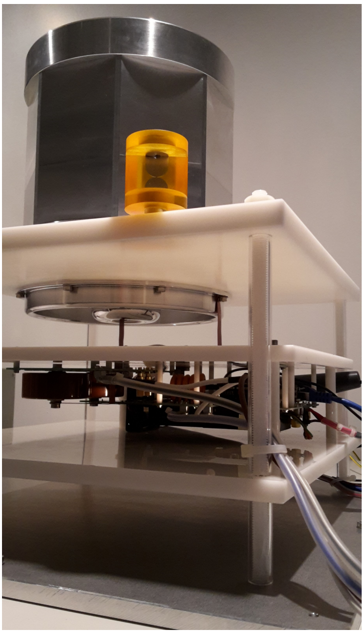
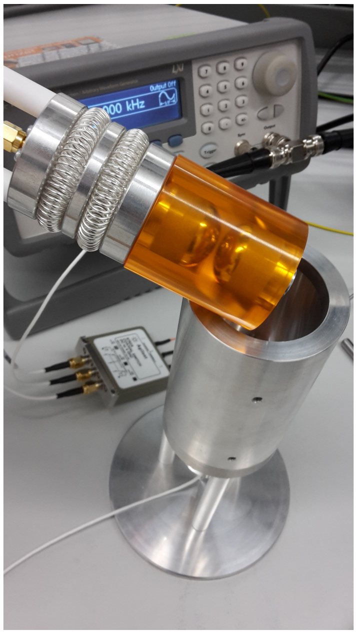
Power Systems and High Voltage Laboratories

Annual Report 2016





High Voltage Laboratory

Power Systems Laboratory

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Annual Report 2016

Issued by

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

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Front Cover: Test cell for applying mixed-frequency medium voltage stress to test samples (left) and dielectric spectroscopy setup for investigating the corresponding aging dynamics (right)

Back Cover: Evaluating the Performance of Smart Meter Privacy Protection Schemes: a) no privacy protection, b) high privacy protection

Preface

Dear colleagues and friends of the laboratory!

We are pleased to present to you the annual report of the Power Systems and High Voltage Laboratories for 2016. We look back on the past year with pleasure and pride. Again, great research results have been achieved and published in numerous peer-reviewed publications and presented on many international conferences. Around 40 students have worked with us in the framework of their group, semester or master thesis. We were able to welcome 7 new colleagues to the team and five group members have successfully defended their doctoral thesis (in alphabetical order): Theodor Borsche, Matthias A. Bucher, Line Roald, Marc Scherrer, and Evangelos Vrettos. Congratulations!
2016 was also the year in which we started an extensive upgrade and refurbishment of our experimental infrastructure. Three new HVDC modules (each $\pm 400\,\mathrm{kV}$) have been purchased according to WTO standards and we are now able to perform HVDC experiments up to $\pm 800\,\mathrm{kV}$ (monopolar) or $400\,\mathrm{kV}$ (bipolar). In december we started to replace the old switchgear and outdated control of the laboratory power supply. The new installations comply to our latest safety standards and experiments can also be automated using external control software.
In the Power Systems Laboratory, a change in head of the lab has occurred in 2016 after Göran Andersson has retired in July. Due to one year of overlap with the new head Gabriela Hug, a smooth continuation of the teaching and research activities was ensured.
We would like to express our thanks to all researchers and other personnel working at our laboratories as well as the external lecturers for their dedicated and highly competent work. It would not be possible to have such a professional and stimulating work environment, achieve high quality research and offer attractive classes without such commitment.
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.
More details, updates and news can be found on our homepage, which is now in the new ETH standard design: www.eeh.ee.ethz.ch.

G. Hug G. Andersson C.M. Franck

Contents

1. Organisation

1.1 Power Systems Laboratory

Head:	Prof. Dr. Gabriela Hug Prof. Dr. Göran Andersson (- Juli 2016)
Secretary:	Judith Eberle
Scientific Staff:	Dr. Petros Aristidou (- September 2016) Dipl.-Ing. Theodor Borsche (- July 2016) MSc ETH Matthias Bucher (- September 2016) MSc Jun Xing (Jack) Chin MSc Nadezhda Davydova M.Sc. El.Eng. Philipp Fortenbacher MSc Andrew Hamann MSc Xuejiao Han (June 2016 -) MSc ETH Adrian Hauswirth MSc ETH Stavros Karagiannopoulos Dr. Evangelos Kardakos (May 2016 -) MSc ETH Uros Markovic (March 2016 -) MSc EPF Olivier Mégel MSc Conor O'Malley (May 2016 -) MSc ETH Line Roald (- December 2016) Dr. Osvaldo Rodriguez Villalon (- July 2016) Dr. sc. ETH Monika Ruh (- May 2016) MSc ETH Marc Scherer (- August 2016) MSc Dmitry Shchetinin Dr. Tomas Tinoco De Rubira Dipl.-Ing. Evangelos Vrettos (- November 2016) MSc ETH Roger Wiget (- July 2016) Dr. Chenye Wu (July - November 2016) MSc ETH Thierry Zufferey (May 2016 -)
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 Dr. sc. ETH Marek Zima, Swissgrid, Laufenburg
Ext. PhD Student:	MSc Michael Händel
Scientific Associates:	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:	Junyao Guo, Carnegie Mellon University, Pittsburgh, USA

1.2 High Voltage Laboratory

Head:	Prof. Dr. rer. nat. Christian M. Franck
Secretary:	Karin Sonderegger Zaky
Scientific Staff:	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 TUM Juriy Pachin (Oct 2016 -) MSc ETH Martin D. Pfeiffer Mag.rer.nat. Mohamed Rabie MSc ETH Andreas Ritter MSc RWTH Tim Schultz MSc RWTH Malte Tschentscher MSc ETH Jonas Truessel (- March 2016)
Technical Staff:	Henry Kienast, Mechanician Fabian Mächler, Automation Engineer (Oct 2016 -) 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 Dr. sc. ETH Nicolas E. Karrer (Spin-Off: kametech - Okt 2016)
Academic Guests:	PhD Student Yang Li (Xi'an Jiatong University, PRC, Feb - Apr 2016) PhD Student Kun He (CEPRI, PRC, Apr - Nov 2016) PhD Student Pengfei Xu (Tsinghua University, PRC, Nov 2016 -)

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. Details of the entire electrical engineering curriculum can be provided upon request (list of compulsory and elective courses).

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, M. Zima, 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
ABB Power Laboratory
Baden, Switzerland
14 April 2016

Power Market II
Rheinhafen-Dampfkraftwerk, EnBW Energie Baden-Württemberg AG, Mercedes-Benz Factory
Karlsruhe and Sindelfingen, Germany
26 and 27 April 2016

High Voltage Engineering
GE Grid Switzerland GmbH
Oberentfelden, Switzerland
29 April 2016

Power System Dynamics, Control and Operation
EKZ Battery
Dietikon, Switzerland
2 May 2016

Power System Dynamics, Control and Operation
Swissgrid Control Center
Laufenburg, Switzerland
17 May 2016

Technology of Electric Power System Components
ABB Surge Arrester Factory
Wettingen, Switzerland
19 May 2016

High Voltage Engineering
ABB Micafil
Zurich, Switzerland
20 May 2016

Technology of Electric Power System Components
Pfiffner Instrument Transformers
Hirschthal, Switzerland
2 June 2016

Introduction to Electric Power Transmission: System & Technology
EWZ Substation Sempersteig
Zurich, Switzerland
23 November 2016

Power Market I
Axpo Baden
Baden, Switzerland
29 November 2016

Power System Analysis
Axpo Control Center
Baden, Switzerland
30 November 2016

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 two semester projects. 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. The two semester projects must be carried out with two different professors. 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.

2.4.1 System Oriented Semester Projects

Nikolaos Chrysogelos
Identification of Consumer Behaviour via Current Smart Metering Infrastructure: Study and Implementation Based on Present Constraints
Supervisor: Jun Xing Chin

Philipp Lütolf
Impact of the rebound effect on area control error when demand response provides secondary control
Supervisors: Olivier Mgel, Evangelos Vrettos, Martin Geidl (swisscom)

Michael Pfister
On the Interdependence of Frequency Containment and Load-Frequency Control
Supervisor: Marc Scherer

Nicolas Pilatte
Setup and analysis of Large-scale Transmission and Distribution Network
Supervisor: Petros Aristidou

Benjamin Schaule
Battery sizing algorithms for storing excess energy from renewable generation in distribution grids
Supervisor: Stephan Koch

Andres Vargas Serrano
Simulation of unit dispatch and scheduling in a hydropower plant
Supervisors: Andrew Hamann

2.4.2 Technology Oriented Semester Projects

Mingkun Liu
Parameter Study of HVDC Circuit Breaker Arcs
Supervisor: Lorenz Bort

Matthias Vöhringer
Simulation of Switching Operations in Multiterminal HVDC
Supervisor: Andreas Ritter

Moritz Staub
Experiments and simulations on thermal-electrical behavior of the tension clamp assembly depending on grease layer
Supervisor: Pascal Bühlmann

Lara Egli
Design and Testing of Supersonic Nozzles for High Current DC Circuit Breakers
Supervisor: Lorenz Bort

Julian Hummel
Simulation of Heated Supersonic Gas Flow in a Circuit Breaker Nozzle
Supervisor: Lorenz Bort

Martina Stadelmann
Investigation and Modelling of HVDC Surface Charging
Supervisor: Malte Tschentscher

Julia Glaus, Manuel Kohli, Michel Nagel
Reduction of Corona Losses and Audible Noise of HVDC Overhead Lines
Supervisors: Sören Hedtke, Martin Pfeiffer

Gabriel Voirol
Design, production and testing of novel thin-film photocathodes for use in Pulsed-Townsend Experiments
Supervisor: Pascal Häfliger

Alice Lépouzé
Understanding the emergence of ion currents from thin-film photocathode
Supervisor: Pascal Häfliger

Ioannis Stavropoulos
Inverse Modelling of HVDC Surface Charging
Supervisor: Malte Tschentscher

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.

2.5.1 System Oriented Master Projects

Christos Antonakopoulos
Investigation of the distribution grid hosting capacity for distributed generation and possible improvements by smart grid technologies
Supervisor: Stephan Koch

Matthias Fetzner
Cost-optimized voltage control in distribution networks
Supervisor: Dmitry Shchetinin

Antoine Gaillard
Modeling and Analysis of Economic Impacts of PV Self-Consumption on Prosumers, Distribution Grid Operators,and Energy Suppliers
Supervisor: Stephan Koch

Maxence Le Grelle
Quantifying the Cost-Benefit of Future Advanced Metering Infrastructures from an Economic Perspective
Supervisors: Jun Xing Chin, Osvaldo Rodriguez Villalon

Peiyan Li
Modern power system equivalents - Model Reduction
Supervisors: Petros Aristidou, Stavros Karagiannopoulos

Tobias Mohrhauer
Market Coupling of Self- and Central-Dispatch Power Markets
Supervisors: Line Roald

Andrew Morrison
Optimal trade-off between cost and security - optmizing epsilon
Supervisors: Line Roald, Sidhant Misra (LANL)

Tianshu Pan
Exploring Model Predictive Control Applications for the Gridbox Pilot project

Supervisor: Adrian Hauswirth

Roduner Cattia
Assessment of the cost effectiveness and impact on the reliability of supply of diverse measures in a rural area medium voltage network
Supervisors: Stavros Karagiannopoulos, Efstratios Taxeidis

Nicolas Stocker
Development of a method to build simplified network models through node aggregation with a focus on storage units
Supervisor: Olivier Mégel

Michiel Andres Tavernier
Short-term reliability in distribution grids- Suitable supply restoration concepts taking into account communication requirements
Supervisors: Stavros Karagiannopoulos, Philipp Fortenbacher, Florian Kienzle (ewz), Evdokia Kaffe (ewz)

Damiano Toffanin
Generation of Customer Load Profiles Based on SmartMetering Time Series, Building-Level Data, and Aggregated Measurements
Supervisor: Andreas Ulbig

Diren Toprak
Modeling and validation of time series based distribution grid simulations based on heterogeneous data
Supervisor: Andreas Ulbig

Martin Zellner
Protecting privacy in smart grids via distributed optimization and differential privacy
Supervisors: Tomas Tinoco De Rubira, Melanie Zeilinger

2.5.2 Technology Oriented Master Projects

Alexander Heller
Outdoor Measurement Concept for HVAC / HVDC Corona Effects
Supervisors: Sören Hedtke, Martin Pfeiffer

Stefan Franz
Optimizing HVDC Disconnectors for Bus-Transfer Switching
Supervisor: Andreas Ritter

Doris Ragna Meyer
Partial Discharge Inception Voltage in Partial Vacuum under different Supply Frequencies, Pressures and Voltage Waveforms
Supervisors: Mohamed Rabie, Christian Franck and Andrea Cavallini (University of Bologna)

3. Completed PhD Theses

Impact of Demand and Storage Control on Power System Operation and Dynamics

Candidate:	Theodor Sebastian Borsche
Thesis:	ETH No. 23274
Date of oral exam:	5 February 2016
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Dr. Florian Dörfler, Prof. Christian Rehtanz

Abstract Both the liberalization of electric energy markets and an increasing share of uncertain, distributed electricity generation create new challenges for operation and planning of power systems. All involved stakeholders, that is energy retailers, Transmission System Operators (TSOs) and Distribution System Operators (DSOs), are looking for sources of flexibility to either make the most of economic opportunities or to operate the grid in a more reliable, secure manner.

This thesis is divided into two parts, each looking at control algorithms for and economics of flexibility provision. The first part investigates demand side participation, specifically Direct Load Control (DLC). Business models are collected and potential savings or earnings are estimated. The following chapters are concerned with the technical implementation of DLC. First, a control topology for tracking of a power reference with a large population of household appliances is described. Communication needs are minimized by employing state estimation and local decision making. This approach is then used to reduce schedule deviations of a Balance Group (BG). The last chapter describes an cost-effective scheme to increase the Photo-Voltaic (PV) hosting capacity of Low-Voltage (LV) feeders by shifting flexible demand to hours of excessive PV generation.

The second part focuses on the role of storage systems in frequency control reserve provision. Frequency control is the main tool to ensure the balance between generation and demand on short timescales. Two chapters describe how refrigerators and Battery Energy Storage Systems (BESSs) can participate in primary frequency control, and highlight challenges and technical and economic benefits. As the energy capacity of BESSs is limited, they need to re- or discharge continuously.

The effect of this recharging on secondary control reserves is analyzed in detail, and it is confirmed that BESSs can (and should) be an integral part of reserve capacity. It is further proposed to redefine frequency control products based on frequency bands in order to allow storage systems to seamlessly integrate into ancillary service markets. The thesis closes with an investigation of rotational inertia distribution, and an algorithm to optimally place inertia with respect to both frequency stability and damping of inter-area oscillations.

Frequency Control in the European Power System Considering the Organisational Structure and Division of Responsibilities

Candidate:	Marc Scherer
Thesis:	ETH No. 23490
Date of oral exam:	10 May 2016
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Prof. Kjetil Uhlen

Abstract One of the core responsibilities of a transmission system operator is real-time control of mismatches between scheduled production and actual consumption of electric power, i.e. frequency control. Since the liberalisation of electricity markets and the increase of decentralised intermittent generation, the Continental European power system has been exposed to high and persisting frequency deviations.

This thesis investigates technical and organisational shortcomings of the existing frequency control framework in Continental Europe. The objective is to contribute to future concepts of frequency control that ensure an efficient and high frequency quality in the interconnected power system. Historical data are statistically analysed and used for time-sequential Monte Carlo simulations which enable the investigation of the current frequency control structure as well as frequency control coupling processes in future demand and production portfolios.

Although the domination of hourly imbalance periods and respective hourly products imposes a highly predictable operational pattern, market-induced imbalances have a severe impact on frequency quality. In this context, the benefits of harmonised ramping requirements and the reduction of the imbalance period are discussed. The current frequency control setup can be gradually centralised across Europe. Imbalance and reserve sharing can be practically implemented, and transfer capacities can be managed. Imbalance sharing does not require additional harmonisation of active power reserve processes and products. Reserve sharing, on the contrary, can only be managed on a non-discriminatory and fair basis if the active power reserve dimensioning as well as the activation rules are harmonised to grant a comparable performance.

The findings imply that system operators and national regulatory authorities should focus more closely on the dependency between schedule-based operation and market activity as well as on local active power reserves and cross-border frequency control processes.

On Operational Flexibility in Transmission Constrained Electric Power Systems

Candidate:	Matthias Andrin Bucher
Thesis:	ETH No. 23487
Date of oral exam:	25 May 2016
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Keith Bell

Abstract This thesis deals with operational exibility in electric power systems with high shares of renewable energy sources (RES) and limited transmission capacity and provides tools to address corresponding challenges. Shares of RES, predominantly photovoltaic plant (PV) and wind, have increased in recent years and led to transmission system-related issues, noteworthy, uncertain and intermittent production and high ramping requirements.

This thesis focuses on different aspects of operational flexibility. The first part characterizes four major challenges as a consequence of increasing production from RES. The term locational flexibility is used to emphasize the location-dependency of the available flexibility. A metric to quantify the available flexibility is presented and the effect of the transmission grid on disturbances that can be contained is presented.

The second part is concerned with the allocation of adequate amounts of suitable reserve products to balance all credible deviations. The method considers transmission limits, corrective measures from high voltage direct current (HVDC) links and location-dependent uncertainty characterizations in an adjustable robust optimization. Compared to deterministic procurements, the method enables a more efficient and economical balancing. Many power systems, for example in central Europe, are composed of many control areas. The third part focuses on the coordination of flexibility between transmission system operators. A versatile framework is presented that allows an efficient and decentralized sharing of reserves. The last part presents approaches to increase the operational flexibility. The integration of dynamic line rating in market processes is discussed as a control-based mean to enable more transmission capacity. Two modeling contributions, a model for concentrated solar power units and power-to-gas technologies complete the thesis.

Control of Residential and Commercial Loads for Power System Ancillary Services

Candidate:	Evangelos Vrettos
Thesis:	ETH No. 23554
Date of oral exam:	17 June 2016
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Steven Low, Prof. John Lygeros

Abstract Due to environmental concerns related to burning fossil fuels and nuclear waste disposal, the energy mix has been changing during the last decades with the integration of Renewable Energy Sources (RES). However, RES inject fluctuating electric power into the grid because they depend on the availability of primary natural resources such as wind and solar power. These fluctuating power injections create frequency and voltage deviations from their nominal values, which have to be mitigated to maintain a secure and reliable power supply. Traditionally, the power system operators control the frequency and voltage using active and reactive power reserves offered by conventional generators. Therefore, a large integration of RES will challenge the traditional power system operation because the need for reserves increases and at the same time the portion of controllable generation resources decreases.

Although the traditional operation paradigm in power systems is to dispatch controllable generators to follow a variable electricity demand, it is also conceptually possible to control some portion of the demand to follow a variable generation power infeed. This idea was already proposed in the 1980's, and since then industrial loads participate in programs to support power system operation in many countries. However, there is a lot of potential for reserve provision from residential and commercial loads that remains widely untapped due to challenges related to control complexity, implementation costs, and regulatory aspects.

The main goal of this thesis is to develop methods to enable provision of power system reserves from residential and commercial loads, and verify their suitability for practical implementation in simulation and experimental studies. In addition, this thesis investigates using load control to reduce the electricity cost of individual customers in a way that is beneficial for the power system. We consider thermal loads, such as refrigerators and Electric

Water Heaters (EWHs) in residential buildings, as well as the Heating, Ventilation and Air-Conditioning (HVAC) systems of commercial buildings, because temporary interruptions in their operation are not noticed by the users due to thermal inertia.

The first part of this thesis presents predictive and rule-based controllers to minimize the electricity cost of buildings by shifting the energy consumption to the low-price intervals or consuming the energy produced by rooftop Photovoltaics (PV) within the building premises. The second part of this thesis develops several methods to provide power system Ancillary Services (AS), namely Primary Frequency Control (PFC), Secondary Frequency Control (SFC) and voltage regulation.

More specifically, we propose a decentralized stochastic control method to allow a large aggregation of refrigerators to provide PFC without real-time communication. In addition, we present centralized control algorithms to allow an aggregation of EWHs to track a SFC signal with different levels of information feedback. These algorithms are then extended to account for the constraints of Distribution Networks (DNs) and provide frequency reserves while regulating the DN voltage at the same time. Furthermore, we develop a state estimation method to enable SFC without the need for real-time communication between the central controller and the loads. A main outcome of this thesis is the development of a hierarchical controller to allow aggregations of commercial buildings to provide SFC reserves reliably and accurately, while trying to maximize energy efficiency. The controller's performance is demonstrated in simulations with models of Swiss office buildings, and its technical feasibility is verified in frequency regulation experiments at a commercial building test facility at the Lawrence Berkeley National Laboratory (LBNL).

The results of this thesis show that with proper control design the flexibility of residential and commercial thermal loads can be used to provide reserves to the power system. Moreover, dynamic frequency studies with a two-area power system model show that a large integration of heterogeneous thermal loads in frequency control will help to reduce frequency deviations and enhance frequency stability.

Optimization Methods to Manage Uncertainty and Risk in Power Systems Operation

Candidate:	Line Alnaes Roald
Thesis:	ETH No. 23918
Date of oral exam:	15 November 2016
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Louis Wehenkel, Prof. Dr. Gabriela Hug

Abstract Electricity from renewable energy sources is essential for a sustainable energy future. One inherent property of renewable generation is however that it is partially unpredictable, with uncertainty arising from forecast errors and real-time uctuations. As the share of renewable generation grows, this uncertainty challenges existing practices for electric grid operation.

In the past, the operation of the electric grid was deemed secure if the system could withstand any credible contingency, typically dened as the failure of any single component. With increasing levels of forecast uncertainty, the system experiences larger deviations from the planned operating point. It therefore becomes more important to account for possible adverse impacts of those deviations to ensure that the system will remain secure in real time operation. This thesis is concerned with the development of optimal power ow methods that help system operators manage uncertainty and mitigate risk in day-to-day operational planning.

In the rst part of the thesis, we focus on chance-constrained optimal power ow, which limits the probability of constraint violation. We pro-pose to formulate the problem using separate chance constraints, which are reformulated using an analytical reformulation based on either full or partial knowledge about the uncertainty distribution. The approach allow us to model policy-based control actions in reaction to uncertainty realizations, which contribute to managing and mitigating possible ad-verse impacts. The method is applied to selected cases in power system operations, including investigations of dierent reserve activation policies and corrective control by HVDC connections and phase shifting transformers. These studies show that a more exible system decreases the cost of handling uncertainty. We also develop and demonstrate a solution algorithm that allow us to solve the problem for large systems.

While the above mentioned applications are based on the linear DC power ow equation, we also suggest an extension based on the non-linear AC power ow equations. We model the system using the full AC equations for the nominal operating point, but apply a linearization around this point to represent the impact of uncertainty. Due to the linear dependence on the uncertain variables, we can apply the analytical chance constraint reformulation, which allows for a tractable optimization problem. We further suggest dierent solution approaches, including an iterative approach which leverages scalability of existing solvers to tackle large problems, and compare the suggested analytical reformulation method with two sample-based methods. We nd that the proposed method provides a good performance at low computational cost.

In the second part of the thesis, we focus on risk-based optimal power ow, where risk functions are used to model how the size of constraint violations inuence risk. First, we suggest a method to dene risk functions for post-contingency overloads based on system properties such as cost and availability of remedial actions, and provide a comparison with the N-1 criterion to argue for the choice of risk limits. We further combine the proposed risk functions with a chance constrained optimal power ow to limit the probability of high risk events.

Second, we introduce the weighted chance constraints, which measure and limit the expected risk of constraint violations, as dened by the probability distribution of the forecast errors and the chosen risk function. It is shown that the weighted chance constraint remains convex for convex risk functions and general control polices. We investigate how the choice of a risk function inuences the number and size of constraint violations, and apply the method to a situation where tertiary control is activated during large wind deviations. Further, we investigate the optimal use of active power control from wind turbines, including reserve provision and enforcement of output caps.

4. Research Activities

4.1 High Voltage Gaseous Insulation

Today, predominantly sulfur hexafluoride (SF_6) is used in high-voltage gas insulated equipment (GIS). 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 alternative insulation gases and gas mixtures.

Our group has developed a new procedure to systematically identify and quantify novel molecular gases with low global warming potential for application in high voltage insulation as gas mixtures. Special focus was on a highly efficient procedure to be able to scan a large number of candidate gases. The procedure contains three steps: To identify new molecules, an empirical correlation between the electric strength of a gas and certain molecular properties, like polarisability or dipole moment is established. The properties themselves can be calculated ab-intio by means of density functional theory. This computational pre-screening is applied to large chemical databases to identify new alternative insulation gases. The swarm parameters of these pre-selected molecules in mixtures with buffer gases is 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. Key element of these PT setups is a new photocathode that works with a high quantum efficiency and long lifetime even when exposed to reactive species during the measurements. 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.

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 2016:

M. Rabie, C. M. Franck, "METHES: A Monte Carlo collision code for the simulation of electron transport in low temperature plasmas"
We present a freely available MATLAB code for the simulation of electron transport in arbitrary gas mixtures in the presence of uniform electric fields. For steady-state electron transport, the program provides the transport coefficients, reaction rates and the electron energy distribution function. The program uses established Monte Carlo techniques and is compatible with the electron scattering cross section files from the open-access Plasma Data Exchange Project LXCat. The code is written in objectoriented design, allowing the tracing and visualization of the spatio-temporal evolution of electron swarms and the temporal development of the mean energy and the electron number due to attachment and/or ionization processes. We benchmark our code with well-known model gases as well as the real gases argon, N_2, O_2, CF_4, SF_6 *and mixtures of* N_2 *and* O_2.
Computer Physics Communications **203**, pp. 268-277 (2016)

A. Chachereau, J. Fedor, R. Janeckova, J. Kocisek, M. Rabie, C. M. Franck, "Electron attachment properties of c-C4F8O in different environments"
The electron attachment properties of octafluorotetrahydrofuran (c-C4F8O) are investigated using two complementary experimental setups. The attachment and ionization cross sections of c-C4F8O are measured using an electron beam experiment. The effective ionization rate coefficient, electron drift velocity and electron diffusion coefficient in c-C4F8O diluted to concentrations lower than 0.6 % in the buffer gases N2, CO2 and Ar, are measured using a pulsed Townsend experiment. A kinetic model is proposed, which combines the results of the two experiments.
J. Phys D: Applied Physics **49**, 375201 (12) (2016)

M. Rabie, C. M. Franck, "A study of the avalanche-to-streamer transition in arbitrary gases by particle simulation"
We systematically investigate the avalanche-to-streamer transition (AST) over a wide range of pressures and homogenous background electric fields and for a comprehensive list of gases, namely pure nitrogen, carbon dioxide, oxygen, argon, sulfur hexafluoride and synthetic air. The discharge starts from an initial seed electron and is temporally followed from the avalanche regime, through the first significant distortion of the background field and the subsequent increasing deviation from the Gaussian electron density profile, up to the occurrence of runaway electrons accompanied by the sudden and dramatic increase of electron energy and electron number multiplication. We detect weak influence of the background electric field value and the gas composition, but strong influence of the gas density on the electron num-

ber at which the transition occurs. The simulations are performed by means of a fully-interacting particle simulation program that combines a particle-in-cell/Monte Carlo collision model (PIC/MCC) with a three-dimensional Poisson solver in order to account for the space charge generated by the electrons and ions. The freely-available program is based on the METHES code and is universally applicable to arbitrary gas mixtures with complete cross section sets.
J. Phys D: Applied Physics **49**, 175202 (2016)

L. C. Pitchford, et al., "LXCat : an open-access, web-based platform for data needed for modeling low temperature plasmas"
LXCat is an open-access platform (www.lxcat.net) for curating data needed for modeling the electron and ion components of technological plasmas. The data types presently supported on LXCat are scattering cross sections and swarm/transport parameters, ion-neutral interaction potentials, and optical oscillator strengths. Twenty-four databases contributed by different groups around the world can be accessed on LXCat. New contributors are welcome; the database contributors retain ownership and are responsible for the contents and maintenance of the individual databases. This article summarizes the present status of the project.
Plasma Processes and Polymers, 14, 1600098 (2017)

A. Chachereau, M. Rabie, C. M. Franck, "Electron swarm parameters of the hydrofluoroolefine HFO1234ze"
In this contribution, the electron swarm parameters of the hydrofluoroolefine HFO1234ze (systematic name trans-1,3,3,3-tetrafluoro-1-propene) are experimentally investigated. The analysis of the electron avalanche current measured in a pulsed Townsend experiment yields the effective ionization rate coefficient, the electron drift velocity and the longitudinal electron diffusion coefficient. The subsequent ion current is analyzed as well, to obtain separately the ionization and attachment rate coefficients. Measurements in pure HFO1234ze at different pressures show that the effective ionization rate is strongly influenced by three-body attachment and the three-body attachment rate coefficient is derived.
Plasma Sources Science and Technology **24**(4), pp. 12 (2016)

4.2 Switching in HVDC Systems

The need for switchgear for use in future multi-terminal HVDC grids is widely established today. 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. Transient simulations are performed to predict the current interruption requirements and experimental tests are performed to investigate the physical processes in the switchgear during 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.

Up to now, no fully satisfying solution for fault current interruption in HVDC systems is commercially available. However, 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. But so far it is not possible to use these breakers to interrupt the current in case of a fault in reasonable time. 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. 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.

Hybrid HVDC CB aim to combine the low on-state losses of mechanical switching devices with the fast switching times of semiconductor 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*

Publications In this research area, the following publications have been published in 2016:

M. K. Bucher, C. M. Franck, "Analytic Approximation of Fault Current Contributions from AC Networks to MTDC Networks During Pole-to-Ground Faults"
HVDC short-circuit calculation standards will be required to simplify the dimensioning and selection of circuit breakers (CBs) in future HVDC networks. This paper proposes new analytical formulas for the calculation of the ac-side contribution through the blocked half-bridge-based converters during pole-to-ground faults in multiterminal HVDC cable networks. Analytic approximations are derived for the steady-state short-circuit currents and the peak of the transient response for point-to-point HVDC links and extended to multiterminal HVDC cable networks with arbitrary grid topology. The results of the proposed expressions are compared with simulations in PSCAD and provide accurate calculations for the transient peak and steady-state values of the ac-side fault current contribution to the prospective CB current.
IEEE Transactions on Power Delivery **31**, Vol 1, pp. 20-17 (2016)

M. K. Bucher, C. M. Franck, "Fault Current Interruption in Multiterminal HVDC Networks"
In a multiterminal HVDC network, dc circuit breakers (CBs) are required at each end of a line to selectively isolate a fault. Several CB concepts have been implemented in PSCAD, which differ significantly in their structure and performance. This paper describes the interaction of the different HVDC CB topologies with a meshed four-terminal network and assesses their performance in terms of maximum currents and voltages. The tradeoff between network parameters and CB requirements is analyzed.
IEEE Transactions on Power Delivery **31**, Vol 1, pp. 87-95 (2016)

A. Ritter, U. Straumann, C. M. Franck, "Novel Method of 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, doi: 10.1109/TPWRD.2016.2609682 (2016)

T. Schultz, C. M. Franck, "Interruption Capability Investigations of a Model Gas Circuit-Breaker for HVDC Switching Applications"
Hybrid HVDC circuit breaker topologies aim to combine the advantages of low loss mechanical switches and high speed power electronics. The performance of the breaker is largely dependent on the behaviour of the mechanical switch. In this paper, a model gas circuit breaker (GCB) is developed for the use in HVDC applications. In a test circuit, the interruption capability of the model GCB is investigated for a set of blowing pressures and current steepness at zero crossing. These investigations are the basis for a future use in HVDC switching applications.
21st International Conference on Gas Discharges and Their Applications, September 11 - 16, Nagoya, Japan (2016)

T. Schultz, V. Lenz, C. M. Franck, "Circuit Breakers for Fault Current Interruption in HVDC Grids"
Today, the interest in HVDC connections is growing throughout the world. First multi-terminal HVDC networks based on VSC technology have been built already and the need for HVDC circuit breakers with extremely fast reaction time is increasing. This contribution is introduced by an overview of factors that influence fault currents in HVDC networks and a comparison to frequently used test currents. In the following, the dimensioning of different circuit breaker topologies is explained using an example fault current. After comparing the interruption performance of selected topologies, the influence of changes in the fault current on the topology dependent interruption behavior is qualitatively discussed. A comparison with currently used test currents indicates, in which areas further investigation is needed.
VDE Fachtagung Hochspannungstechnik 2016, November 14 - 16, Berlin,

Germany (2016)

L. Bort, C. M. Franck, "Effects of Nozzle and Contact Geometry on Arc Voltage in Gas Circuit-Breakers"
At the high voltage laboratory at ETH Zurich switching arcs are investigated in order to understand the physical processes that determine the relationship between current and arc voltage in gas blast circuit breakers. Experiments are performed using a breaker prototype with many independently controllable parameters, and very versatile pulsed DC current source. Previous work showed that the gas pressure has a strong influence on the arc voltage, therefore changing the fluid dynamic conditions in which the arc burns can be used to create different dU/dI characteristics. In the presented paper a method to quantify these changes is presented, and the impact of the axial position of the contacts in a model gas circuit breaker on the voltage as function of current are discussed. The influence of the contact position on the average dU/dI curve were small, but the fluctuations around this average value change depending on the nozzle section in which the arc burns. These results will be used to improve the theoretical understanding of the different arc cooling mechanisms, which in turn should enable the design of new geometries that result in a more favorable arc voltage characteristics for passive oscillation HVDC circuit breaker topologies in the future.
2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE), September 19 - 22, Chengdu, PR China (2016)

A. Ritter, L. Bort, C. M. Franck, "Five Years of Pulsed Current Testing for HVDC Switchgear"
Since passing its commissioning tests in early August 2011, the flexible pulsed dc current source (FPDCS) at ETH's high voltage laboratory has enabled research in different areas of HVDC switchgear as well as its applications with an unprecedented variability and flexibility, establishing many new research opportunities. Over the course of five years of continuous use, a significant number of incremental upgrades were made to hardware, software and to the application practices. Different fields of application were identified and a number of future upgrades were determined, when testing circuit-breaker components, disconnectors and even power semiconductors using FPDCS. In this publication, we strive to share our experiences and recommendations for construction, operation and enhancement of similar current sources for research, development and commercial operation.
2016 IEEE International Conference on High Voltage Engineering and Application (ICHVE), September 19 - 22, Chengdu, PR China (2016)

4.3 Future Overhead Power Transmission Lines

Challenging goals of the climate and energy policy of governments and deregulated electricity markets involve a growth of the electrical energy demand. Besides stronger use of decentralised renewable energy sources, energy is also produced in large scale (offshore) wind and solar parks. This requires an increase of the transmission network capacity. Since restrictions and public acceptance deter utilities from quickly building new overhead lines (OHLs), up-grading and efficient use of existing lines are important topics. Projects in this area research the possibility of increasing the transmission capacity of existing line without (or with minimum) constructional changes. In collaboration with partners, the public acceptance of these new technical solutions is investigated and acceptance critical constraints are influencing the technical optimisation procedures. 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. 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. Due to these assumptions the transmission capacities of OHLs are not only most of the time below their real value, but also (e.g. during low wind periods) they exceed their real values for some periods. 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.

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. Buehlmann, C. Sören Hedtke*

Publications In this research area, the following publications have been published in 2016:

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 -2.4)° C during the day and (0.5 - 1.1)° C during the night.
Cigré Science & Engineering **4**, pp. 53-62 (2016)

M. D. Pfeiffer, T. Schultz, C. S. Hedtke, C. M. Franck, "Explaining the impact of conductor surface type on wet weather HVDC corona characteristics"
Corona of HVDC overhead-lines is important in the planning of transmission corridors. Effects that need to be considered include corona losses (CL), audible-noise (AN), radio-interference (RI) and ground level ion currents. Water on conductor surfaces influences these quantities. It was previously shown that certain conductor surfaces lead to considerable reductions in wet weather CL. This publication studies the causes of these differences using optical methods. A key finding is that the size of water drops is decisive for differences in CL. Furthermore, different discharge mechanisms are shown to be the reason for differences in AN during and after rain showers.
Journal of Electrostatics **79**, pp. 45-55 (2016)

M. Frigerio, P. B. Buehlmann, J. Buchheim, S. R. Holdsworth, S. Dinser, C. M. Franck, K. Papailiou, E. Mazza, "Analysis of the

tensile response of a stranded conductor using a 3D finite element model"
A 3D finite element modelling approach is proposed to investigate the axial force-elongation behaviour of a stranded conductor used for high voltage overhead lines. An all aluminium alloy conductor (AAAC), a four-layer conductor, is analysed based on the stress-strain response measured for individual wires. The aim of the model is to reproduce the complex deformation mechanisms and non-linearities associated with the helical shape of the wires, their contact interactions and the residual stress state from the manufacturing process. The latter is included in the model through a simulation of the stranding procedure. Simulations of the tensile response are compared to corresponding measurements. The results demonstrate improved predictive capabilities of the finite element model when compared to analytical formulae, and show that inelastic elongation at load levels significantly below the nominal yield strength of the constituent wires can be rationalized when residual stresses from the manufacturing process are included in the calculation.
International Journal of Mechanical Sciences **106**, pp. 176-183 (2016)

J. Rodriguez Alvarez, J. Azurza Anderson, C. M. Franck, "Validation of a Thermal Model for Overhead Transmission Lines at High Conductor Temperature"
Incorporating a growing number of renewable energy sources into the existing transmission grids will require an optimal use of the network infrastructure. For transmission lines which are limited by a maximum conductor temperature, the maximum current capacities can be optimized by implementing a Dynamic Line Rating (DLR) scheme. In a DLR scheme the current (or predicted) weather conditions are input to a thermodynamical model of the transmission line, and the output of this model is the present (or future) maximum current capacity of the line. Nevertheless, several transmission system operators are concerned about the reliability of the thermal model at high conductor temperatures. In this contribution, the new outdoor test facility for conductors which was built in ETH is presented. Then, using data acquired in this facility, it is shown that the thermodynamical model introduced here provides a satisfactory description at high conductor temperatures.
2016 IEEE PES General Meeting, July 17 - 21, Boston, MA, USA (2016)

C. S. Hedtke, M. D. Pfeiffer, T. Gaillard, C. M. Franck, "Effect of electrostatic induction and space charges on the audible corona noise of hybrid AC/DC transmission lines"
In contrast to an increasing demand for electric power transmission capacity, the public acceptance for new overhead lines is very low. The concept

of hybrid overhead lines, combining high voltage alternating current (AC) and direct current (DC) transmission on the same existing tower infrastructure, allows to increase the transmission capacity without the need for new lines. However, the altered conductor arrangement with the possible consequence of small separation distances between AC and DC systems on the same side of the tower will influence environmental corona effects via coupling between adjacent bundles. One very important design criterion for high voltage overhead lines is the audible corona noise (AN), which is therefore investigated in this contribution with regard to hybrid AC/DC overhead lines. Through electrostatic induction, the presence of an AC conductor will increase the maximum electric field on an adjacent DC conductor and vice versa. Furthermore, the bipolar ion drift between coronating AC and DC lines affects the space charge density in the conductor vicinity and, thus, also the electric field. Still, literature on these coupling effects with regard to AC and DC AN is very limited and some of the results were not consistently observed. A hybrid laboratory test setup consisting of two parallel conductors was implemented to separate the influence of a pure electrostatic induction from the additional impact of space charge. Therefore, artificial defects on the conductors are applied to control the state of corona of both lines individually. Regarding a pure positive DC bias on the adjacent AC conductor, the observed increase in AN was very significant around the AC corona onset. However, this effect was barely measurable in case the AC voltage was further increased above the onset voltage. Similarly, also a pure AC ripple caused the DC audible noise to increase. Again, the impact was highest around the DC corona onset voltage. Still, also for higher DC voltage a measurable increase was detected for a relatively low AC field ripple. For both, the AC and DC AN, the impact of an adjacent conductor was enhanced if both conductors were coronating and, hence, exposed to space charge in addition to the field coupling.
2016 Cigré IEC Colloquium, May 9 - 11, Montreal, Canada (2016)

P. B. Buehlmann, M. Meier, M. Vifian, M. Mazza, C. M. Franck, "Temperature Profile along an Overhead Line Conductor in and near the Tension Clamp"
Difficulties of building new overhead-lines and the increasing need for more electric power challenge the transmission grid of Switzerland and other countries. Therefore, it is required to improve the efficiency, safety and reliability of the existing lines. Changing from static to dynamic line rating can contribute to the solution, but this can lead to an operation of the overhead line closer to its thermal limits. As the maximum conductor temperature is a major limitation, the longitudinal conductor profile is measured in and near the tension clamp. This zone is studied because of the locally occurring

elevated stresses and strains caused by the tensile and compression force induced by the clamp. The analysis should serve for the lifetime prediction of the existing lines, where the long-term material weakening and creeping are important and strongly depend on stress, strain and temperature. Since this study is aimed for the Swiss transmission grid, an all-aluminum alloy conductor with a core wire and four outer layers is investigated at laboratory conditions at a constant ambient temperature of $21.5^\circ C$. *The steady-state temperature is measured at the surface of the conductor with thermocouples that are fixed in drilled holes of 1 mm diameter and depth. The 15 thermocouples are installed within the wedge clamp and in the thermal transition zone between the clamp and the point where the influence of the clamp is negligible. The tensile force is varied from 2 to 24 kN and an alternating current of 560, 780, and 880 A is used to heat the conductor. The high values of the tensile force and current are chosen according to a possibly extreme but realistic scenario. Qualitatively, the shape of the longitudinal temperature profile along the thermal transition zone is measured to be the same for all cases. Beyond a distance of 120 cm from the clamp, its influence on the conductor temperature is negligible. The variation of the tensile force has a rather small impact on the longitudinal conductor temperature profile with a maximum change of* $1^\circ C$ *in the free span at 880 A. By increasing the electric current, the conductor temperature rises at all points. The rise of temperature is largest in the free span and lowest inside the clamp. The largest temperature gradient occurs next to the clamp and decreases in an exponential manner towards the temperature in the free span. The temperature difference between the clamp and the free span decreases with decreasing current. For the highest measured current of 880 A, the temperature in the free span is* $73^\circ C$ *and* $50^\circ C$ *within the clamp. This significant reduction of* $23^\circ C$ *at the clamp can be caused by decreased Joule heating and increased convective cooling due to the larger cross-section and surface of the wedge clamp, respectively. The direct current resistance was measured for obtaining a first approximation of the lowered Joule heating. The averaged DC resistance of the conductor with the clamp is* $34\,\mu\Omega/m$ *and therefore approx. 41 % lower than the* $58\,\mu\Omega/m$ *resistance of the conductor in the free span.*

Cigré Session 2016, B2-305, August 21 - 28, Paris, France (2016)

4.4 High Voltage Solid Insulation

4.4.1 High Voltage DC Stress

With the use of power electronic devices, 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. 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. 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*

Publications The following publications have been published in 2016:

T. Guillod, R. Färber, U. Krismer, C. M. Franck, J. W. Kolar, "Computation and Analysis of Dielectric Losses in MV Power Electronic Converter Insulation"
The newly available Medium Voltage (MV) Silicon-Carbide (SiC) devices enable a great extension of the design space of MV inverters. This includes the utilization of unprecedented blocking voltages, higher switching frequencies, higher commutation speeds, and high temperature operation. However, all these factors considerably increase the insulation stress. This paper details the computation of dielectric losses, which are directly related to the insulation stress and can be used for the insulation design and diagnostic. After a review of the method used to compute dielectric losses, scalable analytical expressions are derived for the losses produced by PWM waveforms of DC-DC, DC-AC, and multilevel DC-AC inverters. Finally, a Medium-Frequency (MF) transformer is analyzed and the impacts of the insulation material and the operating temperature on the dielectric losses are discussed. It is found that the insulation losses can represent a significant share (17 %) of the total transformer losses.
2016 IEEE Energy Conversion Congress and Exposition, September 18 - 22, Milwaukee, WI, USA (2016)

R. Färber, C. M. Franck, "Modular Arbitrary Waveform Dielectric Spectrometer for Aging Diagnostics of Recessed Specimens"
The advent of solid-state switches with blocking voltages in excess of 10 kV and new medium-voltage multi-level converter topologies raise issues with respect to the long-term endurance of the high voltage insulation systems exposed to the high-frequency pulse-shaped voltage stresses. In this paper we present a modular dielectric spectrometer specifically designed for aging studies on recessed polymeric specimens. Its aim is to quantify the pre-breakdown degradation caused by repetitive pulsed high-voltage stresses by using the complex dielectric permittivity as an aging marker. Moreover, its ability to operate with multi-frequency excitation voltages allows investigations on the possibility of using dielectric spectroscopy as an online monitoring tool for insulation systems exposed to the mentioned stresses. In this contribution a detailed description of the setup and a characterization of its accuracy and precision for sinusoidal excitations is given. It is shown that despite the small specimen capacitances of a few pF, the loss factor can be resolved with a precision of 10^{-4} *for frequencies ranging from 10 Hz up to 600 kHz.*
CEIDP 2016, Conference on Electrical Insulation and Dielectric Phenomena, October 16 - 19, Toronto, Canada (2016)

4.5 Optimal Power Flow and System Operation

The electric power system is a highly complex system governed by non-convex physical equations. Despite decades of research in Optimal Power Flow, it is still a challenge to efficiently solve this non-convex optimization problem. The recent increase in variable renewable generation has further increased the problem complexity due to the inherent stochastic nature of these resources that needs to be incorporated into the problem formulation. To ensure the optimal and most efficient use of existing and new technologies, it is of utmost importance to find suitable formulations and efficient solution approaches in order to operate the system at the optimal operating point or at least close to it and guarantee a reliable supply of the demand. It has also been recognized that the electric power system is only part of an intercoupled energy system and a joint consideration of these coupled systems such as the gas, heat and electricity system can provide opportunities for leveraging the capabilities of one system, e.g. flexibility, to resolve issues in the other system.

A potential approach to efficiently solving the Optimal Power Flow problem is to use a piecewise linear approximations of some of the constraints which introduce some inaccuracies but provide significant advantages with regards to solution times. Depending on how the constraints are linearized, the inaccuracies can be minimized and feasibility can be assured while still benefiting from a significant speed up. Another potential approach is to develop online optimization approaches that use the physical system as the solution engine of the physical equations. The result is a real-time feedback controller that provides continuous solutions to optimal power flow problems as the load in the system changes. The application of the theory of optimization over manifolds enables the development of such controllers.

Stochastic optimization lies at the heart of the integration of variable renewable generation. There are a variety of ways how the stochastic nature of these resources can be incorporated. One approach is the formulation of probabilistic constraints which require an analytical reformulation to enable a tractable and efficient solution process. Another option is to include expectation terms in the objective function as well as in the constraint set but then use a noisy gradients approach to find the solution of the resulting problem instead of reverting to a scenario based approach.

An important role in studying and evaluating proposed changes to system operation is the availability of a comprehensive modeling and simulation platform of the electric power system. As the distribution grid also becomes more active and market mechanism dictate the power dispatch, the simulation ideally includes the various layers from distribution to transmission and generation to the markets. Consequently, the development of such a platform supports a wide range of other research but necessitates research in its own. To further broaden the scope of system modelling, the gas system can be modelled as a system directly coupled to the electric power system. With regards to this, it needs to be studied how the different time constants in the networks affect the dynamics and interactions among the systems.

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: *Xuejiao Han, Michael Händel, Adrian Hauswirth, Evangelos Kardakos, Olivier Mégel, Conor O'Malley, Line Roald, Dmitry Shchetinin, Tomas Tinoco De Rubira*

Partnership: *ETH Control Laboratory, Frauenhofer 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 2016:

Olivier Mégel, Johanna L. Mathieu, Göran Andersson, "Reducing the Computational Effort of Stochastic Multi-Period DC Optimal Power Flow with Storage"
Due to the increase of intermittent renewable energy sources, it is becoming more important to consider renewable generation forecast error when solving the optimal power flow (OPF) problem. The stochastic OPF, which uses multiple forecast scenarios, generally leads to a lower cost compared to the standard deterministic OPF, which uses a single forecast. However, the stochastic OPF is computationally more demanding than the deterministic OPF. Both cost savings and computation times further increase when storage units or ramp-constrained generators are included, as they require solving a multi-period OPF problem. Our contribution is a hybrid method approaching the cost performance of the stochastic OPF while maintaining a computational burden close to the deterministic OPF. The method combines elements from both the stochastic and the deterministic OPF, and relies on Benders Cuts to interface them. Using a receding horizon approach over one year, we find that, based on eleven test cases, one version of our hybrid method leads to at least 70% of the cost improvement of the stochastic OPF, while the computation time increase is at most 40% of the stochastic OPF time increase. Furthermore, the computational advantage of our method increases with the system size. Two different versions of the method allow favoring of either the computational improvement or the cost improvement. We also identify directions for further improvement. Finally, our method can be used for more general problems in which one wishes to combine two models with different levels of complexity.
Power Systems Computation Conference (PSCC), June 20-24, Genova, Italy (2016)

A. Hauswirth, S. Bolognani, G. Hug, and F. Dörfler, "Projected

Dynamical Systems on Riemannian Manifolds with Applications to Power Systems Optimization"
Motivated by online optimization problems arising in nonlinear power system applications, this article concerns optimization over closed subsets of Riemannian manifolds. Compared to conventional optimization over manifolds, we explicitly consider inequality constraints that result in a feasible set that is itself not a smooth manifold. We propose a continuous-time projected gradient descent algorithm over the feasible set and show its well-behaved convergent behaviour. Under mild assumptions on the non-degeneracy of equilibria we show that points are local minimizers if and only if they are asymptotically stable. The proposed algorithm can be implemented as a real-time feedback control law on a physical system. This approach is particularly appropriate for online load flow optimization problem in power systems, in which the state of the grid is naturally constrained to the manifold that represents the solution space to the nonlinear AC power flow equations. We specialize our approach for the case of power distribution systems that need to respect operational constraints while being economically efficient, and we illustrate the resulting closed-loop behaviour in simulations.
54th Annual Allerton Conference on Communication, Control, and Computing, September 27-30, Allerton, IL, USA (2016)

Michael Tschampion, Matthias A. Bucher, Andreas Ulbig, Göran Andersson, "N-1 Security Assessment Incorporating the Flexibility Offered by Dynamic Line Rating"
With increasing shares of renewable energy sources (RES) and intensified electricity trading, the transmission system is operated closer to its limits. Dynamic line rating (DLR) can be used to obtain additional transmission capacity on existing lines by considering current meteorological factors. DLR is hence in general less conservative than nominal line rating (NLR). In this paper an approach on how to include DLR in a N-1 secure dispatch optimization is presented. The evolution of the conductor temperature is simulated and the power flow is then guided by constraints on the conductor temperature rather than by the traditional NLR setting the limit on power flow. Two approaches on N-1 security are described, where either a steady-state or a dynamic conductor temperature calculation is employed. The method is evaluated in case studies regarding RES integration, dispatch cost and computation time using historic load profiles and meteorological data.
IEEE Power and Energy Society General Meeting, July 17-21, Boston, Massachusetts, USA (2016)

Matthias Bucher, Miguel Ortega-Vazquez, Daniel Kirschen, Göran Andersson, "Robust Allocation of Reserves Considering Different Reserve

Types and the Flexibility from HVDC”
Since the production of electric power from renewable resources is intrinsically variable and uncertain, it creates difficulties in balancing demand and generation. On the one hand, the ensemble of dispatchable resources is being required to provide larger and more frequent ramping capabilities. On the other hand, the transmission grid is operated closer to its limits on a more frequent basis. These two factors require a reassessment of the techniques used to provide and ensure the deliverability of reserves and flexibility. In this paper we present an adjustable robust approach for the procurement of reserve, as well as for the repartition of this reserve between manual and policy-based automatic reserves. This approach takes into consideration the location and temporal evolution of the uncertainty on the generation sources and the flexibility offered by HVDC interconnections. The resulting problem is solved iteratively. Case studies compare policy and non-policy based reserves, the allocation of ramping capacity and the resulting operational cost.
IET Generation, Transmission & Distribution, accepted manuscript (2016)

Dmitry Shchetinin, Gabriela Hug, “Decomposed algorithm for risk-constrained AC OPF with corrective control by series FACTS devices”
Maintaining a desired level of security in a power system while maximizing its efficiency is a cornerstone of system operation. In recent years, system security has been jeopardized by increasingly variable power flow patterns caused by renewable generation and market liberalization. One potential solution is to employ corrective power flow control by means of series FACTS devices. However, this requires solving a complex optimization problem, which is difficult to do quickly for large-scale power systems. While several decomposition strategies have been proposed to address this issue, existing approaches rely on a DC approximation of a power system model and thus do not fully capture system's behavior. This paper presents a decomposed iterative algorithm for the probabilistic security-constrained OPF problem, which is formulated for an AC model of a power grid with series FACTS devices and outages of more than one element as credible contingencies. The algorithm is based on so-called locational security impact factors, which represent sensitivities of the security index to changes in generator outputs. The IEEE 24-bus and 118-bus systems are used to examine the effectiveness of the proposed method and to analyze the effect that series FACTS devices have on security and efficiency of system operation.
Electric Power Systems Research **141**, pp. 344-353 (2016)

Tomas Tinoco De Rubira, Gabriela Hug, “Adaptive certainty-equivalent approach for optimal generator dispatch under uncertainty”
The large-scale integration of renewable energy sources, in particular wind

and solar, poses many challenges to power grid operations due to their stochastic and highly-variable nature. One of such challenges is the high cost associated with making real-time power balancing adjustments in order to compensate for forecast errors in renewable powers. To overcome this challenge, stochastic optimization techniques have been explored in the literature for planning generator dispatches taking into account renewable energy uncertainty and balancing costs. The techniques used are typically based on forming Sample Average Approximations (SAA) and applying deterministic optimization techniques that exploit the problem structure. In this work, the performance of alternative algorithms based on Stochastic Approximation (SA) and hybrid techniques for solving the stochastic optimal dispatch problem is analyzed. More specifically, an approach based on updating the certainty-equivalent problem with noisy gradient observations is compared against the stochastic gradient and two SAA-based algorithms on four test cases. This approach is shown to be equivalent to a stochastic proximal gradient algorithm with a non-Euclidean metric when applied to the stochastic optimal dispatch problem. The results obtained show that the adaptive certainty-equivalent algorithm produces better iterates compared to the other algorithms on the test cases considered.
European Control Conference (ECC 2016), June 28-July 1, Aalborg, Denmark (2016)

L. Roald, S. Misra, T. Krause and G. Andersson, "Corrective Control to Handle Forecast Uncertainty: A Chance Constrained Optimal Power Flow"
Higher shares of electricity generation from renewable energy sources and market liberalization is increasing uncertainty in power systems operation. At the same time, operation is becoming more flexible with improved control systems and new technology such as phase shifting transformers (PSTs) and high voltage direct current connections (HVDC). Previous studies have shown that the use of corrective control in response to outages contributes to a reduction in operating cost, while maintaining N-1 security. In this work, we propose a method to extend the use of corrective control of PSTs and HVDCs to react to uncertainty. We characterize the uncertainty as continuous random variables, and define the corrective control actions through affine control policies. This allows us to efficiently model control reactions to a large number of uncertainty sources. The control policies are then included in a chance constrained optimal power flow formulation, which guarantees that the system constraints are enforced with a desired probability. By applying an analytical reformulation of the chance constraints, we obtain a second-order cone problem for which we develop an efficient solution algorithm. In a case study for the IEEE 118 bus system, we show that cor-

rective control for uncertainty leads to a decrease in operational cost, while maintaining system security. Further, we demonstrate the scalability of the method by solving the problem for the IEEE 300 bus and the Polish system test cases.
IEEE Transactions on Power Systems (in press) (2016)

A. Zlotnik, L. Roald, S. Backhaus, M. Chertkov and G. Andersson, "Coordinated Scheduling for Interdependent Electric Power and Natural Gas Infrastructures"
The extensive installation of gas-fired power plants in many parts of the world has led electric systems to depend heavily on reliable gas supplies. The use of gas-fired generators for peak load and reserve provision causes high intraday variability in withdrawals from high-pressure gas transmission systems. Such variability can lead to gas price fluctuations and supply disruptions that affect electric generator dispatch, electricity prices, and threaten the security of power systems and gas pipelines. These infrastructures function on vastly different spatio-temporal scales, which prevents current practices for separate operations and market clearing from being coordinated. In this paper, we apply new techniques for control of dynamic gas flows on pipeline networks to examine day-ahead scheduling of electric generator dispatch and gas compressor operation for different levels of integration, spanning from separate forecasting, and simulation to combined optimal control. We formulate multiple coordination scenarios and develop tractable physically accurate computational implementations. These scenarios are compared using an integrated model of test networks for power and gas systems with 24 nodes and 24 pipes, respectively, which are coupled through gas-fired generators. The analysis quantifies the economic efficiency and security benefits of gas-electric coordination and dynamic gas system operation.
IEEE Transactions on Power Systems, Volume: **32**, Issue: 1, Jan. 2017 (2016)

J. Schmidli, L. Roald, S. Chatzivasileiadis and G. Andersson, "Stochastic AC Optimal Power Flow with Approximate Chance Constraints"
With higher shares of fluctuating electricity generation from renewables, new operational planning methods to handle uncertainty from forecast errors and short-term fluctuations are required. In this paper, we formulate a probabilistic AC optimal power flow where the uncertainties are accounted for using chance constraints on line currents and voltage magnitudes. The chance constraints ensure that the probability of limit violations remain small, but require a tractable reformulation. To achieve this, an approximate, analytical reformulation of the chance constraints is developed based on linearization around the expected operating point and the assumption of normally

distributed deviations. Further, an iterative solution approach is suggested, which allows for a straightforward adaption of the method based on any existing AC OPF implementation. We evaluate the performance of our method in a case study on the 24-bus IEEE RTS96 system. The proposed algorithm is found to converge fast and substantially reduce constraint violations.
IEEE PES General Meeting, 17-21 July, Boston, USA (2016)

A. Zlotnik, L. Roald, S. Backhaus, M. Chertkov and G. Andersson, "Control Policies for Operational Coordination of Electric Power and Natural Gas Transmission Systems"
The abundance of natural gas in the United States and the need for cleaner electric power have prompted widespread installation of gas-fired power plants and caused electric power systems to depend heavily on reliable gas supplies. The use of gas generators for peak load and reserve generation causes high intra-day variability in withdrawals from high pressure gas transmission systems, which leads to gas price fluctuations and supply disruptions that affect electric generator dispatch and threaten the security of both power and gas systems. In this manuscript, we investigate different gas compressor operation policies and their influence on the affected power system. Specifically, we consider constant pressure boost ratios and dynamic adjustment of these ratios to track pressure set-points. We also implement a joint optimization of generator dispatch schedules and gas compressor protocols using a dynamic gas flow model. We develop tractable, physically accurate implementations that are compared using an integrated model of test networks for power and gas systems with 24 and 25 nodes, which are coupled through gas-fired generators. This demonstrates the benefits that can be achieved with globally optimized gas system operations and increased gas-electric coordination.
IEEE American Control Conference (ACC), July 6-8 July, Boston, United States (2016)

G. Chatzis, I. Avrimotis-Falireas, L. Roald, F. Abbaspourtorbati, M. Zima and G. Andersson, "Joint Scheduling of Frequency Control Reserves and Energy Dispatch for Islanded Power Systems"
In this paper, we propose a framework to jointly schedule energy and frequency control reserves in islanded systems, taking into account the system dynamic response. In islanded power systems, the control of system frequency differs considerably comparing to large interconnections, and dynamic models are employed to study the system behaviour. We suggest a way of incorporating relevant aspects of the dynamic response in an optimal power flow formulation, which in addition to including dynamic constraints also accounts for transmission, generation and security constraints. The applicability of the method is demonstrated on the Swiss power system under

a special, critical case where the Swiss system is disconnected from the remaining European grid and energy shortage is a concern. We show that the proposed framework can be successfully applied for the operational planning and allows for a secure and reliable power system islanded operation.
Power System Computation Conference (PSCC), June 20-24, Genoa, Italy (2016)

L. Roald, S. Misra, M. Chertkov, S. Backhaus and G. Andersson, "Optimal Power Flow with Wind Power Control and Limited Expected Risk of Overloads"
Over the past years, the share of electricity production from wind power plants has increased to significant levels in several power systems across Europe and the United States. In order to cope with the fluctuating and partially unpredictable nature of renewable energy sources, transmission system operators (TSOs) have responded by requiring wind power plants to be capable of providing reserves or following active power set-point signals. This paper addresses the issue of efficiently incorporating these new types of wind power control in the day-ahead operational planning. We review the technical requirements the wind power plants must fulfill, and propose a mathematical framework for optimizing wind power control. The framework is based on an optimal power flow formulation with weighted chance constraints, which accounts for the uncertainty of wind power forecasts and allows us to limit the expected risk of constraint violations. In a case study based on the IEEE 118 bus system, we use the developed method to assess the effectiveness of different types of wind power control in terms of operational cost, system security and wind power curtailment.
Power System Computation Conference (PSCC), June 20-24, Genoa, Italy (2016)

K. Sundar, H. Nagarajan, M. Lubin, L. Roald, S. Misra, R. Bent, D. Bienstock, "Unit Commitment with N-1 Security and Wind Uncertainty"
As renewable wind energy penetration rates continue to increase, one of the major challenges facing grid operators is the question of how to control transmission grids in a reliable and a cost-efficient manner. The stochastic nature of wind forces an alteration of traditional methods for solving day-ahead and look-ahead unit commitment and dispatch. In particular, uncontrollable wind generation increases the risk of random component failures. To address these questions, we present an N-1 Security and Chance-Constrained Unit Commitment (SCCUC) that includes the modeling of generation reserves that respond to wind fluctuations and tertiary reserves to account for single component outages. The basic formulation is reformulated

as a mixed-integer second-order cone problem to limit the probability of failure. We develop three different algorithms to solve the problem to optimality and present a detailed case study on the IEEE RTS-96 single area system. The case study assesses the economic impacts due to contingencies and various degrees of wind power penetration into the system and also corroborates the effectiveness of the algorithms.
Power System Computation Conference (PSCC), June 20-24, Genoa, Italy (2016)

L. Roald, T. Krause and G. Andersson, "Integrated Balancing and Congestion Management under Forecast Uncertainty"
Forecast uncertainty related to the power production from renewables frequently leads to significant changes between the scheduled and the actual power injections. Larger and more frequent fluctuations in the power production require new approaches to handle congestion and ensure system security. In this paper, we investigate how different strategies for reserve activation influence the cost of integrating uncertain in-feeds. In particular, we assess under which conditions it is beneficial for the TSOs to balance across a large region and when deviations should be handled close to where they originate. Together with the mathematical formulation of the corresponding OPF model, which involves chance constraints to account for uncertainty, we show how the chance constraints can be reformulated to form a tractable optimization problem. We demonstrate the feasibility of our approach on the IEEE 118 bus system. The case study illustrates in particular the influence of the different balancing policies on the overall system cost as well as on the utilisation of the transmission system. Comparisons are made between the deterministic and the probabilistic approaches in conjunction with the modelled balancing and congestion management schemes. The results show how accounting for congestion when activating reserves can help reducing the overall cost of handling uncertainty.
IEEE EnergyCon, April 4-8, Leuven, Belgium (2016)

4.6 Power System Dynamics and Control

The electric power grid is a dynamical system which is subject to continuous changes and disturbances. Decisions need to be made at various time scales, some referring to steady state and others which ensure the stability of the system. As new technologies penetrate the system, the dynamical reaction of a system to disturbances may change significantly which may require to rethink how the grid is operated. A key issue to address in this regard is the weakening of the inertial response of the power system as more generation sources are connected via power electronic devices.

Frequency so far has been a very important signal measurable throughout the system to adjust the control settings of generators. However, this signal is directly given by the rotational speed of synchronous machines. Hence, the question arises if frequency can still be the dictating signal for short term generation and load balancing in a system with a low number or no synchronous machines and if the traditional stability definitions need to be redefined.

On the other hand, hydro power resources have been and most likely will be important generation resources in a future with high penetration of variable renewable generation as they have a tremendous potential with regards to providing flexible generation. Thereby the optimal coordination of cascaded hydro power plants to maximize their storage and flexibility potential is crucial. This can be achieved by a Model Predictive Control Scheme that incorporates a detailed model including the dependency of the efficiency on the level of discharge, impact on tailrace elevation, etc.

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: *Petros Aristidou, Andrew Hamann, Uros Markovic*

Partnership: *ETH Control Laboratory, 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 transmission networks gradually changes the way TSOs operate the transmission system: system operations and control, together with the changes in protection schemes and the impact on the quality of the delivered power, need to be revisited together with the associated grid codes, this within the framework guidelines which are being adopted at EU level. Since the physical

properties and limitations of converters are very different from the ones of synchronous generators, an evolution of todays control strategies is highly probable. The objective of this project is to develop and validate innovative, technology-based solutions in view of managing the pan-European electricity system experiencing a proliferation of power electronic devices involved in connecting generation and consumption sites.
Funded by Horizon 2020, within WP2 in collaboration with ETH Control Laboratory, RTE, University College of Dublin, Université Lille.

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 2016:

Andrew Hamann, Gabriela Hug, and Stan 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)

Andrew Hamann and Gabriela Hug, “Real-time optimization and simulation of a coordinated hydro-wind system”
This paper discusses the use of cascaded run-of-river hydropower plants to balance wind power variability. We consider a coordinated hydro-wind system in which hydropower is used to firm wind generation at multiple time scales (multi-day, daily, intraday, and hourly) by compensating instantaneous schedule deviations. We use a real-time, sub-hourly optimization scheme to coordinate the operations of the hydropower cascade. This receding horizon control scheme accurately models system hydraulics, hydropower production under time-varying hydraulic head, and all operational constraints. The five municipal hydropower plants on the Mid-Columbia River are used as the hydropower test system, and five-minute wind generation data published by the Bonneville Power Administration is used as the input wind generation signal. The primary contribution of this paper is to evaluate the balancing performance of the hydropower cascade as if it were a battery and to introduce methods for estimating the power capacity, energy storage capacity, and efficiency of the hydropower battery. Simulation results show that the Mid-Columbia can be reasonably said to have balancing power capacity of several hundred MW, energy capacity of several GWh, and round-trip conversion efficiency of approximately 70%. Depending on the chosen modeling assumptions and simulated scenarios, these estimates can be either too conservative or too optimistic, and they are subject to significant uncertainty.
HydroVision 2016, July 27-30, Minneapolis, Minnesota, USA (2016)

Andrew Hamann and Gabriela Hug, “Using cascaded hydropower like a battery to firm variable wind generation”
This paper presents a case study on using a cascaded hydropower system to firm wind generation. We have designed a real-time, sub-hourly optimization scheme for the coordinated control of a hydropower system. The receding horizon control scheme models the nonlinear hydropower production function and system hydraulics. We consider a coordinated hydro-wind system in which hydropower is used to firm wind generation at multiple time scales (multi-day, daily, intra-day, and hourly), balancing deviations from the average production schedule of the wind generation. We use hydro and wind power in the Pacific Northwest region of the United States as a test system, and we evaluate the balancing performance of the hydropower cascade as if it were a battery. The primary contribution of this paper is to introduce methods for estimating the power capacity, energy storage capacity, and ef-

ficiency of a hydropower battery, and to give example calculations for all three metrics.
IEEE Power and Energy Society General Meeting, July 17-21, Boston, Massachusetts, USA (2016)

Andrew Hamann, Gabriela Hug, and Stan Rosinski, "Integrating variable wind power using a hydropower cascade"
In this paper, we examine the ability of a hydropower cascade to balance variability from wind power. We consider a coordinated hydro-wind system that satisfies a single power balance, and we use a real-time control scheme to optimize system operations such that wind and load curtailment is minimized. The control scheme considers system hydraulics (including dynamic tailrace elevations and water travel times) and system constraints. Generation from an individual hydropower plant is modeled using a convex piecewise planar approximation. We give results from a case study involving hydro and wind power in the Pacific Northwest region of the United States. The objective of this paper is to present a framework for evaluating how the regulation of wind generation affects hydropower operations. Our intention is to use this framework in future work to perform a systematic study of balancing capability across different hydraulic conditions, system constraints, and wind generation scenarios.
Energy Procedia **vol. 87**, pp. 108-115 (January 2016)

Michael Koller, Marina Gonzalez Vaya, Aby Chacko, Theodor Borsche, Andreas Ulbig, "Primary control reserves provision with battery energy storage systems in the largest European ancillary services cooperation"
The Transmission System Operators (TSOs) of Germany, Austria, the Netherlands and Switzerland started a joint ancillary services market for Primary Control Reserves (PCR) in April 2015. The participating TSOs are currently discussing the harmonisation of prequalification rules for units with limited storage capacity. The exact terms of these prequalification rules will eventually determine how cost-effective the provision of ancillary services by energy-constrained units is. The paper presents the technical, operational and regulatory suitability of Battery Energy Storage Systems (BESSs) to bid into this largest European ancillary service cooperation, and gives results from the operation of the Zurich 1 MW BESS in this market.
Proceedings of CIGRE Session 2016 (Preprint), August 21-26, Paris, France (2016)

C. Ziras, E. Vrettos, and S. You, "Controllability and stability of primary frequency control from thermostatic loads with delays"

There is an increasing interest in exploiting the flexibility of loads to provide ancillary services to the grid. In this paper we study how response delays and lockout constraints affect the controllability of an aggregation of refrigerators offering primary frequency control (PFC). First we examine the effect of delays in PFC provision from an aggregation of refrigerators, using a two-area power system. We propose a framework to systematically address frequency measurement and response delays and we determine safe values for the total delays via simulations. We introduce a controllability index to evaluate PFC provision under lockout constraints of refrigerators compressors. We conduct extensive simulations to study the effects of measurement delay, ramping times, lockout durations and rotational inertia on the controllability of the aggregation and system stability. Finally, we discuss solutions for offering reliable PFC provision from thermostatically controlled loads under lockout constraints and we propose a supervisory control to enhance the robustness of their controllers.
Journal of Modern Power Systems and Clean Energy, **5:1**, pages 43-54, January 2017 (2016)

Marc Scherer and Göran Andersson, "A Blueprint for the European Imbalance Netting Process using Multi-Objective Optimization"
The concept of imbalance netting is meant to avoid the occurrence of opposing active power reserve activations between control areas that feature a decentralized load-frequency control structure. Upcoming regulations of the European Union are expected to propose this process to European system operators. This paper outlines a basic blueprint for a large-scale imbalance netting process among areas with limited cross-border transfer capacity by means of multi-objective optimization. The algorithm is applied to a model of the European power system in order to test the framework for its practical applicability.
2016 IEEE Energycon Leuven, pages 16, April 4-8, Leuven, Belgium (2016)

Marc Scherer, "Spannungshaltung im Schweizer Uebertragungsnetz - Finanzieller Anreiz für Kraftwerks- und Verteilungsnetzbetreiber"
Im Zuge der Umsetzung des Stromversorgungsgesetzes wurde die Spannungshaltung im Schweizer Uebertragungsnetz als Systemdienstleistung neu konzipiert und wird seit 2009 zentral koordiniert. Mit der Beteiligung von Verteilungsnetzbetreibern an der Spannungshaltung konnte neben der Erfüllung der gesetzlichen Forderung nach Verursachergerechtigkeit und Diskriminierungsfreiheit die Spannungsqualität verbessert werden. Nach einigen Jahren operativen Betriebs kann eine überwiegend positive Bilanz gezogen werden. Allerdings bringt das Konzept tarifliche Herausforderungen mit sich, die eine kontinuierliche Rückführung der Betriebserfahrung und Anpassung an

sich ändernde Marktstrukturen nahelegen.
ew - Magazin für die Energiewirtschaft, Jg. 115(3), Seite 32-35, Februar 2016 (2016)

4.7 Distribution System Applications

Many technologies that make up what is commonly referred to as the smart grid are deployed in the distribution grid: demand side management, distributed generation and storage, sensing and communication technology including smart meters, etc. Consequently, the distribution grid plays an increasingly important role in the management and planning of the overall electric power grid. Traditionally, the distribution and the transmission grids have been studied separately and were basically studied by two different research communities. With the distribution grid becoming more active, the interactions between distribution and transmission grids gain importance. In order to leverage the capabilities provided by a variety of distributed resources, the different layers in the grid need to be carefully coordinated. This is particularly true as more flexibility is needed to integrate variable renewable generation.

While the deployment and usage of smart meters provides many advantages, it also bears risks and challenges. One risk that needs to be addressed is the fact that high resolution demand data enables the extraction of usage patterns and private consumer information. Encryption of such data may protect against third party attackers but it still gives the energy provides unrestricted access to such information. A potential solution is the addition of noise to the actual energy consumption by using a storage device. The objective for the operation of such a storage should be the minimization of privacy leakage. The other side of the coin corresponds to efficiently use the available data for an optimal operation and decision making in the distribution grid. Handling the large amounts of data and turning it into useful information such as load predictions for the coming hours and days is a research question in itself.

As the capabilities in the distribution grids change, also the possibilities to overcome congestions and voltage issues broaden. This on the other hand affects how the infrastructure in the distribution grid should be planned. Active measures such as demand side management or voltage control by distributed generation resources should be considered as a potential replacement for passive infrastructure expansion such as replacing a transformer or a distribution line. Consequently, the planning of distribution grids needs to take into account these active options, meaning that it needs to consider how the grid will be operated in the future and what the controllable elements in the considered feeder are.

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 Karagiannopoulos, Evangelos Kardakos, Evangelos Vrettos, 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.*

Publications In this research area, the following publications have been published in 2016:

Stavros Karagiannopoulos, Petros Aristidou, Gabriela 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, accepted manuscript (2016)

Stavros Karagiannopoulos, Petros Aristidou, Andreas Ulbig, Stephan Koch, Gabriela Hug, "Optimal planning of distribution grids considering active power curtailment and reactive power control"
In this paper, a new planning methodology is proposed for existing distribution grids, considering both passive and active network measures. The method is designed to be tractable for large grids of any type, e.g., meshed or radial. It can be used as a decision-making tool by distribution system operators which need to decide whether to invest in new hardware, such as new lines and transformers, or to initiate control measures influencing the operational costs. In this paper, active power curtailment and reactive power control are taken into account as measures to prevent unacceptable voltage rises as well as element overloads, as these allow postponing network investments. A low-voltage, meshed grid with 27 nodes is used to demonstrate the proposed scheme. In this particular case, the results show that by using control measures, an active distribution system operator can defer investments and operate the existing infrastructure more efficiently. The methodology is able to account for variations in operational and investment costs coming from regulatory influences to provide an insight to the most cost efficient decision.
IEEE Power and Energy Society General Meeting, July 17-21, Boston, Massachusetts, USA (2016)

Philipp Fortenbacher, Martin Zellner and Göran Andersson, "Optimal Sizing and Placement of Distributed Storage in Low Voltage Networks"

This paper proposes a novel algorithm to optimally size and place storage in low voltage (LV) networks based on a linearized multiperiod optimal power flow method which we call forward backward sweep optimal power flow (FBS-OPF). We show that this method has good convergence properties, its solution deviates slightly from the optimum and makes the storage sizing and placement problem tractable for longer investment horizons. We demonstrate the usefulness of our method by assessing the economic viability of distributed and centralized storage in LV grids with a high photovoltaic penetration (PV). As a main result, we quantify that for the CIGRE LV test grid distributed storage configurations are preferable, since they allow for less PV curtailment due to grid constraints.
Power System Computation Conference (PSCC), 20-24 June 2016, Genoa, Italy (2016)

Andreas Venzke, Philipp Fortenbacher, and Göran Andersson, "Optimal Control of Wind Power Systems with Energy Storage"
We investigate how a wind power plant with energy storage can be optimally controlled to comply with power gradient restrictions. For this purpose we use the kinetic energy stored in the turbine rotor and an additional battery storage. As a main contribution we propose a two level control scheme combining a supervisory controller with a low level controller. A model predictive controller acts as a supervisory controller and provides set-points for a low level proportional integral controller. The low level controller applies its input to a higher order wind turbine model in real-time. As a result, the proposed control scheme substantially mitigates power gradients, while keeping energy losses and increased turbine loading to a minimum. For a battery power of 20% the rated wind turbine power, we showed that the maximum power gradient is reduced by 78.5% and the standard deviation by 88.7% compared with a conventional, gainscheduled PI controller.
IEEE EnergyCon, 4-8 April 2016, Leuven, Belgium (2016)

Carsten Heinrich, Philipp Fortenbacher, Alexander Fuchs, and Göran Andersson, "PV-Integration Strategies for Low Voltage Networks"
This paper proposes a method to investigate the potential of Reactive Power Control (RPC) to maximize the utilization of installed PV sources in distribution grids. Different RPC approaches are examined in combination with distributed storage, grid expansions and curtailment. Simulations are carried out on reference distribution grids, representing remote, rural and urban networks. Varying shares of PV penetration and different PV distributions are simulated on a representative irradiance profile. Batteries are optimally dispatched on the basis of load and solar irradiance forecasts using a Model Predictive Control method. Our proposed centralized control scheme deter-

mines optimal active and reactive power trajectories that minimize total operation costs and comply with the grid and storage constraints. The simulation results show, that curtailment and storages can represent a viable alternative to grid expansions, when the PV penetration is moderate. The potential of Reactive Power Control is dependent on the PV distribution and the network.
IEEE EnergyCon, 4-8 April 2016, Leuven, Belgium (2016)

Stavros Karagiannopoulos, Alexandros Rigas, Nikos Hatziargyriou, Gabriela Hug, Alexandre Oudalov, "Battery Energy Storage Capacity Fading and Control Strategies for Deterministic and Stochastic Power Profiles"
As manufacturing costs keep decreasing, battery energy storage systems (BESS) are expected to play a key role in modern grids. However, due to their energy constraints and internal losses, the restoration of the state of charge (SoC) to a reference range is of vital importance to fulfil their tasks. In this paper, we propose SoC control schemes based on existing ones, and then we evaluate their behavior in predictable and stochastic power system applications. The modifications include parameter tuning based on the actual BESS state, as well as alternating the control scheme according to forecasts of the application signal. Furthermore, we extend a Lithium-Ion battery model in order to quantify capacity degradation and hence, investigate the impact of the various SoC restoration strategies. Results show that potentials to increase the lifetime are application dependent, based on the degree of flexibility allowed by a service. Overall, the calendar aging dominates the cycling aging and thus, there is limited space for improvement with different SoC control schemes. On the other hand, by incorporating forecast information, we can reduce the amount of energy needed for the SoC restoration and hence, decrease additional energy costs.
Power Systems Computation Conference (PSCC), June 20-24, Genova, Italy (2016)

Thierry Zufferey, Andreas Ulbig, Stephan Koch, Gabriela Hug, "Forecasting of Smart Meter Time Series Based on Neural Networks"
In traditional power networks, Distribution System Operators (DSOs) used to monitor energy flows on a medium- or high-voltage level for an ensemble of consumers and the low-voltage grid was regarded as a black box. However, electric utilities nowadays obtain ever more precise information from single consumers connected to the low- and medium-voltage grid thanks to smart meters (SMs). This allows a previously unattainable degree of detail in state estimation and other grid analysis functionalities such as predictions. This paper focuses on the use of Artificial Neural Networks (ANNs) for accurate

short term load and Photovoltaic (PV) predictions of SM profiles and investigates different spatial aggregation levels. A concluding power flow analysis confirms the benefits of time series prediction to support grid operation. This study is based on the SM data available from more than 40,000 consumers as well as PV systems in the City of Basel, Switzerland.
European Conference on Machine Learning and Principles and Practice of Knowledge Discovery in Databases, September 19-23, Riva del Guarda, Italy (2016)

E. Vrettos, E. C. Kara, J. MacDonald, G. Andersson, and D. Callaway, "Experimental demonstration of frequency regulation by commercial buildings - Part I: Modeling and hierarchical control design"
This paper is the first part of a two-part series in which we present results from one of the first worldwide experimental demonstrations of frequency regulation in a commercial building test facility. We demonstrate that commercial buildings can track a frequency regulation signal with high accuracy and minimal occupant discomfort in a realistic environment. In addition, we show that buildings can determine the reserve capacity and baseline power a priori, and identify the optimal tradeoff between frequency regulation and energy efficiency. In Part I, we introduce the test facility and develop relevant building models. Furthermore, we design a hierarchical controller for the Heating, Ventilation and Air Conditioning (HVAC) system that consists of three levels: a reserve scheduler, a building climate controller, and a fan speed controller for frequency regulation. We formulate the reserve scheduler as a robust optimization problem and introduce several approximations to reduce its complexity. The building climate controller is comprised of a robust model predictive controller and a Kalman filter. The frequency regulation controller consists of a feedback and a feedforward loop, provides fast responses, and is stable. Part I presents building model identification and controller tuning results. Specifically, we find out that with an appropriate formulation of the model identification problem, a two-state model is accurate enough for use in a reserve scheduler that runs day-ahead. In Part II, we report results from the operation of the hierarchical controller under frequency regulation.
IEEE Transactions on Smart Grid, Early Access Article (2016)

E. Vrettos, E. C. Kara, J. MacDonald, G. Andersson, and D. Callaway, "Experimental demonstration of frequency regulation by commercial buildings - Part II: Results and performance evaluation"
This paper is the second part of a two-part series presenting the results from an experimental demonstration of frequency regulation in a commercial building test facility. In Part I, we developed relevant building models

and designed a hierarchical controller for reserve scheduling, building climate control and frequency regulation. In Part II, we introduce the communication architecture and experiment settings, and present extensive experimental results under frequency regulation. More specifically, we compute the day-ahead reserve capacity of the test facility under different assumptions and conditions. Furthermore, we demonstrate the ability of model predictive control to satisfy comfort constraints under frequency regulation, and show that fan speed control can track the fast-moving RegD signal of the Pennsylvania, Jersey, and Maryland Power Market (PJM) very accurately. In addition, we discuss potential effects of frequency regulation on building operation (e.g., increase in energy consumption, oscillations in supply air temperature, and effect on chiller cycling), and provide suggestions for real-world implementation projects. Our results show that hierarchical control is appropriate for frequency regulation from commercial buildings.
IEEE Transactions on Smart Grid, Early Access Article (2016)

E. Vrettos, C. Ziras, and G. Andersson, "Fast and reliable primary frequency reserves from refrigerators with decentralized stochastic control"
Due to increasing shares of renewable energy sources, more frequency reserves are required to maintain power system stability. In this paper, we present a decentralized control scheme that allows a large aggregation of refrigerators to provide Primary Frequency Control (PFC) reserves to the grid based on local frequency measurements and without communication. The control is based on stochastic switching of refrigerators depending on the frequency deviation. We develop methods to account for typical lock-out constraints of compressors and increased power consumption during the startup phase. In addition, we propose a procedure to dynamically reset the thermostat temperature limits in order to provide reliable PFC reserves, as well as a corrective temperature feedback loop to build robustness to biased frequency deviations. Furthermore, we introduce an additional randomization layer in the controller to account for thermostat resolution limitations, and finally, we modify the control design to account for refrigerator door openings. Extensive simulations with actual frequency signal data and with different aggregation sizes, load characteristics, and control parameters, demonstrate that the proposed controller outperforms a relevant state-of-the-art controller.
IEEE Transactions on Power Systems, Early Access Article (2016)

E. Vrettos, F. Oldewurtel, and G. Andersson, "Robust energy-constrained frequency reserves from aggregations of commercial buildings"
It has been shown that the heating, ventilation, and air conditioning (HVAC) systems of commercial buildings can offer ancillary services to power sys-

tems without loss of comfort. In this paper, we propose a new control framework for reliable scheduling and provision of frequency reserves by aggregations of commercial buildings. The framework incorporates energy-constrained frequency signals, which are adopted by several transmission system operators for loads and storage devices. We use a hierarchical approach with three levels: 1) reserve capacities are allocated among buildings (e.g., on a daily basis) using techniques from robust optimization; 2) a robust model predictive controller optimizes the HVAC system consumption typically every 30 minutes; and 3) a feedback controller adjusts the consumption to provide reserves in real time. We demonstrate how the framework can be used to estimate the reserve capacities in simulations with typical Swiss office buildings and different reserve product characteristics. Our results show that an aggregation of approximately 100 buildings suffices to meet the 5-MW minimum bid size of the Swiss reserve market.
IEEE Transactions on Power Systems, **31:6**, pages 4272-4285, November 2016 (2016)

E. Vrettos, and G. Andersson, "Scheduling and provision of secondary frequency reserves by aggregations of commercial buildings"
Due to thermal inertia, commercial buildings can provide power system frequency reserves with the heating, ventilation and air-conditioning (HVAC) systems. In this paper, we follow up on a recently proposed framework for scheduling and provision of secondary frequency control (SFC) reserves within a building aggregation. We extend this framework with a new reserve scheduling formulation, which is based on a combination of robust and stochastic optimization, to allocate reserve capacities among buildings. The HVAC system setpoints are determined by a model predictive controller, the frequency signal is tracked by heat pump (HP) control with virtually no occupant discomfort, and the tracking quality is evaluated using a dynamic HP model. In simulations, we consider an aggregation of typical Swiss office buildings and compare the robust and stochastic reserve scheduling approaches in terms of performance and complexity. Using the framework, we demonstrate the importance of energy constrained SFC signals and asymmetric reserves with hourly resolution, and we investigate the sensitivity of reserves on the comfort zone's width, capacity payments, and HP constraints. Finally, we show that commercial buildings can track SFC signals well and substitute generators in SFC.
IEEE Transactions on Sustainable Energy, **7:2**, pages 850-864, April 2016 (2016)

1. Q. Hu, F. Oldewurtel, M. Balandat, E. Vrettos, D. P. Zhou, and C. J. Tomlin, "Building model identification during regular opera-

tion - Empirical results and challenges"
The inter-temporal consumption flexibility of commercial buildings can be harnessed to improve the energy efficiency of buildings, or to provide ancillary service to the power grid. To do so, a predictive model of the building's thermal dynamics is required. In this paper, we identify a physics-based model of a multi-purpose commercial building including its heating, ventilation and air conditioning system during regular operation. We present our empirical results and show that large uncertainties in internal heat gains, due to occupancy and equipment, present several challenges in utilizing the building model for long-term prediction. In addition, we show that by learning these uncertain loads online and dynamically updating the building model, prediction accuracy is improved significantly.
American Control Conference (ACC), July 6-8, Boston, USA (2016)

5. Awards and Honours

Göran Andersson
Elected as Foreign Member into the US National Academy of Engineering
Februar 2016

Andreas Venzke
Winner of the Best Paper Award for Optimal control of wind power systems with energy storage," IEEE International Energy Conference (ENERGYCON)
April 2016

Göran Andersson
IEEE PES Prabha Kundur Award for contribution to power system Dynamics, stability and control
Mai 2016

Klaus Fröhlich
Appointed as Guest Professor of the State Key Laboratory of Control and Simulation of Power System and Generation Equipment, Tsinghua University, PR China
June 2016

Gabriela Hug
Young Scientist Participant, Annual Meeting of the World Economic Forum 2016
June 2016

Christian M. Franck
Technical Commitee Award of Cigre in recognition of his outstanding contribution to work of Study Committee A3 - High Voltage Equipment
September 2016

Andreas Ritter
ICHVE 10 Best Student Paper Award for his paper "Five Years of Pulsed Current Testing for HVDC Switchgear", IEEE International Conference on

High Voltage Engineering and Application ICHVE
October 2016

6. Infrastructure

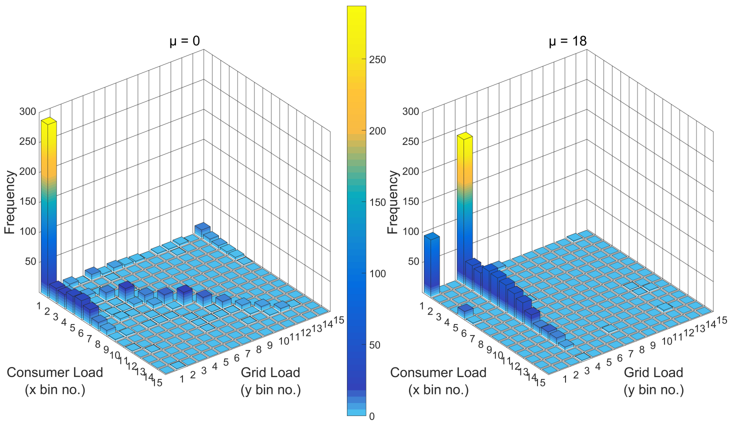
At the institute we have the following main test facilities available for research, teaching and measurements with the following dimensions and characteristics.

- 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
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich