
Supervisor: Pascal Bühlmann

Miriam Vonesch
Dark Currents in Gas-insulated HVDC Equipment
Supervisor: Malte Tschentscher

David Graber
Humidity as an Influencing Factor in HVDC Substations
Supervisor: Malte Tschentscher

Serjosha Robmann
Thermal-mechanical Simulations of OHL AAAC
Supervisor: Malte Tschentscher

Johannes Goedejohann
Development of Highspeed Imaging Evaluation Methods for Arcs
Supervisor: Lorenz Bort

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. The project reports can be found on our website.

2.5.1 System Oriented Master Projects

Arsam Aryandoust
Modeling and Optimization-Based Control of a Dynamic Demand Response System for Active Distribution Networks
Supervisors: Uros Markovic, Stephan Koch

Federica Bellizio
Optimized local control schemes for active distribution grids using machine learning techniques
Supervisor: Stavros Karagiannopoulos

José Sebastian Espejo-Uribe
Analysis of Adaptive Certainty-Equivalent Techniques for the Stochastic Unit Commitment Problem
Supervisor: Tomas Tinoco De Rubira

Jannick Gallmann
Design and operation of microgrids: Ancillary service provision in islanded and grid-connected mode
Supervisors: Stavros Karagiannopoulos, Marina González Vayá (EKZ

Lakshmi Srinivasan
Provision of secondary control by battery energy storage system in combination with a pool of flexible units
Supervisors: Marina Gonzalés Vayà (EKZ), Uros Markovic

Patrick Lieberherr
Parallel Power Flow Algorithm for Large Scale Distribution Network Topologies
Supervisor: Stephan Koch

Severin Mayrhofer
Optimal design of distribution grids - A Greenfield approach
Supervisor: Stavros Karagiannopoulos

Ludovico Nati
Optimal Bidding Strategy of a Decentralized Storage Device in both Energy and Reserve Markets
Supervisors: Xuejiao Han, Evangelos Kardakos

Raphaela Tsaousi
The Influence of Participation in Ancillary Service Markets on Optimal Energy Hub Operation
Supervisors: L. Andrew Bollinger, Conor O'Malley

Andrés Vargas Serrano
Economic Benefit Analysis of Retrofitting a Fixed-Speed Pumped Storage Hydropower Plant with an Adjustable-Speed Machine
Supervisors: Andrew Hamann, Sören Hedtke

Andreas Venzke
Convex Relaxations for Optimization of AC and HVDC Grids under Uncertainty
Supervisors: Uros Markovic, Lejla Halibasic (DTU), Pierre Pinson (DTU), Spyros Chatzivasileidis (DTU)

Xue Wang
Feasibility and Challenges in Microgrids for Marine Vessels
Supervisors: Stavros Karagiannopoulos, Petros Aristidou, Ritwik Majumder (ABB Sweden)

Valentin Wyss
Controller design for self-consumption maximization at the household level
Supervisors: Marina González Vayá (EKZ), Stavros Karagiannopoulos, Jun Xing Chin

2.5.2 Technology Oriented Master Projects

Moritz Staub
Discharges in detectors with environmental friendly gas mixtures
Supervisor: Andreas Hösl

Benjamin Hammerich
Investigating the impact of modifications in the nominal current path on the interruption capability of hybrid HVDC circuit breakers
Supervisor: Tim Schultz

Patrick Herzog
Analysis and optimization of current injection circuits for hybrid HVDC circuit breakers
Supervisor: Tim Schultz

Emiliano Trodini (external student at TU Delft)
Modelling the Electrical Signal in Spark Discharge Generators for Electrode Ablation Control
Supervisors: Richardson, Schmitt-Ott (both TU Delft)

3. Completed PhD Theses

On the Integration of Distributed Battery Storage in Low Voltage Grids

Candidate:	Philipp Fortenbacher
Thesis:	ETH No. 24039
Date of oral exam:	27 January 2017
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Dr. Audun Botterud, Leader of Energy Decision Analytics Group, Argonne National Lab and Principal Research Scientist, MIT, Prof. Dr. Florian Dörfler, D-ITET, ETH Zürich

Abstract Energy storage technologies can play a key role in future to decarbonize the power sector. In particular, distributed battery storage in low voltage (LV) grids is considered to be a promising alternative to balance short-term fluctuations and to alleviate grid congestions caused by a high share of distributed photovoltaic (PV) generators.

This thesis proposes novel methods to improve the integration of dis tributed battery storage (DBS) in LV grids in conjunction with a high PV share. The first part focuses on the improvement of operation schemes for DBS applications. Model predictive control (MPC) strategies are introduced to increase the operational revenue. Appropriate battery models capturing battery degradation and dynamics are developed that are incorporated into the MPC framework. A linearized Optimal Power Flow (OPF) method for LV grids is proposed to improve the grid utilization. This allows for tractable MPC formulations by including them in the form of multi-period OPF problems.

For various DBS applications, a general two stage control framework is developed to deal with the aspects of operational planning and realtime unit dispatch. As a result, it is shown that DBS applications combining OPF methods increase significantly the operational revenue as compared to conventional operating strategies. As a further finding, by including battery degradation models in the control framework, the revenue can be further improved. Furthermore, detailed battery models capturing a more accurate loss approximation are able to additionally enhance the profitability.

The second part of the thesis deals with the planning of DBS. Two methods are developed to optimally place and size DBS in terms of the application objective, grid topology and PV generator configuration.

The first method assumes an infinite prediction horizon for the operational strategy. However, in reality, the horizon of PV and load forecast information is limited to some days, which means that this method is not suitable to assess the impact on seasonality. Therefore, to consider longer simulation horizons, the second method links the operational strategy as individual subproblems with the planning problem by using a Benders decomposition approach.

From the case studies, it is shown that the prediction horizon greatly affects the profitability. As a major finding, best profitabilities are achieved for prediction horizons longer than one day. Horizons greater than one day do not improve the viability, but they increase the self-sufficiency. Moreover, for a market-based DBS application, it is shown that distributed storage configurations are more preferable than centralized configurations, since the impact on the mitigation of PV curtailment outweighs the benefit of reduced network losses from energy arbitrage. However, results show that the optimal DBS configuration is highly dependent on the grid topology, application and generator configuration, such that quantitative conclusions on the optimal battery distribution can only be drawn for particular settings. In general, it can be concluded that optimal placement is achieved by finding the best compromise between saving network losses and PV curtailment.

Storage in Power Systems: Frequency Control, Scheduling of Multiple Applications, and Computational Complexity

Candidate:	Olivier Mégel
Thesis:	ETH No. 24248
Date of oral exam:	7 April 2017
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Dr. Maryam Kamgarpour, IfA, ITET, ETH Zurich, Prof. Dr. Pierre Pinson, Centre of Electric Power and Energy, DTU, Copenhagen, Prof. Dr. Johanna Mathieu, Dep. El. Eng. And Comp. Science, University of Michigan, Ann Arbor (per Videokonferenz)

Abstract The ongoing worldwide deployment of wind and solar power plants is leading to increasing interest in storage technologies. Indeed, storage can effectively time-shift production/consumption profiles. Furthermore, most storage technologies also feature higher response speed and ramping rate than those of conventional generators. Finally, storage units can be installed at specific grid locations to alleviate local issues. However, storage investment cost is still often prohibitive, and storage requires re-thinking numerous power system concepts, due to i) a strong inter-temporal coupling, ii) operating costs driven by physical degradation, and iii) regulation issues, as storage units cannot be classified as either transmission, generation, nor consumption assets.

The main goal of this thesis is to propose different methods to improve storage profitability and reduce computational burden. The focus is on operational problems with characteristic times ranging from minutes to days. It also highlights how the present regulations can hinder storage penetration.

More specifically, this thesis first proposes different methods enabling energy-constrained storage units to participate in Frequency Control (FC). These methods take advantage of the higher ramping rate of storage units, and rely on slower conventional generators to take care of the FC signal bias. The methods presented in the fourth chapter are heuristic-based and consider a single storage unit. They are shown to perform better than other

existing heuristic-based methods. The method proposed in the fifth chapter relies on distributed optimization and considers a set of generators and storage units. This method additionally features low computational burden and robustness to loss of communication links.

Building on these FC methods, the sixth and seventh chapters propose multitasking algorithms that improve the storage profitability by combining revenue streams from different applications, including FC. The sixth chapter develops an algorithm for a set of storage units, and shows that multitasking and aggregation can greatly increase the stor- age profitability. The seventh chapter focuses more on the uncertainty from Photovoltaics (PV) generation and FC signals. This chapter, as well as the following one, also discusses the challenges related to preventing simultaneous charge and discharge in an optimization model and shows how Benders Cuts can help reduce computational burden.

The eighth chapter focuses on a different problem than the rest of this thesis: it proposes a method to reduce the computational complexity of convex multi-period stochastic Optimal Power Flow (OPF) problems. It is motivated by the inter-temporal coupling resulting from storage dynamics. The method includes an iterative algorithm approximating a multi-dimensional convex function that can be used outside of the field of power systems. A 118-bus case study shows that the method achieves between 25 and 81% of the cost improvement of the stochastic OPF (compared to the deterministic OPF), but requires only 12 to 41% of the increase in computation time required by the stochastic OPF. Finally, the ninth chapter provides discussions on regulatory issues associated to storage, for multitasking, FC markets, and tariff structure. It indicates how some of the methods presented in this thesis could be deployed. It also provides additional discussion on the storage complementarity constraint.

A systematic approach to identify and quantify gases for electrical insulation

Candidate:	Mohamed Rabie
Thesis:	ETH No. 24375
Date of oral exam:	22 May 2017
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. Abderrahmane Beroual, École Centrale de Lyon, France

Abstract Equipment for the transmission and distribution of electric power often contains strongly electron attaching compounds to improve the electrical insulation. The most established and widely-used insulation gas sulfur hexafluoride (SF_6) is an extremely long-lived and potent greenhouse gas. The environmental concerns related to the globally increasing SF_6 emissions initiated a search for replacements.

In the past years, chemical and equipment manufacturers introduced novel and promising replacement gases of lower global warming potential, thereby stimulating research efforts towards an SF_6-free transmission and distribution grid. This thesis presents a series of methods that can support the identification of novel synthetic compounds for gaseous insulation and the quantification of their dielectric properties in carrier gases (also: buffer or background gases). Hereby, the well-known concept of a binary gas mixture, which consists of an electronegative compound in a carrier gas, is adopted. The presented methods are based on publicly available and well documented programs.

Within a statistical analysis of a comprehensive data set clear correlations between certain descriptors and the electric strength or the boiling point of gases is found. These descriptors, which are calculated ab-initio by means of density functional theory, are used to computationally screen a large chemical database (the PubChem database of the National Institute of Health) for compounds suitable for electrical insulation. One electronegative sample compound resulting from this screening is octafluoro-2-butene (2-C_4F_8).

Together with the well-known greenhouse gases SF_6 and C_3F_8, electron attachment to 2-C_4F_8 molecules is probed as a function of energy in a swarm experiment. For this purpose, minor proportions (.1 %) of the sample compounds are added to the well-known carrier gases N_2 and CO_2 and the

displacement currents of electron swarms are measured within the Pulsed Townsend method. The electron energy distribution in these carrier gases is calculated with a Monte Carlo collision code that has been developed within this thesis. The measured swarm parameters are unfolded from the electron energy distribution to obtain the total electron attachment cross section of the sample compounds. For this purpose, Tikhonov regularization, which is a well-defined algorithm for discrete linear inversion problems, is proposed and used to directly find robust solutions.

Finally, the electric strength in atmospheric gases (N_2, CO_2, O_2 and technical air) is investigated from low to high proportions of the sample gases by means of Monte Carlos simulations and on the basis of the previously obtained attachment cross sections. The range of application in terms of maximum operating voltage and minimum operating temperature of equipment filled with mixtures of 2-C_4F_8 and atmospheric gases is estimated.

Ion-Flow Environment of HVDC and Hybrid AC/DC Overhead Lines

Candidate:	Martin Pfeiffer
Thesis:	ETH No. 24507
Date of oral exam:	03 July 2017
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. Bo Zhang, Tsinghua University, Beijing, China

Abstract For various applications, HVDC overhead lines (OHL) offer technical and economic advantages over conventional HVAC systems. Boosted by increased demand for transmission capacity, the number of HVDC systems has thus steadily risen over the past decades. Corona effects - processes related to partial electric discharges caused by high electric field stresses at conductor surfaces - are an important factor in the overall environmental, technical and economic performance of HVDC OHLs. They include corona losses, audible noise and the drift of ions towards ground or to other conductors. This latter aspect plays an important role in so-called hybrid AC/DC towers, in which HVAC and HVDC systems run in parallel on the same tower.

This thesis investigates the fundamental effects that lead to the generation of corona discharges on DC conductors. The influence of conductor surface properties on the corona behavior during wet weather is given particular attention. Furthermore, the corona current coupling between different bundles in bipolar DC and hybrid AC/DC systems is studied in detail.

A series of indoor laboratory experiments (monopolar DC, bipolar DC and hybrid AC/DC) form the basis of the presented investigations. Using simulated rainfall and novel imaging methods, the relationship between wetting behavior and corona properties is established. In bipolar DC and hybrid AC/DC measurements, the selective placement of corona sources is used to differentiate between coupling effects caused by Laplace (space-charge-free) fields and mechanisms driven by Poisson (space-charge-enhanced) fields.

A key finding of this thesis is that the conductor surface type strongly influences wet weather HVDC corona losses and the drying rate after a rain shower. The latter is important since audible noise is increased during the drying phase. The presented results and methods can be used in the selection or further improvement of OHL conductors for HVDC applications.

It was also determined that the local concentration of water drops on the lower side of the conductor influences the corona current coupling in bipolar HVDC systems. Neglecting this directional bias in ion flow simulations was shown to lead to significant prediction errors, in particular for narrow pole separations.

Finally, for hybrid AC/DC systems it was shown that DC corona currents in AC and DC conductors are strongly affected by corona emissions on AC conductors. The fundamental reason for this was determined to be the existence of a net DC ion drift from AC conductors to DC conductors. Thus, there exists a bipolar space charge environment between a coronating AC and DC conductor. Neglecting AC corona in ion flow simulations was shown to lead to large under-predictions of the DC corona current in AC conductors. This thesis presents a simple empirical method to account for AC corona in hybrid AC/DC ion flow simulations.

Optimization of the Mid-Columbia Hydropower System

Candidate:	Andrew Hamann
Thesis:	ETH No. 24784
Date of oral exam:	20 November 2017
Examiner:	Prof. Dr. Gabriela Hug
Co-examiner(s):	Dr. Julia Matevosyan, Electric Reliability Council of Texas, USA, Prof. Dr. Hannes Weigt, Wirtschaftswissenschaftliche Fakultät, Universität Basel

Abstract This thesis is about the optimization of the Mid-Columbia hydropower system, which is comprised of seven cascaded hydropower projects on the Columbia River. It is the largest system of its kind in the United States, and it possesses unique qualities that make it useful to power system operators and important for the integration of variable and intermittent wind and solar generation. This research formulates real-time and day-ahead optimization programs to plan system operations and coordinate hydro and wind resources. These programs are used to evaluate the potential benefits of real-time optimization (with and without wind firming) and hydro-wind coordination with day-ahead replanning, and to estimate the battery-like properties of the Mid-Columbia system when it is used to balance wind variability. The system is simulated and tested using a multi-year wind and hydropower dataset that has been compiled from publicly available resources and estimated using bespoke software tools. Our results demonstrate that real-time optimization will increase hydraulic potential by 0.74 percent and stored energy by 0.68 percent. The power capacity of the Mid-Columbia hydropower battery is ±3000 and ±750 megawatts with and without replanning, respectively. Round-trip conversion efficiency exceeds 80 percent, and energy storage capacity is several tens of gigawatt-hours. These estimates may be too conservative or too optimistic depending on modeling assumptions, and they are subject to significant uncertainty. The primary factor inhibiting the performance of the hydropower battery was the maximum generation capacity of the hydropower system.

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 prodminently 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 is 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.

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

Researchers: *Pascal Häfliger, Mohamed Rabie, Alise Chachereau, Andreas Hösl, Juriy Pachin*

Publications In this research area, the following publications have been published in 2017:

M. Rabie, C. M. Franck et all, "Recent Trends in Development of High Voltage Circuit Breakers with SF_6 Alternative Gases"
The available knowledge of state-of-the-art of SF_6 alternative gases in switching applications was collected and evaluated in an initiative of the Current Zero Club [1] together with CIGRE. The present contribution summarizes the main results of this activity and will also include the latest trends. The main properties and switching performance of new gases are compared to SF_6. The most promising new gases are at the moment perfluoroketones and perfluoronitriles. Due to the high boiling point of these gases, in HV applications mixtures with CO_2 are used. For MV insulation perfluoroketones are mixed with air, but also other combinations might be possible. The dielectric and switching performance of the mixtures, with mixing ratios that allow sufficiently low operating temperatures, is reported to be only slightly below SF_6. Minor design changes or de-rating of switchgear are therefore necessary. Differences between the gas mixtures are mainly in the boiling point and the GWP.
XXII Symposium on Physics of Switching Arcs (FSO) 2017, September 4 - 8, Brno, Czech Republic (2017)

A. Chachereau, C. M. Franck, "Measurement of the electron attachment properties of SF_5CF_3 and comparison to SF_6"
The electron attachment properties of SF_5CF_3 are experimentally investigated using a pulsed Townsend setup. Different SF_5CF_3/N_2 and SF_5CF_3/CO_2 mixtures, with SF_5CF_3mole fractions ranging from 2×10^{-4} to 1, are characterized. The effective ionization rate coefficient, electron drift velocity and reduced longitudinal electron diffusion coefficient in these mixture are obtained. For low mole fractions of SF_5CF_3, the effective ionization rate coefficient is compared to calculations from available electron scattering cross sections, and is also used for estimating the electron attachment cross section of SF_5CF_3. For pure SF_5CF_3, the present data is compared to early data

from a steady-state Townsend experiment. The presentation of the measurement results is followed by a discussion on the properties of SF_5CF_3 and SF^6 and their signiffcance for gaseous electrical insulation.
Journal of Physics **50(44)**, 445204) (2017)

A. Chachereau, C. M. Franck, "Characterization of HFO1234ze mixtures with N_2 and CO_2 for use as gaseous electrical insulation media"
The hydrofluoroolefine HFO1234ze was recently proposed as an environment-friendly gas for use in medium or high voltage electrical insulation. Due to its relatively high boiling (254K), it should be used as part of a gas mixture. In this work, the electric properties of HFO1234ze mixtures with N_2 and CO_2 are experimentally characterized using a pulsed Townsend setup. For this purpose, the electric displacement current of electron avalanches in these gas mixtures is recorded and analyzed. The analysis yields the effective ionization rate constant (and in particular the critical electric field), the electron drift velocity and the electron diffusion coefficient. These results are applied to assess the potential of such mixtures for medium and high voltage insulation applications.
20th International Symposium on High Voltage Engineering (ISH), August 28 - September 2, Buenos Aires, Argentina (2017)

A. Hösl, P. Häfliger, C. M. Franck, "Measurement of ionization, attachment, detachment and charge transfer rate coefficients in dry air around the critical electric field"
We obtain pressure-dependent rate coefficients in dry synthetic air (79% N_2, 21% O_2) by fitting Pulsed Townsend measurements over a pressure range from 10 to 100 kPa, around the critical density-reduced electric field from 86 to 104 Td. The physical processes are reviewed and set in relation to a suitable kinetic model. A procedure for fitting kinetic reaction rates, based on finite-volume simulations of charge carrier drift, is described. Rate coefficients are obtained for electron attachment, ionization and detachment, as well as for ion conversion. We find a quadratic pressure dependency in the conversion rate, consistent with three-body collisions, and observe a pressure dependency in the onset of electron avalanche growth in dry air.
Journal of Physics D: Applied Physics **50(48)**, 485207 (2017)

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 capactiy. 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 3kA and 3kV. We are in the phase of modernizing the existing source, investigate a possible upgrade and prepare the purchase of a completely new source with considerably increased performance specifications. For the intermediate step, a master thesis has been carried out in 2017 and two new temporary employees will be hired in 2018.

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 are determined and investigated. Using the international standards and the research performed on traditional AC disconnectors as a starting point, calculations and simulations will be 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*

Publications In this research area, the following publications have been published in 2017:

A. Ritter, U. Straumann, C. M. Franck, "Novel Method for Predicting Limit Performance of Bus-Transfer Switching by Disconnectors"
In order to accurately predict the performance of disconnectors conducting bus-transfer switching in gas insulated substations (GIS), the influencing factors of the switching process itself as well as the reignition characteristics need to be analyzed. For this, an LC-oscillating AC current source in combination with a non-standardized full bus-transfer loop was built. Based on experiment data from a total of 347 reignitions and 570 extinctions, the reignition characteristic of the disconnector at current zero was investigated. Thereby, the derivation of a reignition criterion depending exclusively on the prediction of the instantaneous recovery voltage and the prospective arc voltage was possible. Using this criterion, time-dependent simulations of the bus-transfer process can be made to predict the performance of disconnectors for a wide variety of scenarios such as worst-case bus-transfer current for varying circuit parameters and ratings. Thus minimizing the need for extensive testing during substation planning or disconnector development.
IEEE Transactions on Power Delivery **32(5)**, pp. 2210-2217 (2017)

T. Schultz, C. M. Franck, "Post-Arc Current Measurement in Mechanical Circuit Breakers for HVDC Applications"
Post-arc currents contain valuable information on the breakers performance. In this paper, the dimensioning procedure for a measurement system for such

currents, based on a diode clamped shunt resistor is presented. Based on synthetic low and high power tests, the performance of a mock-up is evaluated. Finally, the post-arc current of a model gas circuit breaker, designed for use in DC applications, is measured.
Plasma Physics and Technology Journal **4(2)**, pp. 137-140 (2017)

E. Kontos, T. Schultz, C. M. Franck et all, "Multi-Line Breaker for HVDC Applications"
This paper presents a breaker arrangement concept, the Multi-Line 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 MMC-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, doi: TPWRD.2017.2754649 (2017)

V. Lenz, T. Schultz, C. M. Franck, "Impact of Topology and Fault Current on Dimensioning and Performance of HVDC Circuit Breakers"
Multiterminal HVDC networks are a key technology for future power transmission. For safe and reliable operation, it is necessary to equip these with HVDC circuit breakers. In the presented paper, four HVDC breakers, representing different breaker classes, are dimensioned and simulated in synthetic and exemplary grid fault cases. The results are used to illustrate topology dependent limitations and individual options to upgrade each circuit breaker. Additionally, differences between commonly used linear fault currents and faults in MTDC grids as well as their implications are highlighted.
4th International Conference on Electric Power Equipment Switching Technology (ICEPE-ST 2017), October 22 - 25, Xi'an, China (2017)

A. Ritter, C. M. Franck, "Prediction of Bus-Transfer Switching in Future HVDC Substations"
Prior research has characterized bus-transfer switching capabilities of dis-

connectors 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, doi: TPWRD.2017.2764386 (2017)

J, Thomas, G. Chaffey, C. M. Franck, "Small Scale HVDC Circuit Breaker"
Multiterminal HVDC networks are a key technology for future power transmission. For safe and reliable operation, it is necessary to equip these with HVDC circuit breakers. In the presented paper, four HVDC breakers, representing different breaker classes, are dimensioned and simulated in synthetic and exemplary grid fault cases. The results are used to illustrate topology dependent limitations and individual options to upgrade each circuit breaker. Additionally, differences between commonly used linear fault currents and faults in MTDC grids as well as their implications are highlighted.
IEEE Transactions on Components, Packaging and Manufacturing Technology **7**, pp. 1058-1068 (2017)

L. Bort, V. Freiermuth, C. M. Franck, "Influence of Ablation on Differential Arc Resistance"
The influence of ablation on the du/di behavior of an arc in a model gas circuit breaker was examined. Specifically the transition from a state without ablation in the nozzle towards states with ablation was of interest, since prior work indicated that for high currents the voltage becomes constant or du/di gets even positive if ablation is present. Measurements with different blow pressures and rectangular DC currents of varying amplitude were

compared, using PMMA-nozzles and dry air as blowing gas. Ablation was measured by weighing the nozzle, scanning the cross section, and using a coordinate measuring machine. The results agreed well, and confirmed that higher pressure shifts the du/di curve towards more favorable value.
Plasma Physics and Technology Journal **4(2)**, (2017)

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 long term aging effects in the free span and 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: *Martin D. Pfeiffer, Pascal B. Bühlmann, C. Sören Hedtke, Pascal T. Bleuler*

Publications In this research area, the following publications have been published in 2017:

M. D. Pfeiffer, S. C. Hedtke, C. M. Franck, "Corona Current Coupling in Bipolar HVDC and Hybrid HVAC/HVDC Overhead Lines"
This publication investigates the corona generated ion flow environment in bipolar HVDC and hybrid AC/DC transmission systems. The emphasis is on the DC ion current magnitude in the conductors. In DC conductors this constitutes the corona power loss, while in AC conductors this quantity is primarily of concern due to the risk of transformer saturation.
Existing prediction methods are compared to full-scale test data from the literature and new laboratory measurements. It is shown that the bipolar HVDC and hybrid AC/DC ion flow phenomena are similar in the sense that mutual space-charge related surface field enhancements are a dominant factor in the determination of the total conductor ion currents. Furthermore, in a hybrid AC/DC environment, the existence of a net DC ion current stemming from the AC conductor is verified and explained. Limitations of existing prediction methods are demonstrated and recommendations for future work is given.
IEEE Transactions on Power Delivery **33**, pp. 393-400 (2017)

A. Vargas-Serrano, A. Hamann, S. C. Hedtke, C. M. Franck, G. Hug, "Economic benefit analysis of retrofitting a fixed-speed pumped storage hydropower plant with an adjustable-speed machine"
For pumped storage hydropower plants with fixed-speed electrical machines, turbines typically operate between 70 and 100 percent of rated power whereas pumps usually run at constant load. If the fixed-speed machine is replaced with an adjustable-speed machine, the operating range of the pump increases, thereby increasing flexibility and enabling the provision of ancillary services in pump mode. This paper estimates the economic benefits of converting an existing fixed-speed pumped storage hydropower plant to adjustable speed. We

consider the test case of the Grimsel 2 pumped storage hydropower plant, located in Switzerland. We implement a mixed-integer linear program to optimize operations at Grimsel 2 considering the structure of Swiss energy and ancillary service markets. Our results show that upgrading a fixed-speed plant to adjustable speed could increase total revenue up to 58 percent.
2017 IEEE PowerTech, June 18 - 22, Manchester, UK (2017)

J. Rodriguez Alvarez, C. M. Franck, "Evaluation of the Accuracy of a Thermal Rating Model to Estimate the Temperature of Operational Transmission Lines"
The CIGRE technical brochure 601 [1] provides tools for calculating the thermal rating of overhead transmission lines calculating. This brochure, which improved upon its predecessor in several aspects [2], also provides methods for dynamic line rating calculations. In order to design a dynamic rating scheme, utilities need to know what is the accuracy of the thermodynamic model of the transmission line. The present publication presents a study where the CIGRE model for line rating was used to estimate the temperature of real transmission lines in the Swiss network, and its accuracy was determined by comparing the results with three years of field data. It is shown that the accuracy of the simulation was improved when a wind cooling expression based on the IEC standard and CIGRE model was used, and when the sky thermal radiation was accounted for. When this was done, deviations of model from the measurements were approximately (1.0 ś 2.4)řC during the day and (0.5 ś 1.1)řC during the night.
CIGRE Science and Engineering **4**, pp. 53-62 (2017)

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 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 integral characterisation methods such as polarisation and depolarisation current (PDC) and dielectric spectroscopy (DS), but combined with 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 and currently under review in peer-reviewed journal. 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.

4.4.2 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.

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

Researchers: *Malte Tschentscher, Raphael B. Färber*

4.5 Optimal Power Flow and System Operation

The physical steady state dependencies in the electric power system are described by non-convex equations. When optimizing the operation of the system, these physical equations need to be taken into account as constraints rendering the optimization problem non-convex and difficult to solve for real scale systems. Hence, simplifications that yield low levels of inaccuracies and efficient solution algorithms are required to solve the problem within an acceptable amount of time and sufficient accuracy. This holds for the basic Optimal Power Flow problems but even more so for the stochastic version of this optimization problem which incorporates the uncertainty from renewable resources into the problem formulation.

With regards to the efficient formulation and solution of the Optimal Power Flow problem, piecewise linear approximations of particular constraints enable a simplification of the overall problem. If such linearization is applied to the non-linear line current constraints, the resulting optimization problem yields close to optimal solutions at lower computational cost and time for large scale systems. Depending on the focus of the linearization, i.e. if the resulting equations are a conservative or a relaxed version of the original problem, it is possible to provide a lower or an upper bound on the actual solution. A very different approach on the same optimization problem is the development of online optimization approaches that have gained interest in the past few years. The goal of these approaches is to derive controllers that track the optimal solution of the problem with varying loads in real time. For example, using a projected gradient approach on the power flow manifold, feedback controllers that achieve such tracking can be derived.

These days a particular focus of these optimization problems is on how to optimally balance the variability and uncertainty from the renewable resources. Balancing sources include conventional power plants, storage devices and load management. Hence, the coupling to other systems that are by some means coupled to the electric power system via generation or load is playing an increasingly important role. Consequently, such coupling should be incorporated into the optimization problems as well to ensure optimal usage of all resources. 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).

For any approaches, it is indispensible to verify and evaluate their performance on a time-varying system. Hence, comprehensive modelling and simulation is a very important aspect of this overall work. As many of the future generation and balancing resources will be located in the distribution system interacting with the resources in the transmission system governed by the physical equations but also market rules, such modelling and simulation needs to span these different parts of the system. Consequently, the development of a simulation platform supports a wide range of other research but necessitates research in its own.

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: *Xuejiao Han, Michael Haendel, Adrian Hauswirth, Aleksandar Jovicic, Evangelos Kardakos, Olivier Mégel, Conor O'Malley, Tomas Tinoco De Rubira, 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*

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

Publications In this research area, the following publications have been published in 2017:

Dmitry Shchetinin, Tomas Tinoco De Rubira, Gabriela Hug, "Conservative Linear 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. To enable the application of efficient and robust solution algorithms, various linear approximations of the nonlinear system model are used. However, this may lead to solutions that are AC suboptimal or even infeasible. This paper proposes new linearization techniques for constructing accurate line flow constraints that reduce the complexity of the AC optimal power flow problem without compromising the solution quality. In particular, it investigates the shape of the nonlinear constraints in polar coordinates and presents methods for producing conservative linear approximations with a desired accuracy. Numerical experiments are performed on systems with 118, 300 and 1354 buses. Obtained results indicate that the proposed formulation leads to a significant decrease in the computation time while at the same time providing high quality approximations of the exact line flows.
IEEE PowerTech, June 18-22, Manchester, UK (2017)

Adrian Hauswirth, Alessandro Zanardi, Saverio Bolognani, Florian Dörfler, and Gabriela Hug, "Online optimization in closed loop on the power flow manifold"
The focus of this paper is the online load flow optimization of power systems in closed loop. In contrast to the conventional approach where an AC OPF solution is computed before being applied to the system, our objective is to design an adaptive feedback controller that steers the system in real time to the optimal operating point without explicitly solving an AC OPF problem. Our approach can be used for example to simultaneously regulate voltages, mitigate line congestion, and optimize operating costs under time-varying conditions. In contrast to related work which is mostly focused on distribution grids, we introduce a modeling approach in terms of manifold optimization that is applicable in general scenarios. For this, we treat the

power flow equations as implicit constraints that are naturally enforced and hence give rise to the power flow manifold (PFM). Based on our theoretical results for this type of optimization problems, we propose a discrete-time projected gradient descent scheme on the PFM. In this work, we confirm through a detailed simulation study that the algorithm performs well in a more realistic power system setup and reliably tracks the time-varying optimum of the underlying AC OPF problem.
IEEE PowerTech, June 18-22, Manchester, UK (2017)

A. Venzke, L. Halilbasic, U. Markovic, G. Hug, 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 ow (OPF). Current approaches follow either a linearized approach or an iterative approximation of non-linearities. This paper proposes a semidefinite relaxation of a chance constrained AC-OPF which is able to provide guarantees for global optimal- ity. Using a piecewise affine policy, we can ensure tractability, accurately model large power deviations, 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 semidedefinite 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 Transactions on Power Systems (Volume: PP, Issue: 99) (2017)

4.6 Power System Dynamics and Control

The load in the electric power systems is constantly changing with the result that the system is never truly in a steady state. However, because the system operators need to plan ahead, they assume a steady state system for their hour ahead, day ahead and longer term planning. But they also need to be able to react in real time to changes in load and renewable generation infeeds and have to take into consideration the dynamics that the system exhibits as a consequence of all of these variations.

An important aspect when it comes to dynamics in future electric power systems is the fact that with the increased penetration of renewable generation the number of power electronic connected resources increases. Different to synchronous machines, these resources do not provide natural inertia to the system, significantly changing the overall dynamics of the system. This can be partially compensated for by the means of inverter controls. Designing these controls particularly for a low-inertia system is still an open question.

While the consideration of low inertia systems is an important topic, a resource that will likely always be available and does provide inertia is hydro power. While it provides such inertia naturally, the question is to what level and how efficient can hydro plants be used to provide balancing services from the sub-minute to the hourly time frame. This heavily depends on how these plants are operated. The coordinated operation among cascaded power plants thereby plays an important role and determines to what level such a cascade can act as a storage resource.

Components that are less visible but play a crucial role in keeping our power systems secure are protection devices. As new resources are connected to the system that exhibit different short circuit behaviour and bi-directional flows become common even in the distribution system, it is likely that new protection systems and approaches are necessary. This includes approaches for detection as well as identification of all possible types of faults.

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: *Andrew Hamann, Uros Markovic, Nadezhda Davydova*

Partnership: *ETH Control Laboratory, University of Leeds, RTE, University College of Dublin, Université Lille, EPRI*

Externally Funded Research Projects:
MIGRATE - Massive InteGRATion of power Electronic devices: The increasing penetration of power electronic components in the HVAC trans-

mission 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.

Coordinated Control of Cascaded Hydropower Plants: Hydropower is an important renewable energy resource supplying a major portion of electric power generation, especially in the Northwest region of the United States. While it is a valuable resource by itself, it could also enable the increased penetration of non-dispatchable variable intermittent resources, like wind and solar power, due to its fast response times and storage capabilities. The objective of this project is to derive an efficient optimization tool that optimizes the water usage of cascaded river power plants to produce the requested electricity to balance wind and solar generation while at the same time adhering to all operational constraints.
Funded by the Electric Power Research Institute (EPRI).

Publications In this research area, the following publications have been published in 2017:

A. Hamann, G. Hug, and S. Rosinski, "Real-time optimization of the Mid-Columbia hydropower system"
This paper presents a coordinated model predictive control scheme for the Mid-Columbia hydropower system. The Mid-Columbia system consists of seven hydropower plants on the Columbia River in the United States. The state-space model used in the control scheme accounts for system hydraulics, modeling time-delayed hydraulic coupling and dynamic tailrace elevations. We approximate the power generation from a hydropower plant using a piecewise planar function of turbine discharge and hydraulic head, and we demonstrate how this approximation can be written as a set of linear constraints and integrated into a quadratic program. We introduce a flow minimizing

objective function that maximizes system hydraulic potential by efficiently allocating water. Compared to historical operations, the proposed control scheme reduces ramping, increases total system hydraulic head, increases system energy content, and operates the system within all elevation and flow constraints.
IEEE Transactions on Power Systems , vol. 32, no. 1, pp. 157-165, January 2017 (2017)

A. Vargas-Serrano, A. Hamann, S. C. Hedtke, C. M. Franck, G. Hug, "Economic benefit analysis of retrofitting a fixed-speed pumped storage hydropower plant with an adjustable-speed machine"
For pumped storage hydropower plants with fixed-speed electrical machines, turbines typically operate between 70 and 100 percent of rated power whereas pumps usually run at constant load. If the fixed-speed machine is replaced with an adjustable-speed machine, the operating range of the pump increases, thereby increasing flexibility and enabling the provision of ancillary services in pump mode. This paper estimates the economic benefits of converting an existing fixed-speed pumped storage hydropower plant to adjustable speed. We consider the test case of the Grimsel 2 pumped storage hydropower plant, located in Switzerland. We implement a mixed-integer linear program to optimize operations at Grimsel 2 considering the structure of Swiss energy and ancillary service markets. Our results show that upgrading a fixed-speed plant to adjustable speed could increase total revenue up to 58 percent.
IEEE PowerTech, June 18-22, Manchester, UK (2017)

Nadezhda Davydova and Gabriela Hug, "Traveling wave based protection for medium voltage grids with distributed generation"
High penetrations of distributed generation in distribution grids may cause malfunctioning of conventional protection systems due to bidirectional flows and highly variable short-circuit levels. While there has been extensive research on this topic, developing a reliable cost-efficient protection system for active distribution grids remains a challenging task. This paper presents a new protection algorithm for medium voltage lines based on Traveling Wave theory. The fault direction is determined by analyzing differential equations that describe the behavior of fault-induced current waves in the vicinity of the protection terminal. The distinction between external and internal faults is performed by classifiers based on Neural Networks. The protection algorithm uses only current measurements as inputs and does not require any information exchange, which makes it a potentially low-cost yet reliable solution. The algorithm's performance is evaluated on the IEEE 34-bus test distribution system.

IEEE PowerTech, June 18-22, Manchester, UK (2017)

Nadezhda Davydova and Gabriela Hug, "Wavefront-based Protection for Active Distribution Grids"
Installation of distributed generation in distribution grids may cause malfunctioning of conventional protection systems due to bidirectional flows and increased range of short-circuit current levels. Despite considerable efforts to address these challenges, development of low-cost, high-speed and reliable protection systems for active grids remains an open research question. This paper presents a new wavefront-based protection system for medium voltage lines of a substation in an active grid. The protection does not require voltage measurements and relies only on local current measurements and binary signals received from neighboring protection terminals. The fault occurrence is detected by capturing fault-generated current waves using Wavelet Transform. A faulted line in the protection zone is identified through comparative analysis of slopes' signs of current wavefronts obtained locally and from neighboring terminals. The proposed algorithm potentially offers high-speed and reliable protection of any number of interconnected lines, which is demonstrated on the IEEE 34-bus distribution system.
IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe), September 26-29, Torino, Italy (2017)

U. Markovic, P. Aristidou, G. Hug, "Stability Performance of Power Electronic Devices with Time Delays"
This paper deals with the impact of time delays on small-signal stability of power systems with an all converter interfaced generation. For this purpose, a delay differential-algebraic equation model of the voltage source converter and its control scheme is developed. The regulation is based on replicating the dynamical properties of a synchronous machine through appropriate controller configuration. Therefore, a virtual inertia emulation is included in the active power control loop. A transcedental nature of the characteristic equation is resolved by implementing the Chebyshev's discretization method and observing a finite number of critical, low-frequency eigenvalues. Based on the proposed approach, a critical measurement delay is evaluated. Furthermore, a bifurcation analysis of the droop gains and inertia constant is conducted. Stability regions and optimal parametrization of the voltage source converter controls are evaluated and discussed.
IEEE PowerTech, June 18-22, Manchester, UK (2017)

U. Markovic, P. Aristidou, G. Hug, "Virtual Induction Machine Strategy for Converters in Power Systems with Low Rotational Inertia"
This paper presents a novel comprehensive control strategy for grid-connected

Voltage Source Converters (VSCs) in power systems with low rotational inertia. The proposed model is based on emulating the physical properties of an Induction Machine (IM) and taking advantage of its inherent grid-friendly properties, i.e. self-synchronization, virtual inertia, power and frequency oscillation damping. For that purpose, a detailed mathematical model of the IMs working principles is derived, which includes the possibility of obtaining the unknown grid frequency without a dedicated synchronization unit, but rather via processing the voltage and current magnitude measurements at the converter output. This eliminates the need for an inherently nonlinear phase-locked loop, characteristic for virtual synchronous machines, while simultaneously preserving the synchronization and damping properties of a conventional electrical machine. Several case studies are presented that validate the mathematical principles of the proposed model and conclusions on VSC performance are drawn.
IREP 2017, Aug 27-Sep 1, Espinho, Portugal (2017)

4.7 Distribution System Applications

The deployment of new sensing, communication and control technologies has been a major topic in the development of what is commonly referred to as the smart grid. While the transmission system has been well equipped with monitoring equipment for a long time, this has not been true for the distribution system. This but also the fact that many of the distributed resources, e.g. distributed generation, distributed storage and load management, are deployed in the distribution system, shifts the main focus onto these lower levels of the system.

Given these enhancements and developments in the distribution grid, it can be expected that not only a significant part of the additional variability originates in the distribution system but also a significant level of the available flexibility. The consequence is that the intercoupling between distribution and transmission systems increases necessitating more coordination between these levels. This can be achieved by better monitoring and prediction of the system behavior of the distribution system using the newly available data. However, this requires the development of new approaches originating in data mining and machine learning.

Smart meters are the devices placed at the very end of the supply/demand chain in order to measure consumption in higher granularity and potentially also provide signals to the consumers. However, higher resolution consumption information bears the risk of endangering the privacy of the consumer. Consequently, it is necessary to protect that data not just from third parties but also from the utility. Possible means 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 optimizing the consumption with regards to costs.

With the many controllable elements available also in the distribution system, the question arises of how to determine the optimal settings of all of these devices. From a practical standpoint, it makes sense to enable local decision making as opposed to trying to implement a centralized optimizer. However, the resulting local decision making should yield a performance that is close to optimal for the overall system. This can be achieved by learning offline the interdependencies and/or sensitivities between system variables and the optimal settings for the control variables and based on these interdependencies to create decision making curves.

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, Philipp Fortenbacher, Xuejiao Han, Stavros Kara-*

giannopoulos, Evangelos Kardakos, Tomas Tinoco de Rubira, Gustavo Valverde, Thierry Zufferey

Partnership: *Adaptricity, ABB, EWZ, Ernst Basler + Partner, Swissgrid, 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.

Smart Planning: Electrical distribution grids are facing numerous challenges caused by distributed generation (Wind, PV) and new load types (electric vehicles, heat pumps). Increasing and, at times, reversed power flows create grid upgrade needs. The project develops new grid planning guidelines that consider the entire range of grid upgrade options, including SmartGrid technologies and Smart-Markets using real network cases from participating European grid operators. *Funded by the Bundesamt für Energie (ETH part), in collaboration with ABB, EWZ, TU Dortmund, TU Eindhoven, Enexis.*

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)*

Publications In this research area, the following publications have been published in 2017:

S. Karagiannopoulos, P. Aristidou, L. Roald, and G. Hug, "Operational planning of active distribution grids under uncertainty"
Modern distribution system operators are facing constantly changing operating conditions caused by the increased penetration of intermittent renewable generators and other distributed energy resources. Under these conditions, the distribution system operators are required to operate their networks with increased uncertainty, while ensuring optimal, cost-effective, and secure operation. This paper proposes a centralized scheme for the operational planning of active distribution networks under uncertainty. A multi-period optimal power flow algorithm is used to compute optimal set-points of the controllable distributed energy resources located in the system and ensure its security. Computational tractability of the algorithm and feasibility of the resulting flows are ensured with the use of an iterative power flow method. The system uncertainty, caused by forecasting errors of renewables, is handled through the incorporation of chance constraints, which limit the probability of insecure operation. The resulting operational planning scheme is tested on a low voltage distribution network model using real forecasting data for the renewable energy sources. We observe that the proposed method prevents insecure operation through efficient use of system controls.
X Bulk Power Systems Dynamics and Control Symposium IREP2017, August 27 - September 1, Espinho, Portugal (2017)

S. Karagiannopoulos, P. Aristidou, and G. Hug, "Hybrid approach for planning and operating active distribution grids"
This paper investigates the planning and operational processes of modern distribution networks hosting distributed energy resources (DERs). While in the past the two aspects have been distinct, a methodology is proposed in this paper to co-optimise the two phases by considering the operational flexibility offered by DERs already in the planning phase. By employing AC optimal power flow (OPF) to analyse the worst-case scenarios for the load and distributed generator injection, the optimal set-points for the DERs are determined such that the networks security is ensured. From these results, the

optimised individual characteristic curves are then extracted for each DER which are used in the operational phase for the local control of the devices. The optimised controls use only local measurements to address system-wide issues and emulate the OPF solution without any communication. Finally, the proposed methodology is tested on the Cigre LV benchmark grid confirming that it is successful in mitigating with acceptable violations over- and under-voltage problems, as well as congestion issues. Its performance is compared against the OPF-based approach and currently employed local control schemes.
IET Generation, Transmission & Distribution Issue Number: 11(3):685695, Feb 2017 (2017)

Jun-Xing Chin, Tomas Tinoco De Rubira and Gabriela Hug, “Privacy-Protecting Energy Management Unit through Model-Distribution Predictive Control”
The roll-out of smart meters in electricity networks introduces risks for consumer privacy due to increased measurement frequency and granularity. Through various non-intrusive load monitoring techniques, consumer behavior may be inferred from their metering data. In this paper, we propose an energy management method that reduces energy cost and protects privacy through the minimization of information leakage. The method is based on a model predictive controller that utilizes energy storage and local generation, and that predicts the effects of its actions on the statistics of the actual energy consumption of a consumer and that seen by the grid. Computationally, the method requires solving a mixed-integer quadratic program of manageable size whenever new meter readings are available. We simulate the controller on generated residential load profiles with different prices of privacy loss in a two-tier time-of-use energy pricing environment. Results show that information leakage is effectively reduced at the expense of increased energy cost. The results also show that with the proposed controller the consumer load profile seen by the grid resembles a mixture between that obtained with non-intrusive load leveling and lazy stepping.
IEEE Transactions on Smart Grid, 8 (6): pp. 3084-3093 (2017)

Thierry Zufferey, Andreas Ulbig, Stephan Koch, and Gabriela Hug, "Unsupervised Learning Methods for Power System Data Analysis"
This chapter focuses on the use of the K-Means clustering algorithm for an enhanced visibility of the electrical distribution system which can be provided by advanced metering infrastructure and supported by big data technologies and parallel cloud computing environments such as Spark and H2O. Based on smart meter data of more than 30000 loads in the City of Basel, Switzerland, and thanks to an appropriate cluster analysis, it is shown that useful knowledge of the grid state can be gained without any further information concerning the type of consumer and their habits. Once energy data is judiciously prepared, the features extraction is an important step. A graphical user interface is presented which illustrates the potentially great flexibility in the choice of features according to the needs of Distribution System Operators (DSOs). For example, the distribution of the various types of customers across the power system is of interest to DSOs. This chapter presents thus some pertinent examples of clustering outcomes that are visualized on the map of Basel, which notably enables to easily identify heating and cooling demand or gain insight into the energy consumption throughout the day for different neighborhoods.
Big Data Application in Power Systems, 1st Edition, Editors: Reza Arghandeh and Yuxun Zhou, my chapter: p. 107 - 124 (2017)

C. Roduner, S. Karagiannopoulos, E. Taxeidis, and G. Hug, "A reliability and cost assessment methodology of medium voltage feeders"
In this work, we introduce a methodology which quantifies medium voltage (MV) feeder reliability in the form of commonly used indices. The contribution of the proposed methodology focuses on the modelling not only of the grid itself, but also of the detailed actual operational practices of the Distribution System Operator (DSO), taking into consideration the specific parameters of the examined network. By doing so, the influence of diverse reliability enhancement measures on different feeders can be evaluated and assessed. The method is tested using real (MV) feeders, considering as measures the installation of protection units and remote control capabilities to the switches. Furthermore, by considering the cost of protection and remotely controlled units, the proposed methodology performs techno-economic analyses to assess the trade-offs between enhancing grid reliability and increasing costs, serving as a decision-making tool for modern DSOs.
CIRED Workshop (2017)

S. Karagiannopoulos, P. Aristidou, and G. Hug, "Co-optimisation of Planning and Operation for Active Distribution Grids"
Given the increased penetration of smart grid technologies, distribution sys-

tem operators are obliged to consider in their planning stage both the increased uncertainty introduced by non-dispatchable distributed energy resources, as well as the operational flexibility provided by new real-time control schemes. First, in this paper, a planning procedure is proposed which considers both traditional expansion measures, e.g. upgrade of transformers, cables, etc., as well as real-time schemes, such as active and reactive power control of distributed generators, use of battery energy storage systems and flexible loads. At the core of the proposed decision making process lies a tractable iterative AC optimal power flow method. Second, to avoid the need for a real-time centralised coordination scheme (and the associated communication requirements), a local control scheme for the operation of individual distributed energy resources and flexible loads is extracted from offline optimal power flow computations. The performance of the two methods is demonstrated on a radial, low-voltage grid, and compared to a standard local control scheme.
IEEE PowerTech, June 18-22, Manchester UK (2017)

Jun-Xing Chin, Tomas Tinoco De Rubira and Gabriela Hug, "Time Aggregation for Privacy-Protecting EMU based on Model-Distribution Predictive Control"
Smart meter adoption in electricity networks introduces privacy risks for consumers due to the increased measurement frequency and granularity. In particular, consumer behaviour and lifestyle choices may be inferred from their metering data using various Non-Intrusive Load Monitoring techniques. To protect consumer privacy, energy storage controlled by a Model-Distribution Predictive Control scheme can be utilised to mask the actual energy consumption by measuring privacy loss through the mutual information between actual and grid-visible energy consumption. However, the poor scalability of this approach limits the size of the prediction horizon, which is important for both energy cost and privacy loss reduction. In this paper, we propose using time aggregation to increase the reach of the controller's prediction horizon, and describe how to correctly model the statistics in this setting. Results show that with the proposed time aggregation, information leakage and energy costs can be further reduced without increasing the controller's computational requirements.
IEEE PowerTech, June 18-22, Manchester UK (2017)

Xuejiao Han, Evangelos G. Kardakos, Gabriela Hug, "Trading strategy for decentralized energy resources in sequential electricity markets: A Swiss case study"
This paper derives optimal day-ahead trading strategies for an aggregator of a decentralized energy resources mix, who participates in a multi-market

environment, including a day-ahead, an intraday and a balancing market. The optimization problem is solved using multi-stage stochastic programming, which is subject to different levels of uncertainties such as variable generation output, day-ahead and intraday market prices. Risk management is conducted to investigate the effect of risk exposure on the total revenue of the aggregator. A case study based on the data from the Swiss electricity market demonstrates the effectiveness of the proposed model.
ISGT Asia, 4-7 December, Auckland, New Zealand (2017)

5. Awards and Honours

Adrian Hauswirth
Basil Papadias Student Award for Best Paper, IEEE PES Powertech 2017, Manchester, UK
Juni 2017

Uros Markovic
High Quality Paper Award, IEEE PES Powertech 2017, Manchester, UK
Juni 2017

Alise Chachereau
Winner of ISH Student Award 2017, Buenos Aires
September 2017

Xuejiao Han
Runner-up Poster Award, ISGT Asia 2017, Auckland
December 2017

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.

High Voltage Laboratory

Power Systems Laboratory

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich