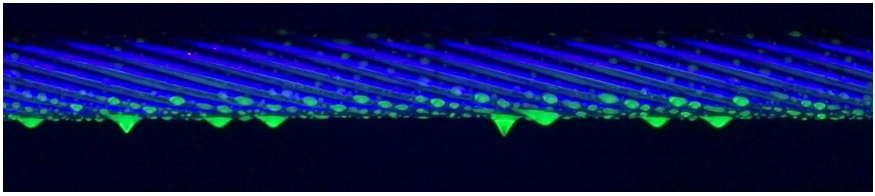
Power Systems and High Voltage Laboratories

Annual Report 2014



eeh elektrische energieübertragung und hochspannungstechnik

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Annual Report 2014

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

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Front Cover: Rain Drop Distribution on an ACSR 265/35 Overhead Line under Positive DC Voltage (25kV/cm Surface Field Strength)

Back Cover: Dependency of Post-contingency Line Flow on Outage Probability and Severity Function

Preface

Dear colleagues and friends of the laboratory!

It is a pleasure to present you our annual report for 2014 of the Power Systems and High Voltage Laboratories. The global interest in energy questions and the challenge of the energy turn around has kept us busy with interesting topics and we are able to look back to our extensive and successful work in research and teaching.

Public and political discussions about the future of our energy supply are still being held and the key role of the electric power system is widely accepted. The details of the planning and building of the necessary infrastructure, in turn, is under intense discussion. In Switzerland, two national research initiatives have been started to support the energy turnaround: the "Swiss Competence Centers for Energy Research (SCCER)" and the "National Research Programmes (NRP)". The EEH institute has successfully applied for projects in both initiatives and a total of 4 Ph.D. students are supported. On the European level, a new EU SET-Plan project was initiated together with five partners from Switzerland, Germany, and the Netherlands.
We are very happy to report that the search for a new professor in Power Systems has been successfully completed. Prof. Gabriela Hug will join us as an associate professor starting in June 2015 as the early succession of Göran Andersson, who will retire from ETH in July 2016. Gabriela is currently an Assistant Professor at Carnegie Mellon University in Pittsburgh (USA) and works in the area of Power Systems, Optimization, Control, Energy Networks, and Decomposition in Optimization.
Moreover, the electric energy area at D-ITET is strengthened with an additional professorship in power semiconductor devices. Prof. Ulrike Grossner will join us as a full professor in February 2015 with a research focus in (wide-bandgap) devices and packaging. She has had a scientific career in academia at the universities of Jena and Oslo, the Paul-Scherrer Institute in Switzerland as well as industrial experience in the research centres of GE and ABB. We are happy to welcome her and are looking forward to extending our collaborative research projects in the energy area also towards the device and insulation level.

In November 2014, the whole Department of Information Technology and Electrical Engineering (D-ITET) was evaluated by a panel of more than a dozen external experts, a procedure that takes place every seven years on behalf of the ETH board. The experts visited also our labs and had discussions with all the professors, some staff members and students. The feedback was very positive and we are encouraged to continue our research plans as intended.
In 2014, six doctoral students finished their research and successfully defended their dissertations. We congratulate (in alphabetical order) Christof Bucher, Matthias K. Bucher, Marcus Hildmann, Emil Iggland, Michael Schueller, and Andreas Ulbig. Doctoral students of our laboratories received in total five research awards for their excellent and dedicated scientific contributions. Researchers from our lab also successfully presented their work at the top international conferences and meetings; in total with more than 44 contributions. In addition, 14 articles were published in peer-reviewed journals.

We would like to thank all researchers and other personnel working at our laboratory, as well as the external lecturers. Without the dedicated and competent work of all co-workers of our laboratory, it would not have been possible to present all the interesting projects and important achievements in research and teaching in this annual report.

Finally, we take the opportunity to thank all our partners from the power industry, universities, and other research institutions for their support and cooperation in numerous research projects. Without the support and input from our partners it would not be possible to do the research we actually do. We look forward to continued cooperation in the future.

G. Andersson C. M. Franck

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1. Organisation

1.1 The Power Systems Laboratory

Head:	Prof. Dr. Göran Andersson
Secretary:	Judith Eberle (December 2014 -) Rita Heigert (- December 2014)
Scientific Staff:	MSc ETH Hubert Abgottspon Dr. Luis Baringo (- September 2014) Dipl.-Ing. Theodor Borsche MSc ETH Matthias Bucher M.Sc. El.Eng. Philipp Fortenbacher Dipl.-Ing. Marina González Vayá Dipl.-Ing., M.A. (econ.) Tobias Winfried Haring Dipl.-Ing. Marcus Hildmann MSc ETH Emil Iggland (- July 2014) MSc ETH Markus Imhof Dr. sc. techn. Thilo Krause MSc EPF Olivier Mégel Dr. sc. ETH Frauke Oldewurtel (- February 2014) MSc ETH Line Roald Dr. Osvaldo Rodríguez Villalón (September 2014 -) Dr. sc. ETH Monika Ruh MSc ETH Marc Scherer (September 2014 -) Dr. sc. ETH Maria Vrakopoulou (- March 2014) Dipl.-Ing. Evangelos Vrettos MSc ETH Roger Wiget
External PhD Students:	MSc ETH Christof Bucher (- June 2014) MSc ETH Raffael La Fauci
Scientific Associates:	Prof. em. Dr. Hans Glavitsch Dr. sc. ETH Stephan Koch (Spin-Off: Adaptricity) Dr. sc. ETH Andreas Ulbig (Spin-Off: Adaptricity)
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

Academic Guests:	Martin Andreasson, Kungliga Tekniska Högskolan, Stockholm, Sweden
	Prof. Dr. Ian Hiskens, University of Michigan, Ann Arbor, USA
	Sven Christian Müller, TU Dortmund, Germany
	Juan de Santiago, Uppsala University, Sweden

1.2 The High Voltage Laboratory

Head:	Prof. Dr. rer. nat. Christian M. Franck
Secretary:	Karin Sonderegger Zaky
Scientific Staff:	MSc ETH Lorenz Bort (Jan 2014 -) MSc ETH Matthias K. Bucher (- December 2014) MSc ETH Pascal B. Buehlmann MSc Alise Chachereau MSc EPFL Raphael Faerber (September 2014 -) MSc ETH Pascal Häfliger MSc TU Darmstadt Soeren C. Hedtke (July 2014 -) MSc ETH Moonjo Kang (- February 2014) Dipl. Ing. Myriam Koch MSc ETH Martin D. Pfeiffer Mag.rer.nat. Mohamed Rabie MSc ETH Andreas Ritter PhD José Rodriguez Alvarez (May 2014 -) Dipl.-Ing. Michael Schüller (- October 2014) MSc RWTH Tim Schultz (May 2014 -) MSc RWTH Malte Tschentscher MSc ETH Jonas Truessel (June 2014 -)
Technical Staff:	Henry Kienast, Mechanician Claudia Stucki, System Engineer El.-Ing. FH Hans-Jürg Weber, Senior Technician
Ext. PhD Student:	Dipl.-Ing. Markus Bujotzek, ABB Schweiz AG
External Lecturer:	Dr. tech. Werner Hofbauer, ABB Schweiz AG Dr. sc. ETH Ueli Straumann, ABB Schweiz AG Prof. Dr. Jasmin Smajic, HSR
Scientific Associates:	Prof. Dr.-techn. em. Klaus Fröhlich Dr. sc. ETH Nicolas E. Karrer (Spin-Off: kametech) Dr. rer. nat. Timm H. Teich
Academic Guest:	Master Stud. Aditya Shekhar, Delft University/NL (October 2014 -)

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

Electric Power Systems 6 ECTS points
Elektrische Energiesysteme
Lecturer(s): G. Andersson and Ch. 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: 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.

High Voltage Technology 6 ECTS points
Hochspannungstechnik
Lecturer(s): Ch. 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. Andersson

The electrical power transmission system, the network control system, requirements for power transmission systems (supply, operation, economics), network planning and operation management, models of N-port components (transmission line, cable, shunt, transformer), data specification per unit (p.u.), Linear Modelling of networks, Linear und non-linear calculation (Newton-Raphson), non-linear load flow (specification and solution methods), three-phase und generalized short-circuit current calculation, further applications of load flow calculation. Introduction to dynamics and stability in power systems. Rotor angle and voltage stability. Equal area criterion. Control of power systems.

Technology of Electric Power System Components 6 ECTS points
Technologie der Komponenten elektrischer Energiesysteme
Lecturer(s): Ch. 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. Andersson and other lecturers

The aim of the course is to give an introduction to the methods and tools for analysing energy consumption, energy conversion, and energy flows. Environmental aspects are included as well as economic considerations. Different sectors of society are treated, such as electric power, buildings, and transportation. Models for energy system planning will also be introduced.

Power System Dynamics and Control 6 ECTS points
Systemdynamik und Leittechnik in der elek. Energieversorgung
Lecturer(s): G. Andersson and M. Zima

Dynamic properties of electrical machines, networks, loads and interconnected systems. Models of power stations and turbines, control of turbines, load- and frequency control, power exchange between networks, model of the synchronous machine connected with the network, transient model, block diagram, behaviour of the machine in case of disturbances, transient stability, equal area criterion, model for small disturbances, voltage control. Facts-Devices. SCADA/State Estimation. EMS-Implementations, Protection, Asset Management, Future Trends in IT for Power Systems.

Optimization of Liberalized Electric Power Systems 6 ECTS points
Optimierung liberalisierter elektrischer Energiesysteme
Lecturer(s): R. Bacher

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.

Power Market I - Portfolio and Risk Management 6 ECTS points
Strommarkt 1 - Portfolio und Risk Management
Lecturer(s): D. Reichelt and G. Koeppel

Knowledge on the worldwide liberalisation of electricity markets, pan-European power trading and the role of power exchanges. Understand financial products (derivatives) based on power. Management of a portfolio containing physical production, contracts and derivatives. Evaluate trading and hedging strategies. Apply methods and tools of risk management.

Power Market II - Modelling and Strat. Positioning 6 ECTS points
Strommarkt 2 - Modellierung und strateg. Positionierung
Lecturer(s): D. Reichelt and G. Koeppel

Part 1: Modelling
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.
Part 2: Strategic Positioning
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
Internationales Businessmanagement für Ingenieure
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.

Electrical Engineering II for Mechanical Engineers 4 ECTS points
Elektrotechnik II für Maschinenbauer
Lecturer(s): G. Andersson

Signals and systems in the time and frequency domain, principle of operation and design of basic analog and digital circuits, analog-digital conversion. Basic power electronic circuits, design of magnetic components and concept of force and torque generation, electromechanical energy conversion, principle of operation and characteristics of stationary and selected rotating electrical machines.

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 Switzerland, Surge Arrester Factory
Wettingen, Switzerland
20 March 2014

Power Markets II
Munich, Germany
25-26 March 2014

Technology of Electric Power System Components
EWZ Letten, Power generating station and gas insulated switchyards
Zurich, Switzerland
27 March 2014

High Voltage Technology
Alstom Grid, Gas Insulated High Voltage Switchgears
Oberentfelden, Switzerland
4 April 2014

High Voltage Technology
ABB Micafil
Zurich-Altstetten, Switzerland
9 May 2014

Power System Dynamics and Control
Swissgrid
Laufenburg, Switzerland
20 May 2014

Electric Power Systems
ewz, Unterwerk Sempersteig
Zurich, Switzerland
28 November 2014

Power System Analysis
Axpo
Baden, Switzerland
3 December 2014

2.3 Seminars

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

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

PPS: Electrotechnology in Everyday Life
(Elektrotechnik im Alltag)

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

HS3: High-Temperature Superconductors
(Hochtemperatur-Supraleiter)

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

Franziska Bosshard
Economic Assessment of Power2Gas Technology
Supervisors: Matthias Bucher, Tobias Haring

Georgios Chatzis
The influence of power flow control on wind power integration
Supervisor: Line Roald

Luka Cuderman
Analyse der Netznutzungsgebühren in der Schweiz
Supervisor: Theodor Borsche

Julian Diederichs
Determining optimal time-of-use tariffs for the smart-charging of plug-in electric vehicles
Supervisors: Marina González Vayá, Luis Baringo

Teng Feifei
Recursive System Identification Methods for Li-Ion Battery Systems
Supervisor: Philipp Fortenbacher

Xiangkun Li
Supporting PV Integration in Low-Voltage Feeders with Demand Response
Supervisor: Theodor Borsche

Vasileios Markgiannakis
Development of a Dynamic Optimal Power Flow Algorithm using the Power Nodes Framework
Supervisor: Philipp Fortenbacher

Uros Markovic
Fast Demand Response with Cooling Devices
Supervisor: Theodor Borsche

Tianshu Pan
Exploitation of DLR for Improved Power System Dispatch Optimization
Supervisors: Andreas Ulbig, Matthias Bucher

Haoyuan Qu
Modelling the Propagation of RES Fluctuations
Supervisor: Line Roald

Michiel Tavernier
Dynamic model of multi-terminal HVDC grid
Supervisor: Roger Wiget

Ekaterina Telegina
State Estimation in Power Systems with Combined AC and HVDC grids
Supervisors: Roget Wiget, Philipp Fortenbacher

Emanuel Thoma, Robert Strietzel
The Influence of Power Plant Portfolios and Congested Area Borders on a European Frequency Control Market
Supervisors: Emil Iggland, Marc Scherer

Michael Tschampion
Value of Locational Flexibility
Supervisor: Matthias Bucher

Gumbry Vytis
Analysis of Swiss Market for Secondary Control
Supervisors: Tobias Haring, Hubert Abgottspon

Thierry Zufferey
Aggregate Modeling of Price-responsive residential loads and Design of Optimal Day-ahead Price Profiles
Supervisor: Evangelos Vrettos, Stephan Koch

2.4.2 Technology Oriented Semester Projects

Viktor Lenz
Identification of Discharge Parameters of Insulation Gases
Supervisor: Myriam Koch

Michiel Tavernier
Investigation in the DC Corona Charateristics of Solid Rain Drop Models on Overhead Conductors
Supervisor: Martin D. Pfeiffer

Uros Markovic
Development of an Outdoor Test Facility for Overhead Power Lines
Supervisor: José Rodriguez Alvarez

Daniel Schenk
Analyse der räumlichen Relativbewegungen der Drähte vom Leiterseil in der Nähe der Abspannklemme
Supervisor: Pascal B. Bühlmann

Matthias Meier
TeKaF - Analyse des Temperaturgradienten des Leiterseils innerhalb und in der Nähe der Abspannklemme
Supervisor: Pascal B. Bühlmann

Alexander Heller
Investigation of Magnetically Driven Disconnector Arcs
Supervisor: Andreas Ritter

Matthias Britt
Development of a High Voltage lowpass filter
Supervisor: Malte Tschentscher

Remo Brühwiler
Investigation of rain drop formation and corona effects on HVDC Overhead Conductors
Supervisor: Martin D. Pfeiffer

J. Böhler/Johannes Frick
Doppel-Puls-Prüfstand
Supervisor: Nico E. Karrer

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

Eren Cam
The Effect of Renewable Energy on Electricity Price Arbitrage Opportunities
Supervisor: Line Roald

Luka Cuderman
Alternative Netznutzungstarife für Schweizer Verteilnetzbetreiber
Supervisor: Theodor Borsche

Stefan Deml
The Role of Aggregation in Power System Simulation
Supervisors: Andreas Ulbig, Theodor Borsche

Martin Gahr
Using Micro-Synchrophasors for Topology Detection in a Micro Grid
Supervisor: Monika Ruh

Gabriel Hidalgo-Barquero Pérez
Optimal Placement and Operation of Multi-Terminal HVDC interconnection for increased operational flexibility
Supervisors: Matthias Bucher, Roger Wiget

Julius Hübner
Joint Optimization of CHP Plant, Electric and Thermal Storage Units
Supervisor: Olivier Mégel

Gregory Ledva
Residential load control with communication delays and constraints
Supervisors: Evangelos Vrettos, Johanna Mathieu, Sylvia Mastellone (ABB)

David Lehnen
Simulation und Analyse der dynamischen Wechselwirkung von Synchronmaschinen im Axpo-Verteilnetz
Supervisor: Markus Imhof

Manuel Mühlebach
Auswirkung der Netzzeitregelung auf die Frequenzqualität
Supervisors: Emil Iggland, Marc Scherer

Jonas Müller
Spot Market Analysis and RES Impacts
Supervisors: Andreas Ulbig, Marcus Hildmann

Vasileios Poulios
Optimal placement and sizing of battery storage to increase the PV hosting capacity of low voltage grids
Supervisor: Evangelos Vrettos, Florian Kienzle (ewz)

Vasileios Saplamidis
Nonlinear security constraint optimal power flow for combined AC and HVDC grids
Supervisor: Roger Wiget

Robert Strietzel
Verbrauchermodellierung im Bahnstromnetz
Supervisor: Stephan Koch

Christoph Trabert
Risk Limiting Dispatch
Supervisor: Andreas Ulbig

David Trüssel
Stochastic Control for Combined PV Integration and Battery Energy Storage System Operation
Supervisors: Olivier Mégel, Theodor Borsche

Tamara Tursijan
Dynamic Model to Improve Control Reserve Operation using Multi-terminal HVDC grids
Supervisors: Matthias Bucher, Roger Wiget

Christina Tzanetopoulou
Techno-Economic Assessment of Battery Solutions for Solar Plants and Distribution System Operation
Supervisors: Philipp Fortenbacher, Theodor Borsche, Olivier Mégel

Olég Valgaev
Controlled Islanding using VSC-HVDC Lines to Minimize Load Shedding
Supervisor: Markus Imhof

Hannes Vollenweider
Grid Integration of PV Systems and Local Storage in Distribution Networks
Supervisors: Philipp Fortenbacher, Christof Bucher

Alexandra Zigkiri
Comparison of central dispatch and self-scheduling market designs and their impact on ancillary services under influence of uncertainties
Supervisors: Luis Baringo, Marek Zima (swissgrid)

Charampos Ziras
Evaluation of dynamic performance of power systems with large shares of demand-side resources in frequency control
Supervisor: Evangelos Vrettos

2.5.2 Technology Oriented Master Projects

Loukas Theodolou
Extension of a laser-speckle technique for circuit breaker to two or more beam lines
Supervisor: Christian M. Franck

Julien Thomas
Small scale testing of HVDC circuit breakers
Supervisor: Christian M. Franck

Jonas Trüssel
Entwicklung, Aufbau und Test einer Standard-Steuereinheit für die modularen Hochspannungs-Baukastenprüfanlagen des HVL
Supervisors: Hans-Jürg Weber, Christian M. Franck

Jonas Schmutz
Investigation of Ion Current Coupling in Hybrid AC/DC Overhead Lines
Supervisor: Martin D. Pfeiffer

René Sonderegger
Novel test method to characterize limit performance of power electronic switches
Supervisor: Christian M. Franck

Tim Schultz
Development and Verification of Corona Models for Numerical Investigations of Ion Flow in Hybrid HVAC/HVDC Fields
Supervisor: Martin M. Pfeiffer

Denis Tehlar
Approximate methods to calculate the electric strength of Gas Mixtures
Supervisor: Christian M. Franck

Ronny Steinhaus
Abschätzen der elektrischen Festigkeit umweltfreundlicher Isoliergase
Supervisor: Pascal Häfliger

3. Completed PhD Theses

Operational Flexibility in Electric Power Systems

Candidate:	Andreas Ulbig
Thesis:	ETH No. 21882
Date of oral exam:	1 April 2014
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Dr. David J. Hill, Prof. Dr. Martin Greiner

Abstract This thesis deals with operational flexibility in power system operation and analyzes its role for mitigating operation disturbances and improving grid integration of variable Renewable Energy Sources (RES). The topic is motivated by the increasing challenges for power system operation, mainly due to rising energy shares from variable RES but also caused by impacts of power market liberalization, notably higher grid utilization.

Operational flexibility is an important property of electric power systems, especially for the transition of existing power systems, many of them based on fossil fuels, to power systems effectively accommodating high shares of variable RES. Availability of sufficient operational flexibility is a necessary precondition for the grid integration of large power in-feed shares from variable RES, notably wind turbines and photovoltaic (PV) units.

The provision of operational flexibility can be enabled and/or improved by introducing more sensing, i.e. sensor elements, computation, e.g. in the form of optimization schemes, as well as control, i.e. actuators, into power system operation. Improving controllability and observability of power system processes will help to improve power system operation & management, i.e. enabling the secure, efficient and stable operation of power systems.

The role of operational flexibility for power system operation is discussed and analyzed from different angles, ranging from power system modeling approaches to analytic approaches inspired by well-known control theory concepts to qualitative and quantitative simulation-based assessments.

A supplementary idea that is discussed in the thesis is the concept of control-based grid adaptation as an alternative to conventional hardware-based grid adaptation for the operational challenges related to large-scale RES deployment. This allows a cost-saving trade-off between costs for computation and communication versus conventional grid investment.

The thesis structure has three parts, each addressing a separate topic stream. The first part focuses on the operation of power systems. It gives an overview of the on-going paradigm change in power system operation, which is driven by new challenges to power system operation and control, mainly related to the large-scale deployment of variable RES generation units but also to increasing power market activity. A discussion of opportunities for mitigating these operational challenges concludes this part.

The second part focuses on the modeling of power & energy systems and the topic of operational flexibility. An overview of established modeling frameworks for power & energy systems is given. Notably, the Network Preserving Modeling Framework and the Energy Hub Concept are presented and the motivation for complementary modeling frameworks is discussed. The Power Nodes Modeling Framework is introduced and new contributions to it are presented. A discussion of operational flexibility as well as necessary flexibility metrics and modeling approaches, both for individual units as well as for aggregations, i.e. pools, of diverse power system units, concludes this part.

The third part focuses on the analysis of operational flexibility. An analysis of operational flexibility in power systems is presented. A purely qualitative analysis of the flexibility of individual power system units and small pools is conducted. This is then followed by a quantitative analysis of the operational flexibility of the German, Swiss and interconnected European power system.

Methods for the secure and economical operation of inter-connected electrical power systems

Candidate:	Lars Johan Emil Iggland
Thesis:	ETH No. 21931
Date of oral exam:	9 May 2014
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Dr. Anastasios Bakirtzis

Abstract This thesis considers aspects of the operation of electric power systems. In particular the focus is on the operation in systems where multiple operators are jointly responsible for the operation of an interconnected system, but where each operator is solely responsible for a sub-system. Due to the manner in which the operation is separated, the operators have detailed information about the subsystem they control, but only limited information about the rest of the system.

The market liberalization, and an interest in an integrated panEuropean energy market, are leading to increased cross-border power flows. These increased cross-border flows increase the interdependencies between the areas. With increasing interdependencies the problems associated with operators only having limited knowledge about the entire system increase.

In order to reduce these issues, which include an inability to properly dispatch generation and being able to perform security analysis, this thesis presents methods which can be used to perform data-exchange without requiring that all information needs to be exchanged.

By using repeated exchange of the price and amount of energy traded together with an iterative solution of the local generation dispatch problem, a multi-lateral solution for the interconnected system is achieved. The method is evaluated with respect to how close its solution is to the central one, both for the non-security constrained and the security constrained case. This method is then extended to include HVDC transmission systems.

In order to allow the operators to evaluate the effect of contingencies which occur in other areas, the operators must exchange the contingencies which they consider with each other. In order to reduce the amount of data which must be transmitted this thesis proposes a method which summarizes contingencies which are similar into a common one.

Thus allowing for a smaller number of contingencies to be considered, without reducing the coverage. This method is compared to a reduction method which is based on the effect of the contingency.

Analysis and Simulation of Distribution Grids with Photovoltaics

Candidate:	Christof Bucher
Thesis:	ETH No. ETH No. 22001
Date of oral exam:	26 June 2014
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Dr.-Ing. Rolf Witzmann

Abstract When this thesis was in preparation in the beginning of 2010, Germany had just celebrated 10 GWp of installed PV capacity. Switzerland and Austria were still far away from 100 MWp each, and the Spanish PV boom was already over. The "50.2 Hertz problem" - the fact that all PV power plants in Germany (and probably in the rest of the UCTE grid) had to switch off immediately if the grid frequency should rise above 50.2 Hertz and thereby could provoke a UCTE-wide blackout – was already built in and identified, but the remedy against it had not been found yet.

Many scientific and industrial papers that explained how to integrate more PV power systems into the grid were published. The inverter manufacturers reacted quickly and implemented a broad variety of functionality into their devices, allowing owners of PV power plants many sophisticated operation modes. But the grid operators were not ready yet. Their job seemed to be by far more difficult, as they were forced to change their grids completely without knowing where the future was going to take them. Thinking in decades rather than in years, grid operators of course hesitated to install a couple of iPhones in every substation to make their grid look smart.

In this environment, the idea of the thesis "Analysis and Simulation of Distribution Grids with Photovoltaics" was born. A simulation method should be found which was able to bring all possible approaches to increase the PV hosting capacity of a distribution grid together and to compare them. In a few simple tables or graphs, the authors wanted to show the benefits of various grid integration measures, always keeping the grid in the main focus.

Today - almost four years later - the 50.2 Hertz problem has almost been solved and the first methods to increase the PV hosting capacity of a grid are being implemented in the grid codes of Germany. But there is still the same uncertainty about how the grid is going to develop, and neither the grid operators nor the operators of PV power plants really know how to integrate all solar energy into the grid. This thesis will not solve all these problems and uncertainties. But it will show and give both qualitative and

quantitative answers to the question "How much PV can be integrated into the low voltage distribution grid?" and "How can these limitations be mitigated or removed?"

Role and impact of different charge sources on surface charge accumulation in gas insulated HVDC systems

Candidate:	Michael Schueller
Thesis:	ETH No. 22283
Date of oral exam:	23 October 2014
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. Yuriy Serdyuk, Chalmers University of Technology, Sweden

Abstract Within the framework of this thesis an experimental setup for measuring surface potentials that are due to accumulated surface charges on gas insulated HVDC model insulators is designed, built and operated.

As measurement sensor a vibrating Kelvin probe is used that enables non-contact surface potential measurements. The insulator is moved by a 3-axes handling system inside the gas insulated vessel which enables automated measurements of the potential on the entire surface. Because the time constant of the surface charge accumulation in DC case is in the order of days to weeks, experiments can be conducted automatically providing long term measurements of the charge evolution on HVDC gas insulated test samples.

Previous studies dealing with the problem of surface charge accumulation due to DC stress, tried to identify the main responsible charging mechanism: surface conduction, bulk conduction or charge transport through the gas phase. Typically this was done using one principle test arrangement. Even though the used setups were quite similar, different authors concluded differently, which charging mechanism dominates.

In a first step, a simulation model incorporating the state of the art of surface charging via insulator bulk and gas phase is implemented and applied to real size GIS insulators under no-load and load conditions. It is shown that the responsible charging mechanism in a single experimental setup depends on many parameters like for example the active gas volume size, electric field strength, the exact electric conductivity distribution in the solid insulation, present charge sources in the gas phase etc. Out of these findings, different electrode and sample configurations are designed to investigate the different contributing parts individually and to quantify their specific contribution to the surface charging.

The main focus in this work is the charging from the gas phase and the transition between ion currents in the gas phase and bulk currents in the solid as main responsible surface charging mechanism. The effect of surface conduction is not addressed in this thesis.

In this thesis the three charge sources in the gas phase, which are natural ionization, (micro) discharges and field emission and their individual contribution to the total surface charging are investigated. Also their temporal evolution is studied.

The ohmic and saturated conduction regime in the gas phase is demonstrated experimentally with only natural ionization present as charge source. The direct correlation between active gas volume size and surface charge accumulation is shown under the same conditions.

If additional charge sources like partial discharges or micro discharges are present, a large amount of additional ions is released into the gas phase. These micro discharge currents, which cannot be detected by classical PD measurements, are due to imperfections or rough electrodes and studied in detail as well. Design field strengths to avoid micro discharges when constructing gas insulated HVDC equipment are given.

As the current arising from the bulk does not saturate with increasing field strength a transition where the bulk current takes over the charging in a setup exists. This transition is shown by experiments.

Quantitative Methods for the Economic Analysis of Liberalized Power Markets

Candidate:	Marcus Hildmann
Thesis:	ETH No. 22311
Date of oral exam:	24 October 2014
Examiner:	Prof. Dr. Göran Andersson
Co-examiner(s):	Prof. Dr. Shmuel Oren

Abstract This thesis considers price modeling aspects in European, mainly German power markets. In particular, we focus on day-ahead price modeling, the calculation of the Hourly Price Forward Curve (HPFC) and the impact of renewable energy sources (RES) on the price profiles and market structures.

The market liberalization in Germany leads to the need of new methodologies and tools to price electricity contracts, measure market risk and enable quantitative analysis of markets and portfolios. This has become even more important with the kick-in of the support scheme driven large-scale deployment of (RES) in Germany in 2006. As a result, the market dynamics and price structures change frequently over time. We present several methods and algorithms for price modeling, price forecasting and quantitative analysis.

In the first part of the thesis we present methods to model the merit-order curve based on exponential-models and heat-rate models. In addition, we present a model to for hourly resolution long term load forecasting based on weather, seasonal patterns an economic growth. Both together form the basis of the fundamental models of power prices.

The second part consists of methods and algorithms to model the HPFC. First we present a modeling approach which is robust against not-normal distributed data and shows significant better performance than models with the normality assumptions. The second contribution is the modeling of the HPFC for market coupling or nodal pricing markets. In this approach, all HPFC are estimated together in one optimization problem based on aggregated demand and supply curves. The third aspect is the introduction of systematic quality measurement for the HPFC. We present qualitative and quantitative criteria for the HPFC testing to ensure a certain quality of the curve.

The third part is the quantitative analysis of the impact of RES on power market price structures. We present a new method for non-linear estimation of RES feed-in as a basis for our analysis. Based on the previous methods presented in this thesis, we analyse the merit-order effect as a result of large quantities of feet-in tariffs subsidized RES including analysis and recommendations how to overcome the problem in the short term and also in a post-EEG scenario. Finally we provide an analysis of the effect of RES feed-in on the economic value of storage in which we show, that storage facilities are unprofitable with an increase feed-in of photovoltaic.

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Role and impact of different charge sources on surface charge accumulation in gas insulated HVDC systems

Candidate:	Matthias Karl Bucher
Thesis:	ETH No. 22304
Date of oral exam:	19 November 2014
Examiner:	Prof. Dr. Christian M. Franck
Co-examiner(s):	Prof. Dr. Hans Kristian Høidalen, NTNU, Norway

Abstract Multiterminal HVDC networks are a promising technology for future bulk power transmission. The protection of such a network,however, poses still a major challenge. In contrast to traditional point-to-point HVDC links, a real DC network requires HVDC circuit breakers at each end of a line to selectively isolate a fault and to keep other parts of the system operating. In order to specify the requirements of such HVDC circuit breakers, a full understanding of the transient fault currents and voltages is needed.

This thesis provides a detailed analysis of the prospective transient fault currents and their in influencing factors in a multiterminal HVDC grid.

The effect of various network components on the transient fault current development is investigated, as well as the interaction between these components and the circuit breaker. The studies and analysis performed in the thesis have demonstrated that the fault currents are influenced by both, the network and circuit breaker parameters.

The design of a circuit breaker, therefore, results in the trade-off between network and circuit breaker requirements.

4. Research Activities

4.1 Power System Dynamics and Control

G. Andersson is academic advisor for the projects in section **??**.

Optimization and Planning of Hydro-Power Production

Hubert Abgottspon, Advisor: Göran Andersson

Abstract A significant portion of electric power in Switzerland is produced by storage hydro power plants, which enable the storage of water inflows to schedule power production at convenient times, i.e. producing energy in most attractive economical conditions. The storage capacity is however limited and the evolution of influence factors such as electricity prices and water inflows not fully known in advance and volatile. Therefore to take a correct decision about the utilization of the water in reservoir is not trivial at all.
A traditional way of addressing these uncertainties is to rely on tacit knowledge and/or improve the forecast of the volatile factors (e.g. a Hourly Price Forward Curve). This is however becoming increasingly more difficult with the structural market changes (e.g. ancillary services markets) and price dynamics (e.g. negative prices).

Goals of the project The goal of this project is a prototype software which assists power producers with an optimal production strategy for typically Swiss hydro storage power plants (relatively small reservoirs, high heads, complex structure). Key aspects of the software is the integration of the market and regulatory conditions in Switzerland (e.g. handling of ancillary services) as well as the consideration of uncertain factors (e.g. water inflows, market prices). With this software it shall be not only possible to plan the energy production more profitable and more robust but also to plan it with a minimized and known risk.

Project Description Proposed for the medium-term planning is an algorithm, which decomposes the problem into inter- and intrastage subproblems. With this formulation it is possible to account for hourly flexibility like hourly bidding, production and water balances for a time horizon of typically a full year. Secondly the provision of secondary frequency control

reserves are considered. This results in both decision support for these products as well as realistic water values. Solution method is stochastic dynamic programming for power plants with a few reservoirs and stochastic dual dynamic programming otherwise.

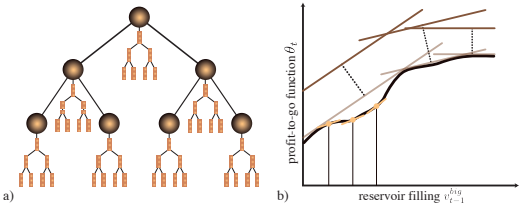

Figure 4.1: a) Detailed consideration of short-term flexibility. b) Approximation of non-convex profit-to-go functions.

Progress in 2014

- In collaboration with BKW AG the established algorithms were applied to one of the most complex Swiss hydro power plants (Kraftwerke Oberhasli) and compared to their framework. Some of the results were presented at the ifors conference.
- A detailed evaluation of different methods of how to consider short-term flexibility in a medium-term optimization was presented at the PSCC conference. [**??**]
- Risk-aware operation was considered where stochastic dual dynamic programming was applied to non-convex problems as well as risk measures were introduced in stochastic dynamic programming. The outcomes of this work were presented at the PMAPS conference. [**??**]
- Some thoughts and results about how to hedge cashflows from provision of ancillary services were presented at the informs conference.

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Distributed Load Management

Theodor Borsche, Advisor: Prof. Göran Andersson

Motivation Load Management, that is an active switching of consumers, can be used to offer flexibility to the power system. The focus is on thermostatically controlled loads (TCLs). This load type usually has some kind of thermal storage and therefor flexibility in the time of electricity consumption without impeding the user comfort. Often discussed use-cases for demand flexibility include peak-shifting, renewable integration or provision of frequency control reserves. *Distributed Load Management* builds on previous research [**??**] and tries to answer questions such as

- How can loads best be controlled with minimal communication and measurement effort?
- How can load flexibility be optimally used? Which use-cases have the highest economic impact?
- How do regulatory frameworks such as the unbundling of grid operation from energy retailing affect the discussed strategies?

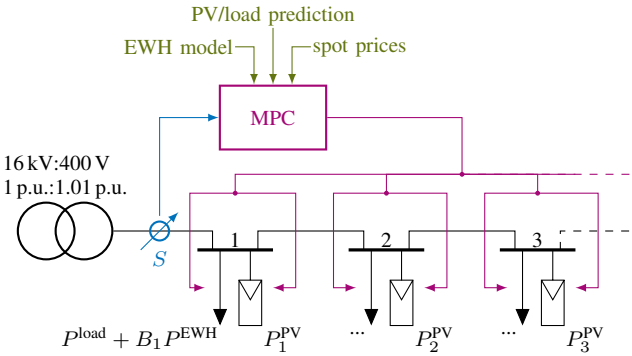

Figure 4.2: Control scheme for PV-integration.

Results The project produced a number of results, which are outlined here:

1) A control strategy for large populations of TCLs is proposed. This control strategy relies only on one-way broadcasts, considerably reducing the requirements for communication infrastructure. This is mainly achieved by

using state estimation to observe the available demand flexibility. Tracking accuracy is excellent.

2) Load Management for schedule compliance is investigated. Here, the retailer tries to avoid costly deviations from the schedule it had to submit day-ahead. A hierarchical control scheme based on load scenarios is used to find the optimal trade-off between energy cost and deviation penalties.

3) Integration of photo-voltaic (PV) generation can be supported by locally consuming excess production. A model-predictive control ensures that PV induced voltage limit violations are avoided while flexible loads are always served sufficient energy. Only power flow at the transformer needs to be measured in real-time. Hosting capacity is increased by 25 % [**??**].

4) Provision of primary frequency control with both batteries and refrigerators is investigated. The battery algorithm is used by the Zurich utility EKZ to offer primary reserves in the Swiss ancillary service market.

5) Business models of different load management schemes are critically analyzed, and their respective benefit and control effort compared. Regulatory issues are highlighted [**??**].

Outlook The project partners PSL, EKZ and Landis+Gyr are currently discussing the implementation of the PV integration scheme in a pilot project.

Partnership: *Landis+Gyr, EKZ, KTI*

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Power System Performance Enhancement through Voltage Source Converter (VSC) Based HVDC in the ENTSO-E system

Markus Imhof, Advisor: Göran Andersson

Introduction Historically the interconnections in the transmission system were not designed for power trading, but for the exchange of regulating power. As a result of the deregulation of power markets, particularly in Europe, the tie-lines are quite often subject to heavy loading caused by power trading between countries. Deregulation also brings increased variations in power flows. These developments are the cause of severe challenges for the transmission system and its operators. Without adding more transport capacity and controllability to the grid could cause the instability of the transmission system.
This project investigates how Voltage Source Converter based High Voltage DC (VSC-HVDC) can be used to stabilize and control the High Voltage AC (HVAC) transmission networks using the three independent control outputs active power, reactive power at the rectifier and reactive power at the inverter.

Project Summary The aim of this project will be to systematically investigate the possibilities to use VSC-HVDC in meshed networks, such as the ENTSO-E grid, in order to increase system transmission capacity and security. In particular it will be studied how VSC-HVDC, placed in Switzerland or in other countries, can be used to increase the transmission capacity through Switzerland. The focus will be laid on these four main topics:

- geographical placement of VSC-HVDC in a meshed grid
- investigate active and reactive power modulation of VSC-HVDC to dampen inter-area oscillations
- use VSC-HVDC for transient stability control
- use VSC-HVDC for voltage and reactive power control

On Going Tasks During the last year the Model Predictive Control (MPC) damping controller introduced in [**??**] has been extended to include voltage stability presented in [**??**]. The objective of the controller has been modified such it is able to control the AC voltage at the terminals and tries to keep all the AC voltages within its bounds. It has been shown in the Kundur Two Area test system that a voltage collapse could be prevented using the proposed controller.

Due to an increase penetration of renewable energy sources such as wind and photovoltaic and simultaneously decommission of large fossil power plants with synchronous generators the inertia of the system is reduced. This results in higher frequency dynamics. VSC-HVDC links give the possibility to add additional damping to the system and replaces the lost inertia with an appropriate modulation of active and reactive power. In [**??**] we showed how such a damping controller could be formulated. It was tested in the European network with a large share or renewable energy sources. It was shown, that the VSC-HVDC link were able to damp the frequency dynamics and ensure a secure operation of the AC system.

Currently an algorithm for controlled islanding including VSC-HVDC links is developed. The goal is to form the islands after a disturbance in such a way that VSC-HVDC links connect two different islands. This enables to exchange active power between the islands thus reduces under-frequency load shedding or over-frequency generator tripping. This lowers the cost of a large disturbance and expedites the synchronization of the islands.

Project Partners ABB, Automatic Control Laboratory ETH Zurich (ifa), swisselectric research, swissgrid

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HVDC Networks — Interaction between HVAC and HVDC system

Roger Wiget, Advisor: Göran Andersson

Introduction In recent years there has been an increased interest in High Voltage Direct Current (HVDC) networks due to a number of reasons. Many existing bulk transmission systems have reached their capability limits and a significant increase of the transmission capacities is foreseen. There are several reasons calling for this upgrade, where the most significant are the expected increase in new renewable energy sources that are located far away from the load centers and an expected overall increase in consumption of electric energy. Furthermore, the fluctuating nature of many renewable energy sources require higher transmission capacities to provide the regulating power from other power plants. Another driving force is the latest developments in HVDC technology such as higher power ratings of semiconductor devices and the introductions of Voltage Source Converters (VSC) for power transmission, which are deemed to make HVDC network viable option for future transmission systems.
Even if the general conception is old there are numerous technical issues that needed to be solved or further elaborated before actual planning, design and implementation of an actual HVDC network can commence.

Project Summary The primary aim of the project is to contribute to the question: "Under which conditions is a true HVDC network of advantage and what would be the preferred scheme?" The project will focus on three different topics with overlaping areas. The basis for a new network is the power flow in a combined HVAC and HVDC network. The HVDC network could be constructed as an offshore grid with only few connections to AC grid or as a "Supergrid", which means an overlay network as a superior layer to the existing HVAC network, like proposed in the "Friends of the Supergrid (FOSG)" project. Furthermore the power flow and the whole network have to be controlled in steady state and under emergency conditions to ensure a stable and secure operation.
In general the main topics for investigation

- Optimal topology or configuration of HVDC
- Economic considerations and investigations
- Optimal Power Flow (OPF) of combined HVAC and HVDC networks
- Control strategies of HVDC network in steady state both in normal and emergency state

The above topics have already been researched for traditional point-to-point HVDC systems, but HVDC networks will introduce new degree of freedom and possibilities.

Progress in 2014 This year the OPF formulation was further investigated and improved. The main focus was to incorporated security constraints in even the linearized version [**??**] of the OPF as well as in the non-linear algorithm. The results are to formulation, where one is an approximation which can be calculated within very limited time, whereas the other is exact, but need a lot of calculation efforts. Similar approach is possible within different areas, which exchange limited amount of data [**??**].
The second topic was the dynamic behavior of the combined AC and MTDC grid. The idea there was to find an decentralized controller which balance the disturbances in the AC and MTDC grid. The prevent the use of communication infrastructure, the controller was design to use only local measurement for the operation. With this method primary frequency reserves can be share between different AC grids, which are combined with an HVDC grid, that could react much faster than any generator. This grid can be built with different topologies, an investigation is done in [**??**].

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Partnership: *ABB, Alstom Grid, SIEMENS, Swiss Federal Office of Energy*

Frequency Stability in the European Interconnected Power System in respect of Changes in Control Structure and Responsibility

Marc Scherer, Advisor: Göran Andersson

Abstract This project investigates technical and organisational shortcomings of the current frequency control setup in Continental Europe under expected future conditions. It derives solutions for those insufficiencies which are evaluated with regard to their effectiveness.

Project Goals One of the key elements of operating power systems is real time control of mismatches between consumption and production, i.e. frequency control. The current framework has been defined after the Second World War. Its initial motivation was to improve security of supply in each vertically integrated national power system. Political realignments effecting real time system operation, especially with regard to liberalised electricity markets and sustainable generation capacities, have not been anticipated:

- Electricity trading implies a schedule based grid operation instead of real time load following.
- Intermittent generation capacities like wind and solar power have been adding volatility and operational complexity to the system in the past years.
- Generation structure is changing from centralised large conventional units to distributed production underlined by the decision of several countries to abandon nuclear power.
- Recent efforts have been made to incentivise demand response. This will lead to new load profiles and could increase load controllability.

The project hypothesises a link between those trends and a decrease of frequency quality the European power system has been exposed to during the past few years. Assuming these developments continue under the decentralised framework, security of supply has to be weighed against cost effectiveness. Hence, the objective is to solve that trade-off and to outline future concepts of frequency control ensuring an efficient frequency stability in the European interconnected power system under on-going structural changes.

Progress We have focused on developing a reduced frequency control framework for the Continental European power system which exhibits a four-level hierarchy. Therefore, we rely on a power system model for a steady-state frequency analysis, and utilise time sequential Monte Carlo simulations. For a realistic engineering design, we used system adequacy outlook data to parameterise the simulation framework by considering different scenarios for the generation portfolio, forecasting methods, and the availability of active power reserves. Future work will focus on using these models for different control strategies and structures.

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Smart Grid State Estimation for Fully Transparent Distribution Management Systems

Monika Ruh, Advisor: Göran Andersson

Introduction Passive distribution grids are becoming more and more active distribution grids due to the increasing amount of decentralized energy sources. Therefore, it is only a matter of time before these decentralized energy sources will considerably impact the operation, monitoring and control of these networks. A future distribution management system (DMS) assigned with the task to control and monitor such an active distribution grid, possibly involving genuine smart grid (SG) solutions, has to meet high requirements in order to guarantee secure, reliable and economical grid operation. Particularly, the deployment of an advanced metering infrastructure (AMI) with smart meters (SM), intelligent electronic devices (IED), high-precision phasor measurement units (μPMUs) and other telemetered measuring instruments will cause a huge amount of real-time data.

- These real-time data has to be processed, checked and verified before being passed to the application functions of the DMS.
- The data verification has to be done by a robust distribution state estimator that is adapted to the typical topological structures of active distribution grids.

As a consequence, the importance of distribution system state estimation (DSSE) will increase significantly, and a robust distribution state estimator will be a key tool for a future DMS capable of controlling and monitoring active distribution grids.

Project Description A joint research and development project was started to cope with the new challenges that emerging active distribution grids will bring up. The aim of this project is to enhance the DMS of the industrial partner with grid application functions needed for the operation of active distribution grids. Thereby, the university partner has the task of developing a distribution grid state estimator.

This distribution grid state estimator shall be an important component of the future DMS because it will serve as a kind of filtering function between the SCADA data and the data for the application functions. In addition, it also has to provide an interface between SCADA functions using the SCADA data model and application functions using their particular grid model.

Progress in 2014 The MATLAB test bed has been improved and enhanced so that new algorithms and procedures can be implemented with ease. Also some visualization functions have been improved.

As the state estimator and many application functions need a simplified node-branch-grid model as their particular grid model, the desired interface has to be provided between this node-branch-grid model and the SCADA data model, which is often referred to as physical grid model. The providing of the desired interface has to be done by a special algorithm, which has been therefore developed. As this algorithm derives the node-branch-grid model from the detailed physical grid model by filtering, or rather condensing, it is denominated as topology condensing algorithm.

A first version of a state estimation algorithm has been developed. The principle idea of this algorithm is to solve the so called topological equation system in a calculation sequence given by the topological structure of the distribution grid. This first state estimation algorithm has been extensively tested by means of a small test distribution grid implemented in MATLAB.

Since this thorough verification showed that the principle idea of this first state estimation algorithm works, the development of a second algorithm, denominated as non-topological state estimation algorithm, has been started. In general cases of overdetermined measurement configurations, this algorithm has to determine the optimal estimate for the system state. The working principle of this second algorithm is to derive the normal equations of the overdetermined equation system, so that the latter can be solved like a minimization problem. The idea is to determine the calculation sequence by the topological structure of the distribution grid. Thereby, the challenge is that depending on the measurement types additional coefficients can appear in the normal equation expressing second-neighborhood between nodes of the distribution grid. To cope with these kind of coefficients, an auxiliary function is needed, which is currently under development.

Project Partners This work is done in collaboration with Rittmeyer AG and is supported by the Commission for Technology and Innovation CTI.

Smartgrid-Polysun: Design Tool for Local Load Management

Evangelos Vrettos, Advisor: Göran Andersson

Introduction The increasing shares of fluctuating renewable energy sources in the grid require active participation of demand in power system control. This is expected to significantly increase the operational flexibility of power systems in various time scales, and it is known as demand response (DR).

Project Goals In this project, we develop a software tool that integrates DR methods for power system applications. The tool allows aggregations of residential loads and commercial buildings to participate in energy and ancillary service markets, in particular primary and secondary frequency reserves and voltage regulation. Load aggregators can use the tool to estimate the DR potential under different control strategies and communication architectures.

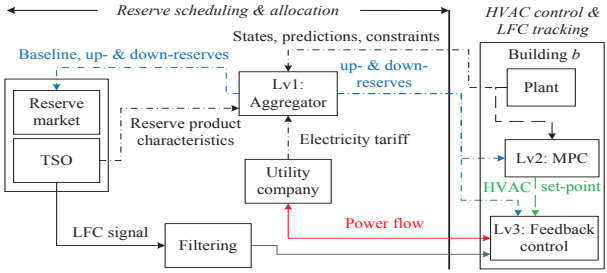

Figure 4.3: Control scheme for reserve provision by commercial buildings.

Progress During 2014, our research covered mainly the following topics:

- Scheduling and provision of secondary frequency reserves by commercial building aggregations considering energy-constrained signals [**??**].
- State estimation and control of aggregations of thermostatically controlled loads (TCLs) under constrained communication networks [**??**].
- Primary frequency control by aggregations of residential refrigerators considering startup dynamics and lockout constraints [**??**].
- Control scheme to integrate heterogeneous thermal loads in frequency regulation, and assessment of frequency dynamics [**??**].
- Scheduling and real-time control of loads and storages in electricity markets under wind power and spot market price uncertainties [**??**].

Outlook In 2015, we plan to integrate multi-zone thermal models and a state estimator in our framework for reserve provision from commercial buildings. Additionally, we are interested to apply distributed optimization techniques to improve the scalability of the method. Furthermore, we plan to benchmark the state estimation methods for TCL aggregations against methods from the literature. Also, we will work more on power system frequency dynamics with large DR shares in frequency control. Last, we will try to validate the methods on frequency control via experiments on a real building.

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Partnership: *BFE, Vela Solaris AG, swisselectric research*

4.2 Power Markets

G. Andersson is academic advisor for the projects in section **??**.

BPES — Balancing Power in the European System

Matthias A. Bucher, Advisor: Göran Andersson

Introduction A future European power system will require more operational flexibility in order to accommodate the increasing amount of fluctuating power producers, i.e. primarily wind power and photo-voltaic. In a sustainable scenario this balancing power must be provided by renewable power sources in order to fulfill the energy policies of EU and other European countries, e.g. Norway and Switzerland. There are different means to reduce the need for balancing power or to provide the needed balancing power in a sustainable way. On the one hand, improved forecasts of power production and increased controllability of fluctuating power sources reduce the need for balancing power. On the other hand, designated storage devices close to the fluctuating power producers and hydro power from a storage reservoir as well as demand side participation will increase the operational flexibility.
In Europe hydro power is of limited capacity and is located in a few geographical areas, i.e. basically in Scandinavia and in the Alps, implying that a certain transmission capacity is required. Grid expansion or the use of controllable HVDC interconnections can enable an efficient integration of hydro power in an European-wide balancing power scheme. It is clear that the need for a more flexible system operation will also introduce additional requirements on the transmission system. These requirements are concerning needed transmission capabilities but also the management and control of the transmission grid. Both these aspects are addressed in order to obtain an effective solution for handling balancing power in the European system.

Research Objectives The research objectives of the project are to address challenges related to balancing power in a future power system with a substantial part of the power generation in form of fluctuating renewable power sources. The main focus lays on the development of planning methods and operational strategies for the future European system incorporating the needs of balancing power considering technical, economical and environmental aspects.

Progress The work conducted in 2014 investigated three different aspects: firstly, a framework to quantify the flexibility available at a certain location in the grid using an unified flexibility metric is proposed. The framework can be used to support reserve procurement, system operation or also system expansion. Secondly, in [**??**] we present a method that addresses the cross-border coordination of flexibility between TSOs and the added flexibility from corrective control measures in this regard. It is an alternative to current operation using the available transmission capacity (ATC). Thirdly, different tasks focused on how to increase the operational flexibility: A method to place HVDC interconnections was presented that not only considers the reduction of operational costs but also the additional flexibility that is enabled due to the controllability of the power flows on the HVDC interconnections. Further, a method that allow to robustly operate power systems with line ratings that are dynamically adapted depending on current meteorological conditions and finally, initial steps towards models of power-to-gas plants were done [**??**],[**??**].

Future Tasks Planned research tasks are a twofold: firstly, we attempt to extend the methods to integrate dynamic line ratings and secondly we integrate the metric for locational flexibility in different planning and operational methods.

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Partnership: *Technical University of Denmark (DTU), Norwegian University of Science and Technology (NTNU), Swissgrid*

MoVeS - Modeling, Verification and control of complex Systems - From foundations to power network applications

Tobias Haring, Advisor: Göran Andersson

MoVeS The aim of the MoVeS project was to propose methods for modelling, analysis and control of complex, large scale systems. We adopted the framework of stochastic hybrid systems (SHS), which allows one to capture the interaction between continuous dynamics, discrete dynamics and probabilistic uncertainty. In the context of power networks, SHS arise naturally: continuous dynamics model the evolution of voltages, frequencies, etc. discrete dynamics changes in network topology, and probability the uncertainty about power demand and (with the advent of renewables) power supply (http://www.movesproject.eu/). As a concrete power network application, the issue of ancillary service market design for active power was chosen. The future requirement of handling large-scale integration of renewable energy carriers calls for contributions in this framework. Furthermore demand side participation will become a key aspect in the provision of positive or negative balancing power.

Research Objectives The research objective is the economic sound setup of ancillary service markets in order to provide financial incentives for market-based renewable energy-infeed and demand response. This includes:

The keen procurement of ancillary services through the determination of the necessary amount of reserve capacity and the economic valuation on customer side. Further, decentralized market designs encourage fluctuating energy injections to hold their schedule (see also [**??**], [**??**], [**??**], [**??**]).

The implementation of market designs which enhance the participation (aggregated) demand units (see also [**??**], [**??**], [**??**]) and deal with issues of privacy and competition.

Current tasks

- The assessment of the cost-efficiency of real-time pricing approaches vs. direct load control via pre-defined contracts,
- The assessment of market-based renewable energy support and investments in storage,
- The development of a simulation framework for evaluation of investments in HVDC or gas infrastructure.

Future Outlook

- The identification of the role of competition for aggregation units on a retail level,
- The assessment of a European-wide capacity support mechanism.

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4.3 Future Electric Energy Systems

In the projects of this research area we contribute to the goal of transforming our energy demand towards a sustainable, environmentally friendly and secure supply. Main drivers of this transformation are the world-wide efforts to reduce CO_2 emission, increase the share of new renewable energy production, increase the efficiency of energy use and (at least in Switzerland and Germany) to phase out nuclear power plants. Our projects cover both, systems and technology oriented questions, and are in the area of electric vehicles, local load management, optimized use of transmission infrastructure, planning of the whole European energy infrastructure, and HVDC networks and breakers. G. Andersson and C. Franck are advisors for projects in section **??** as indicated.

THELMA - Technology-centered Electric Mobility Assessment

Marina González Vayá, Thilo Krause, Advisor: Göran Andersson

Introduction

The main goal of this project is to perform a holistic sustainability assessment of electric mobility in Switzerland. This can only be realized by means of an interdisciplinary system analysis that draws on the expertise of different research institutions. The project's technology-centered system analysis comprises the areas of powertrain technologies (ETHZ-LAV), power system models (ETHZ-PSL), transport simulations (ETHZ-IVT), energy demand and supply modeling (ETHZ-ESD) and life cycle analysis (EMPA-LCAM). The project management and coordination is provided by the Paul Scherrer Institute.

The Power Systems Laboratory focuses on the power systems analysis, specifically on the impact assessment of a large-scale introduction of plug-in electric vehicles (PEVs) on distribution and transmission grids, as well as the investigation of Vehicle to Grid (V2G) schemes.

Progress

This project was finalized in 2014. Figure **??** gives an overview of the tools developed by the PSL, and the corresponding inputs and outputs. PEV penetration scenarios, season-dependent electric vehicle energy consumption models, driving patterns from the transport simulation MATSim, and supply and demand scenarios for electricity have been integrated into an Optimal Power Flow (OPF) model for the Swiss high voltage network.

With that, the future loading of network assets, power plant dispatch and potential for provision of ancillary services have been simulated. With the charging patterns obtained from the OPF, the impact of electromobility on BKW's medium voltage distribution grid has been assessed, including transformer aging. Finally, the impact of different charging strategies on battery aging has also been analyzed.
The results suggest that PEVs could be integrated into power systems without any major impact on the electricity supply side, as well as the transmission and distribution networks. Moreover, PEV charging is a very flexible load that can be shaped to reduce the costs of generation, to avoid congestions and even to provide network ancillary services. PEVs could also potentially play a role in system restoration after a blackout.

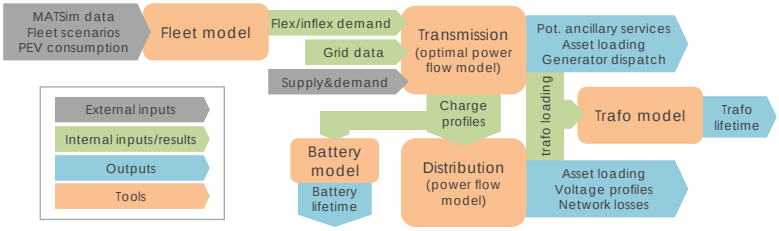

Figure 4.4: Overview of the tools developed by PSL for the project THELMA.

PlanGridEV - Distribution grid planning and operational principles for EV mass roll-out while enabling DER integration

Marina González Vayá, Luis Baringo, Thilo Krause, Advisor: Göran Andersson

Introduction

The anticipated mass roll-out of electric vehicles (EVs) in Europe and the continuously increasing number of distributed energy resources (DER) are posing major challenges to Europe's Distribution System Operators (DSOs) with regard to ensuring a secure and reliable energy supply and network operation. The overall objective of PlanGridEV is therefore to develop new network planning tools and methods for European DSOs for an optimized large-scale roll-out of electromobility in Europe whilst at the same time maximizing the potential of DER integration. The comprehensive approach of PlanGridEV takes into account requirements and constraints of all relevant stakeholders, in particular through an effective cooperation between Original Equipment Manufacturers (OEMs) and DSOs, accompanied by leading scientific and technological research partners in the consortium.

Progress

In 2014, work focused on work package 4, whose objective is to develop methods and tools to manage controllable loads and to optimize distribution grid development in the presence of DER, EV and other storage devices. The PSL is involved in developing models for representing flexible/inflexible EV charging (and discharging), which are to be included in an optimization minimizing distribution grid operational costs. Individual and aggregated EV models were developed for four different DSO scenarios defined in the project:

- **Conventional scenario:** Charge management is not available and therefore EV load is considered inelastic. Charging is modeled to start as soon as an EV parks, yielding an exogenous load profile for the optimization problem.
- **Safe scenario:** EV charging is not directly controlled, but a Time-of-use (ToU) tariff sets incentives to shape the load to the benefit of the DSO. EV load is derived by computing a cost-optimization problem for each EV, and then introduced as an exogenous load in the grid optimization problem.

- **Proactive scenario:** In this scenario an aggregator can start/stop the charging of EVs in response to a request by the DSO. The available flexibility of the fleet can be represented by a set of power and energy constraints in the grid optimization problem. Because charging can only be on/off controlled, this introduces integer decisions into the problem.
- **Smart grid scenario:** This scenario extends the previous case by considering that charging can be modulated and bidirectional. Again, the charging (and discharging) flexibility is represented by a set of power and energy constraints in the grid optimization problem.

Because driving patterns cannot be perfectly forecasted, models to take into account this uncertainty were also developed [**??**],[**??**].

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UMBRELLA - Innovative tools for the future coordinated and stable operation of the pan-European electricity transmission system

Line Roald, Frauke Oldewurtel, Thilo Krause, Advisor: Göran Andersson

Introduction The growing share of electricity generated from intermittent renewable energy sources (RES) as well as increasing market-based cross-border flows and related physical flows are leading to rising uncertainties in transmission network operation. The objective of the UMBRELLA project is to create a toolbox for common forecasting, risk assessment, and operational optimisation, and thus enable the successful integration of RES and the creation of an internal European energy market.
The topic of Workpackage 4 (WP4) is risk-based security assessment, which encompasses both the probability and the severity of events. A risk-based measure carries more information than the deterministic criterion and allows for a quantitative definition of how secure the system is, as opposed to the binary N-1 criterion which only deems the system secure or insecure. A risk-based criteria allows for a more explicit definition of the trade-off between security and cost, and can lead to a more effective utilization of existing transmission capacity. Due to the more comprehensive treatment of probabilities, risk-based methods are better suited for incorporation of different kinds of uncertainty.
However, the advantages of the risk-based assessment also come with some major challenges. First, a proper modeling of outage probabilities and severities is needed in order to come up with a meaningful risk measure. Second, the methods should not be too computationally demanding. Third, the risk information must be condensed for easy interpretation and user-friendly visualization in control centers.

Progress Since the beginning of the project, we have experimented with different models for power system operational risk and different representations of uncertainty related to fluctuating in-feeds from RES, developing a set of risk-based, probabilistic optimal power flow (OPF) formulations.
One focus has been to find a representation of risk related to cascading events for use within an OPF. By placing a limit on the probability of cascade initiation, so-called "risk-based N-1 constraints" are obtained. The method with results is described in [**??**] and [**??**].
Further, we have developed of a unified approach to account for risk related to both forecast uncertainty and random outages. By combining risk-based security constraints for the outages with a probabilistic representation of

the forecast errors, we get a risk-based, probabilistic SCOPF. This formulation allows us to control the risk level in the system even in presence of uncertainty, and also to investigate how risk-based formulations can help us to cope with uncertainty [**??**], [**??**].
Another objective within the UMBRELLA project over the past year is the further development of the probabilistic security-constrained OPF (pSCOPF) presented in [**??**] to include state-of-the-art technological means like PSTs and FACTS devices. The formulation has been extended to include corrective control from HVDC and PSTs. While corrective control usually refers to *post-contingency* corrective control, the formulation also includes corrective control related to *forecast deviations*. By allowing the HVDC and PSTs to react to the forecast deviations, it is possible to optimize the uncertainty margins (i.e., the security margins necessary to secure the system against forecast uncertainty) and thus reduce the cost of renewable integration. The result of this work can be found in [**??**], where it is also used to assess the impact of different market designs. Finally, a first step towards extending the pSCOPF to AC power flow has been taken. In [**??**], we propose to use a linearized version of the AC power flow equations to define uncertainty margins for use with AC power flow equations, which can be included in an AC pSCOPF.

Future Tasks

- Further development of probabilistic and risk-based security criteria
- Evaluation of how the probabilistic and risk-based methods influence electricity market and grid operation in Europe

Partnership: *TU Delft, TU Graz, RWTH Aachen, UDE, FGH, 9 Members of the TSO Security Cooperation (TTG, Amprion, CEPS, Eles, TransnetBW, Swissgrid, TTB, PSE, APG)*

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HeatReserves — Demand response for ancillary services: thermal storage control

Evangelos Vrettos, Theodor Borsche, Frauke Oldewurtel, Advisor: Göran Andersson

This is a joint project with the Automatic Control Laboratory.

Abstract The electricity grid has been going through drastic changes and will continue to do so in the upcoming years. One important cause of the changes originates from the strong increase of renewable energy sources, such as wind and solar, which are fluctuating and hard to predict. Since in a power grid demand and supply must be balanced at all times, the uncertainty in renewable generation increases the need for so-called ancillary services. Control reserves are the most important form of ancillary services and provide a fast reacting compensation for a power shortage or surplus in the network. Control reserves are traded in the control reserve market and are today mainly covered by conventional generators. In Switzerland, control reserves are prominently provided by hydro power plants.

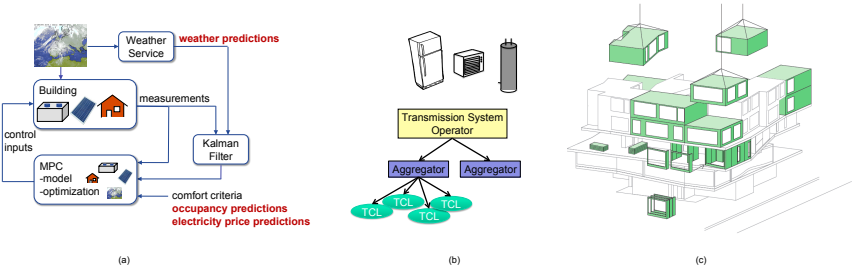

Figure 4.5: As thermal loads we consider the HVAC system of building aggregations (a) and thermostatically controlled loads (b). Our proposed algorithms will be tested in simulation as well as in a case study on a modular test building (c).

We propose to use thermal loads as additional means for ancillary services. To achieve this, we develop appropriate demand response schemes for the thermal loads. One advantage of thermal loads is their ability to react locally. The increase in the number of ancillary service providers also leads to higher market liquidity. Finally, demand response can help to reduce electricity peaks. We propose two main options for providing ancillary services with thermal loads: first, control of Heating, Ventilation, and Air Conditioning (HVAC) systems of an aggregate of several office buildings (c.f. Fig.**??**(a)); second, control of a large number of household appliances (c.f. Fig.**??**(b)). These two options share a number of challenges:

Modeling and estimation Modeling and estimation are crucial in order to provide good control performance. The challenges are due to modeling the fast dynamics of buildings given their complex HVAC systems as well as uncertainty in building parameters and weather forecasts; and due to a large-scale and distributed population of household appliances in the power grid and very limited measurement possibilities.

Control and communication The models in both options are large-scale, distributed, hybrid (discrete and continuous modes of operations) and stochastic. Effective and tractable control schemes for these systems have to be developed. For office buildings the communication infrastructure is already in place (internet access of most building management systems), but privacy considerations put limitations on the information exchanged. For household appliances existing communication infrastructure is limited, and investment in advanced communication should acknowledge the trade-off between performance and costs.

Economic considerations and user incentives Even if all technical problems are solved, the crucial factor for a successful implementation of demand response will be whether users take part in the proposed schemes. This, to some extent, will be determined by economic incentives balancing benefits to the grid with potential losses or investments to the participants. To ensure user participation, we will investigate market structures, consumer behaviors and design incentives such as rewards, or lottery schemes.

Partnership: *Automatic Control Laboratory, ETH Zurich; Swissgrid; EMPA Dübendorf, Laboratory of Building Science & Technology; University of St. Gallen, Institute of Economy & the Environment*

Distributed Energy Storage, Control, and Allocation (DESCA)

Philipp Fortenbacher, Olivier Mégel, and Johanna Mathieu, Advisor: Göran Andersson

Abstract The rapidly growing share of intermittent Renewable Energy Sources (RES) in the electricity mix will modify the way the grid is operated. More flexibility will be needed to accommodate RES from which a significant amount of electricity will be generated directly at the distribution grid level. Distributed storage can provide flexibility at the system-wide level through aggregation of many small scale units, while individual units can alleviate overloading at the distribution level. To recover high investment costs associated with energy storage, the units should provide several different services to increase their utilization factors [**??**]. The main services considered here are provision of frequency control, upgrade deferral, customer peak shaving, and mitigation of RES prediction errors.

Project Description The project was conducted in cooperation with the company Ampard. The project was divided into three work streams (WS) described as follows:

- WS 1: Modeling of resources
  We modeled flexible assets (e.g. energy storage, demand response, distributed generation), which can provide services to the customer or participate in electricity markets. Simplified models are needed to incorporate these resources into a control framework that is able to coordinate additional services while providing a primary application. We primarily focused on developing a battery model that can describe battery degradation associated with battery usage. By quantifying battery degradation, it is possible to develop optimal control strategies that maximize battery lifetime and enhance the economic viability of the battery system.
- WS 2: Development of local and central control algorithms
  To coordinate distributed assets, supervisory control schemes must be combined with local control strategies that allow resources to provide their primary applications. Moreover, we can manage the additional flexibility of resources to provide secondary applications that enhance profitability. This work stream focused on developing and evaluating local and central control algorithms to manage distributed resources in ways that maximize utilization of their aggregated flexibility.
- WS 3: Develop methods to determine and characterize resource allocation strategies
  The energy and power capacities to be allocated to each application was estimated through historical data and predictions while considering technical and regulatory requirements of each application. The goal was to provide the customers with different allocations strategies to be selected based on their own interests and other portfolio assets. The allocation schedules can be passed on to the control algorithms developed in WS2.

Progresses

- In the scope of WS2 and WS3, we developed Approximate Dynamic Programming and Stochastic Dynamic Programming methods to schedule a storage units providing multiple services [**??**]. Additionally, the Model Predictive Control algorithm previously developed was expanded to coop with forecast error [**??**].
- As part of WS 2 we developed methods to control battery systems in real-time [**??**]. In particular, we proposed an explicit and online Model Predictive Control Scheme that minimizes battery degradation and power losses.
- As a further contribution we presented a method that is able to dispatch a large number of battery systems in distribution grids [**??**]. We suggested a distributed dispatch scheme to reduce the computational complexity as compared to a centralized scheme.

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SCCER-FURIES WP 2: Bulk Multi-Energy Grids

Alexander Fuchs, Advisor: Göran Andersson

Background The stability and reliability of the energy system are critical for all aspects of daily life. It encompasses the electrical infrastructure, but also other energy forms like gas, heat and the water networks. Recent and planned energy policies encourage increasing the share of renewable energy sources (RES) to reduce the dependency on fossile and nuclear sources, manage the climate impact and ensure the long-term sustainability of our society.

The variable nature of RES represents a challenge to the fundamental stability requirement of the power system to match consumption and generation on a second-by-second basis. Solution approaches to address this volatility include the network extension, a more flexible network operation and the use of overcapacities.

Another key element to ensure the security of the overall energy supply lies in the synergies between different energy forms. The benefit from the smart operation of energy conversion and storage components is not systematically exploited in today's energy infrastructure, both on the regional and national level.

The main questions to the global energy transition lies in the proper coordinated modification of the regional grid infrastructures. However, a strong backbone of bulk energy grids is still required and also brings several potential benefits of an improved international collaboration and market integration.

Current Activities The SCCER-FURIES workpackage *Bulk Multi-Energy Grids* (WP2) focuses on the design, operation and practical market integration of the future energy system in Switzerland, while also accounting for regional and international constraints:

- Modeling and optimal operation of large scale multi-energy grids (WP 2.1)
- Development of upgrade strategies for the energy transmission system (WP 2.2)
- Coupling of the developed strategies to energy market structures (WP 2.3)
- Integration of the results with other FURIES workpackages and across SCCERs

Within WP 2.1, four topics are followed to develop a reliable framework for the optimal operation of multi-energy grids that are the prerequisite for network planning and market integration in WP 2.2 and WP 2.3 :

1. Modeling of multi-energy grids and definition of a benchmark model.
2. Generation of energy patterns from predictions of aggregated parameters.
3. Development of tools for the optimal design and operation of energy grids.
4. Application of the models, scenarios and tools to integrated grid simulations.

Presentations There were two public presentations and one poster of the project activities:

- Alexander Fuchs: *SCCER-FURIES WP 2: Bulk Multi-Energy Grids*. SCCER-FURIES Plenary Meeting. Lausanne, 1 July, 2014. (Presentation)
- Alexander Fuchs: *SCCER-FURIES WP 2.1: Large scale multi-energy systems*. SCCER-FURIES 1st Annual Conference. Lausanne, 15 December, 2014. (Poster and Presentation)

IDEAS4cities — Integration of Decentralized Energy Generation and Storage Systems for Cities

Andreas Ulbig, Advisor: Göran Andersson

Introduction The project IDEAS4cities is centered at introducing the concepts of the urban energy hub, a facility that manages the energy flows within a city quarter or community, and the urban microgrid, a small-scale urban energy system integrating local electrical and thermal generation, loads and storage. The two concepts enable decentralized units to locally interact with each other thereby achieving optimal control functionalities.

The integration of energy hubs and microgrids in urban energy systems would lead to new urban energy system configurations, where the specific advantages of the different energy carriers are better exploited when compared with today's urban energy system setup. In this project, optimal system configurations will be designed based on different scenarios. These urban energy scenarios will cover different conceivable futures concerning penetration of distributed generation and energy storage devices. The results of these studies will form the basis for the planning of future urban energy systems and the related energy grids (heat, gas and electricity).

Main Research Objective The aim of this project is to propose and analyse a holistic approach for the optimal planning of decentralised, adaptive energy systems at the city scale, based on the integration of building-integrated renewable energy sources and energy storage, that are interconnected via urban energy hubs and microgrids.

The activities of the Power Systems Laboratory (Work Package B1) aim to

- develop and extend the existing Energy Hub and Power Nodes modeling frameworks to be amenable for modeling and simulating clusters of realistic building blocks and city quarters,
  - incorporating all relevant energy carriers (gas, heat, electricity),
  - fluctuating distributed generation and load demand,
  - efficiencies and limitations of energy storage and other storage-like functionality (demand side participation), and
  - optimization & control techniques for multi-energy grids.
- The urban energy hub model is used for the analysis of case studies using various operation performance criteria, i.e. economic/environmental metrics, security of supply and exergy.

Current Activities

- Development of aggregation methods for power&energy system simulation. Time & asset aggregation significantly reduces the computational effort when simulating large-scale energy & power systems (Fig. **??**).

- Assessing the challenges of changing electricity demand profiles caused by evolving building stock and climatic conditions on distribution grids.

Partnership: CCEM, ETH domain (ETHZ, EPFL, PSI, EMPA)

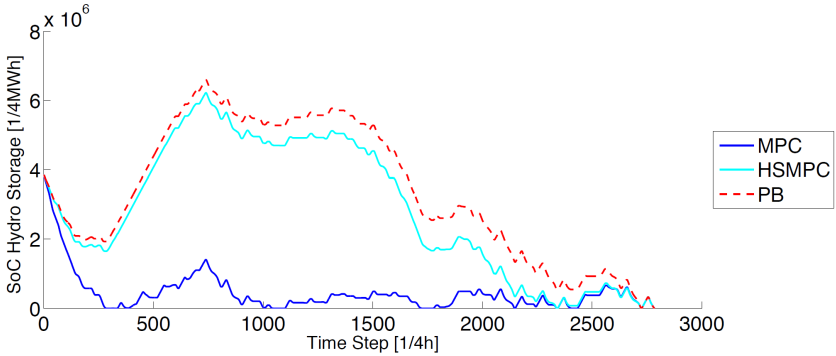

Figure 4.6: Storage dispatch performance for different prediction horizons: homogeneous sampling (N=192), heterogeneous sampling (N=192), performance benchmark (N=672, full simulation length) [**??**].

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Decision Support Software for Optimal Planning and Sizing of Active Electricity Distribution Networks

Osvaldo Rodríguez-Villalón, Francesco Ferrucci, Stephan Koch, Andreas Ulbig, Advisor: Göran Andersson

Introduction The power industry is currently facing an unprecedented and disruptive transformation. Particularly, the following developments pose new challenges for the design and planning of electricity grids: the rapid expansion of distributed generation from variable Renewable Energy Sources (RES), i.e. wind and PV, as well as distributed energy storage, demand response on short time scales, and electric mobility.

The ongoing liberalization of the electricity sector in many countries triggers changes in system operation due to increased trading activities and economic optimization carried out by electricity market participants. A major concern is the constrained physical grid infrastructure. In particular, the distribution grids are increasingly being used for hosting generation units. This causes several problems such as altered power flow patterns and the threat of voltage limit violations. Distribution System Operators (DSOs) need to approach these problems proactively in order to ensure a secure electricity supply. However, it is becoming apparent that conventional grid upgrades, i.e. dimensioning the line capacities for the worst-case load and generation, supported by currently available grid design tools, will yield a highly over-dimensioned and expensive power system when high shares of fluctuating power feed-in are present. New technologies in the context of so-called *SmartGrids* provide novel options to mitigate the need for excessive grid expansion. The cost-optimal choice of *SmartGrid* technologies for a specific distribution grid, e.g. decentralized reactive power control, controllable transformer stations (OLTCs), power feed-in management, dynamic demand response and storage, is case-dependent and highly non-obvious and can be answered only by in-depth technical analysis and simulation-based assessment. DSOs are currently lacking industry-grade computational tools to quantify and rank *SmartGrid* benefits and make informed grid investment decisions regarding *SmartGrid* technologies for their particular power system. This is a unique opportunity that is addressed with this R&D project.

Main Research Objective The project will develop a new Decision Support System (DSS) for the design and planning of electricity distribution networks with large shares of wind and solar power, flexible loads, and storage. While existing planning software does not incorporate the specific properties of these new elements, the proposed DSS provides numerical, optimization-based support to DSOs in multi-million grid investment decisions by automatically ranking tens of thousands of extension scenarios according to economic viability, while taking operational and technical details such as grid stability and optimal sizing of new grid elements into consideration.

Current Activities

- Development of faster grid simulation & optimization algorithms than the currently existing state-of-the-art (Fig. **??**).

Partnership: CTI, ETH IfA, Adaptricity, embotech, Inspire

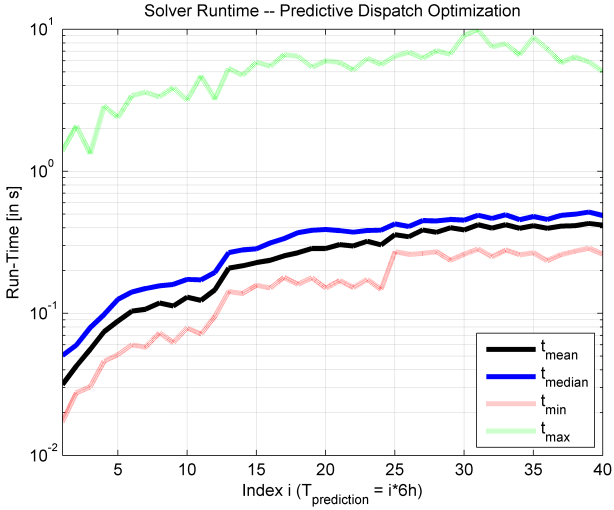

Figure 4.7: IBM CPLEX computation times (predictive dispatch benchmark).

Smart Planning — Optimal planning of future distribution grids considering *SmartGrids* and *SmartMarkets*

Stavros Karagiannopoulos, Philipp Fortenbacher, Andreas Ulbig, Advisor: Göran Andersson, Gabriela Hug-Glanzmann

Introduction Electric distribution grids are facing numerous new requirements and challenges caused by increased amount of installations of Distributed Generation (DG), i.e. wind turbines and Photovoltaics (PV), as well as new load types, i.e. electric vehicles and heat pumps, at low and medium voltage levels. Increasing and, at times, reversed power flows create grid upgrade needs. The project develops new distribution grid planning guidelines that consider the entire range of grid upgrade options, including both *SmartGrid* technologies and *SmartMarket* operation concepts, using real network cases from participating European grid operators. Such distribution grid guidelines should enable the optimal usage of *SmartGrid* elements and *SmartMarket* operation concepts for improved grid operation.

Main Research Objective This project will do research to analyze how these new guidelines should look like and how to find the optimum between grid development and *SmartMarket* activities. In general, with these new aspects the strategy for network enhancement gets more complex, since much more options are available. The general questions to be studied are:

- How to define innovative planning guidelines under consideration of new network technologies (information technology, flexible voltage control, demand side management, supply side management, storage, ...)?
- Where is the optimum between grid extension and grid restrictions limiting *SmartMarket* applications? What are the risks?
- How can *SmartGrid* and *SmartMarket* be considered for asset management, and how can the reliability of assets be evaluated under these new conditions?
- How much access is needed for the distribution grid operator into *SmartMarket* activities?
- How to specify requirements and guidelines in EU countries leading towards common standards?

To answer these questions, the project will analyze today's planning guidelines and create models of real networks in selected European countries. These models will be extended by the new technological options. The demand scenarios will be created by simulations of *SmartMarket* concepts (Demand Side Management and Supply Side Management). For the investigation of new guidelines and the practically relevance of results, it is crucial to explore concrete study cases, enabling reflection about specific issues and evaluating concrete design choices. For further reference confer to [**??**].

Current Activities

- Case study development of urban, suburban, rural distribution grids.
- Investigation of the state-of-the-art practices in distribution grid planning. Key results from a short report on grid planning practices in Switzerland are illustrated in Fig. **??**.
- Investigation of investment costs for conventional network reinforcement as well as *SmartGrid* elements and *SmartMarket* concepts.

Partnership: ewz, TU Dortmund, ABB Germany, TU Eindhoven, Enexis

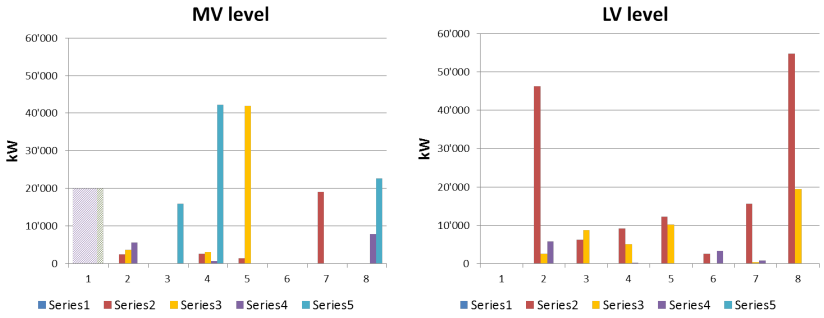

Figure 4.8: Distributed generation connected to low/medium voltage grid.

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SmartMetering — Optimized Distribution Grid Operation by Utilization of SmartMetering Data

Osvaldo Rodríguez-Villalón, Francesco Ferrucci, Stephan Koch, Andreas Ulbig, Advisor: Göran Andersson

Introduction *SmartMeters* are sensor elements that provide accurate high resolution measurements on both the spatial scale, i.e. on a household level, and the temporal scale, i.e. every few minutes, for parts of the low-voltage distribution grid topology for which previously only highly aggregated measurements, i.e. on the substation and transformer level, were available.

In principal, such detailed *SmartMeter* data sets allow a previously unattainable detailedness for state estimation and other grid analysis functionality.

Main Research Objective The objective of this research project is to investigate methods that utilize *SmartMetering* data for distribution grid planning and operation. The main motivation for this project is the enhanced visibility and controllability of the electrical distribution system state which can be provided by *SmartMetering* infrastructure if, and only if, the Distribution System Operators (DSOs) possess suitable methods and tools for data processing, aggregation, analysis, and visualization.

Industrielle Werke Basel (IWB), the utility of the City of Basel, currently gathers *SmartMetering* data from about 40,000 households. This *SmartMeter* data (15-min active energy consumption) are being provided by IWB to ETH and the ETH spin-off Adaptricity. Furthermore, generation data of Photovoltaic (PV) units and Combined Heat & Power (CHP) plants as well as consumption data from large individual customers are integrated.

With these vast data sets and using the combined expertise of the project partners IWB, the multi-national IDS group (a SCADA and energy management software provider, ETH and Adaptricity, ambitious *SmartMetering* data analytics tasks are undertaken. The goal is to derive valuable insights for both grid operation and grid planning from the vast amount of analyzed measurement data generated from the about 40,000 *SmartMeters*. Aggregate measurement time series from the coupling substations to the transmission grid in terms of active and reactive power will be used for calibration.

Current Activities

- One of the focus areas of the first project phase was the exploration of abilities and limitations of *SmartMetering* systems. Special attention was given to the measureable customer- and grid-related variables by the various kinds of *SmartMeters* available on the market.
- A modelling concept for *SmartMeters* was established and implemented in Adaptricity's software tool *DPG.sim*.

- A concept for state estimation methods for the underlying grid variables has been developed. Besides other topics this concerns the distribution grid model including Geographical Information System (GIS) data, *SmartMetering* time series as well as individually measured consumer, distributed generator and aggregate measurement time series.
- Adaptricity has developed software interfaces for importing the relevant data into the simulation environment *DPG.sim*.

Partnership: BFE, Industrielle Werke Basel (IWB), IDS, Adaptricity

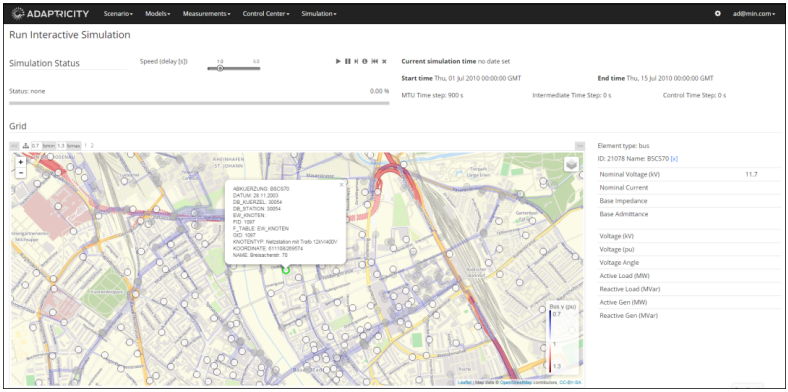

Figure 4.9: Snapshot of IWB's urban grid topology (GIS layer) in *DPG.sim*.

TeKaF: Temperature-based Transmission Capacity Utilization of Overhead Line Networks

Pascal Buehlmann and José Rodriguez, Advisor: Christian M. Franck

Introduction Challenging goals of the climate and energy policy of governments and deregulated electricity markets involve a growth of the electrical energy flows, thereby asking for an increase of the transmission network capacity. Since restrictions and public acceptance deter utilities from building new overhead lines (OHLs), up-grading and efficient use of existing lines are important topics.

A more efficient and safe use of the network 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 unusual warm periods) they exceed their real values for some periods.

Dynamic Thermal Line Rating (DTLR) introduces flexibility to the transmission capacity of the network by making more realistic estimations of the current capacity of the lines by using accurate weather and conductor conditions [**??**] [**??**]. This ensures that the line limits are not exceeded at any time and can also lead to an 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.

The TeKaF project To implement a DTLR scheme, the thermal and mechanical limits of the OHLs have to be known and an accurate model of the OHL temperature needs to be available. Further more, a DTLR scheme needs to take into account the fact that the operation of the line at higher temperatures during long times can affect the mechanical properties of the OHLs. The goal of the TeKaF project is to address all these points. In the High Voltage Laboratory we are responsible for two work packages of the TeKaF project: *i*) We develop and implement accurate models of OHL temperature, and *ii*) we study the electrical-thermal-mechanical coupling effects of the OHL in the free span and near the clamps.

Activities 2014

- Experimental investigation of the relationship between line tension, electrical current and radial thermal conductivity.
- Experimental investigation of the thermal transition zone between the free span and the clamped conductor (Fig.**??**, Bottom).
- Development of OHL thermal models for real transmission lines on the Swiss transmission network.
- Investigation of the cooling capacity of natural convection.

- Construction of an outdoor test facility for OHL (Fig.**??**, Top).
- Improvement of the computed tomographical (CT) evaluation of structural changes of the conductor near the clamp.
- 3D FEM simulations of the clamped conductor with thermal-mechanical coupling effects (Fig. **??**, Center).

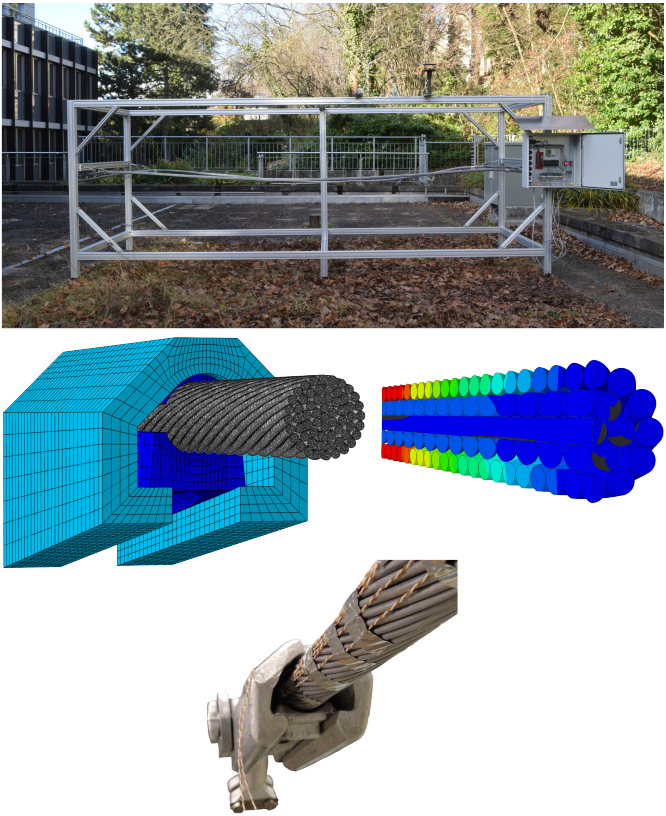

Figure 4.10: Outdoor test facility for OHL (top), FEM model of the clamped conductor (centre), clamped conductor with installed thermocouples (bottom)

Outlook 2015

- Commissioning of the outdoor test facility for OHLs.
- Data collection and analysis on the outdoor test facility for OHLs.
- Development of a practical wind-speed criteria for the implementation of a DTLR scheme.

- Further experiments of thermal behavior and structural changes of the conductor in and near the clamp.
- Entirely coupled 3D FEM simulations of the conductor in the free span and in the clamped zone in respect to the production process.

Partnership: *swisselectric research, CCEM, Axpo AG, Pfisterer Sefag AG, swissgrid*

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SmaCS — Small Current Switching for Future HVDC Substations

Andreas Ritter, Advisor: Christian M. Franck

Background The need for switchgear for use in future multi-terminal HVDC grids is widely established today. A number of challenges have been identified in recent years concerning the realization of this switchgear technology, such as the charging of solid insulation or the breakdown of gaseous insulation by moving particles [**??**]. In terms of switching HVDC currents, research used to be primarily focussed 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. In today's AC substations, these cases are handled by disconnector and earthing switches.

Objectives The **SmaCS** project aims at defining the small-current switching requirements for HVDC substations by means of HVDC disconnectors. 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. Available AC disconnector and earthing switches will be stressed according to these calculations by the new Flexible Pulsed DC Source developed at EEH [**??**]. Potential modifications and redesign suggestions arising from these experiments will be incorporated in future switch designs. The combination of results from calculations and experiments will also serve as a basis for recommendations for the specification of standardized tests for HVDC disconnector and earthing switches.

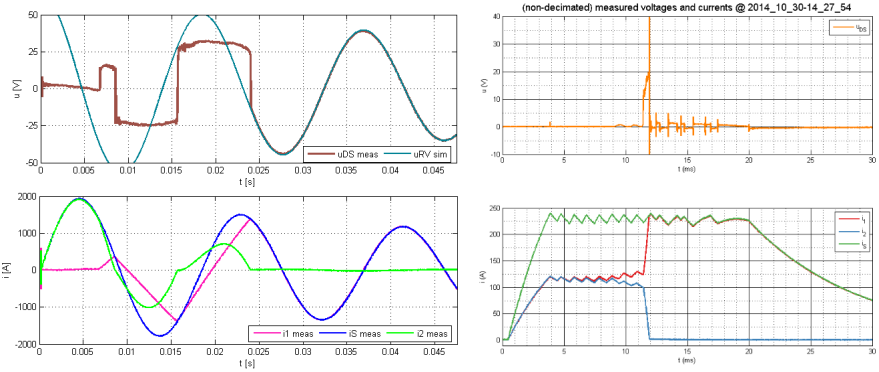

Figure 4.11: Examples of measured bus-transfer switching in AC (l) and and in DC (r) under different recovery voltage and pre-switching current stresses.

Progress In 2014, the non-standardized proof of concept AC disconnector test facility was further improved in terms of measurement accuracy and usability of its experimental data. 502 successful bus-transfer tests were conducted, resulting in enough data to draw first hypotheses with regard to the DC switching capabilities of disconnectors. In addition, valuable input with regards to future setups for testing DC bus-transfer was gained. The details of the AC experiment setup as well initial results were received well at their presentation at the Cigré Session 2014 [**??**]. Publication of the results is expected to follow in early 2015.
Conversion of the now-established testing method to DC currents has been successfully performed and initial measurements have been conducted in late 2014 as shown in Figure **??**. In parallel to the continuation of these measurements, a robust software toolbox to analyze switching conditions will be developed in 2015.

Partnership: *ABB Switzerland Ltd*

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Switching Arcs in HVDC Circuit Breakers

Lorenz Bort, Advisor: Christian M. Franck

Introduction A trend towards an increasing number of HVDC projects for off shore wind farms and long distance on shore energy transmission systems is clearly observable. Naturally, the wish for meshed HVDC-grids follows. However, no circuit breaker technology fully satisfies the requirements for fault protection equipment in such networks yet. The major challenge of DC current interruption is the absence of natural current zero crossings. One possibility for artificial current zero creation are active or passive resonance circuits, of which the latter one requires a negative voltage characteristic ($du/di < 0$) of the switching arc. The influence of the convective cooling of an axial gas flow on this u(i) characteristic is investigated.

Activities 2014 This project was continued by Lorenz Bort who joined the group in January 2014 after Michael Walter finished his PhD at the end of 2013. The previous work used empirical methods to show that the convective cooling is a key parameter for the voltage characteristic of an arc in the investigated regime of 0.5 to 2 kA, using a quasi-stationary current with superimposed transients of several hundred amperes to evaluate the black box model parameters P(g) and tau(g). The new focus of the project is to physically understand the observed changes of the arc characteristic when varying the external parameters that influence the convective cooling. In addition, the experiment setup was improved, for example by installing and testing a new current sensor or reducing the pick-up noise by rewiring the experiment. Furthermore, the previous results for the variation of the blowing tank pressure were verified, using a new and more robust data post-processing routine. Additionally, literature on the physics of high current arcs was reviewed to find a more physics-based model of the arc, in order to enhance the simple black-box approach which was used up to now.

Planned activities 2015

- Design of new de Laval type nozzles with well-defined gas flows in the converging and diverging part
- Predict static arc characteristic using models for the convective cooling in different nozzle geometries
- Measurements to confirm the assumptions regarding the flow made in those models, including pressure measurements at various points along the nozzle
- Measurement of the arc behavior in different flow regimes (subsonic / supersonic, laminar / turbulent flow)
- Validation or improvement of the existing convective cooling models of high current arcs
- Investigation which physical effects and gas parameters influence the static cooling power P(g) and thermal inertia τ(g) of the arc

Partnership: *ABB Switzerland Ltd, Corporate Research*

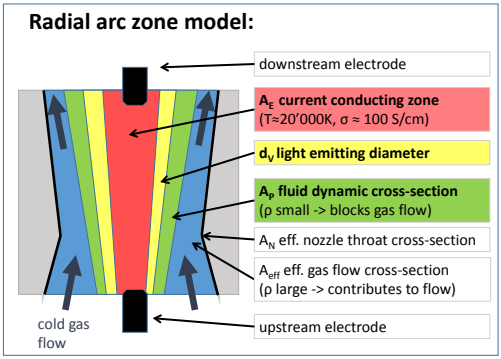

Figure 4.12: Simple model of the convective cooling flow in a nozzle [1]

References

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4.4 Gaseous Insulation

This area of research is a multi-disciplinary field where we study the development of and conditions for electrical breakdowns in gases. Projects topics cover the wide range from studying the the insulation of dc voltages, mixed ac/dc voltages, mixed ac/dc/high-frequency voltages to experimental and theoretical approaches to find a gas-mixture able to replace sulfur-hexafluoride.

Breakdown Behaviour of Electronegative Gases other than Sulphur Hexafluoride

Myriam Koch, Advisor: Christian M. Franck

Introduction In the literature a model to calculate the discharge development of the stepped leader process in the strongly attaching gas SF_6 is described [**??**]. Bujotzek and Seeger [**??**] provide an extension to predict the breakdown voltages for arbitrary field configurations and standard voltage waveforms. The aim of this project is to prove if it is possible to apply these models to other attaching gases to predict their breakdown voltages in technical relevant geometries. This could replace time consuming classical breakdown experiments to characterize potential replacement candidates for SF_6.

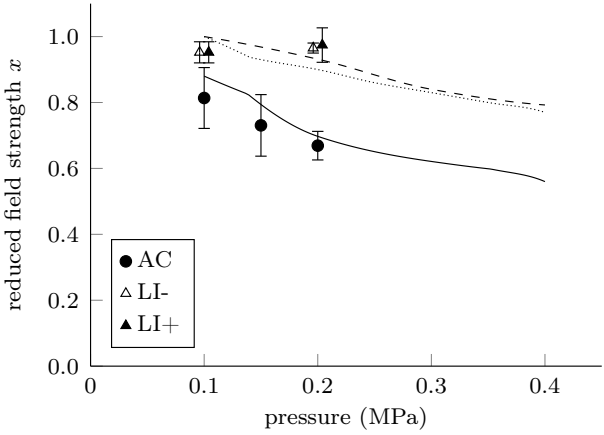

Figure 4.13: Prediction of the breakdown voltage in HFO1234ze for a homogeneous field with rough surface for AC (solid line), positive (dashed line) and negative (dotted line) lightning impulse and results of classical breakdown experiments.

Activities 2014 After the validation of the experimental setup in 2013 with the investigation of SF_6, in the last year several gases were examined: the well-known octafluoropropane (C_3F_8) with dielectric characteristics similar to SF_6 and the well-known but substantially less attaching tetrafluoromethane (CF_4). Both gases were used to validate the model for other gases than SF_6. As they are well-known from literature, they could be easily compared to available data. For both gases good results were obtained [**??**], [**??**].

In a second step a quite unknown gas was investigated: the hydrofuoroolefin HFO1234ze. First the temporal development of partial discharges and breakdowns was investigated in a principal experimental setup. From these experiments parameters can be derived which are needed for the prediction of the breakdown voltages. To validate these predictions, classical breakdown experiments in a homogeneous field configuration with a rough electrode and with a very long protrusion were executed. Figure **??** presents the results for the rough surface. The good agreement between the prediction of the breakdown behaviour and the experimental results show, that even for quite unknown gases the modelling gives reasonable results. Thus, the models according to [**??**] and [**??**] can be used for the calculation of breakdown voltages for replacement candidate gases.

Outlook 2015

- Investigation of further replacement candidate gases.

References

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[4] M. Koch and C. M. Franck; "Prediction of partial discharge and breakdown voltages in CF_4 for arbitrary electrode geometries", J. Phys. D: Appl. Phys., Vol. 48, 055207, 2015

SParX - Swarm Parameter Experiment

Mohamed Rabie, Pascal Häfliger, Alise Chachereau, Advisor: Christian M. Franck

Abstract Within this project, we perform an efficient search for environmentally friendly insulation gases and gas mixtures, as potential replacements for the greenhouse gas SF_6. Considering the enormous number of all conceivable chemical compounds, the number of candidate gases was reduced using computer programs [**??**]. A quantitative investigation of the electric strength follows for the top-candidates with our swarm parameter experiment [**??**]. The experiment implements the pulsed Townsend electrical method. It is semi-automated, which enables rapid screening of gas mixtures. We measure the electron swarm parameters: drift velocity, effective ionization rate and diffusion time constant. These quantities are the necessary input data for fluid models of electric discharges, for instance electron avalanches.

Activities 2014

Investigating the existence of an optimal natural gas mixture. The measurement of the CO_2-O_2 mixtures was completed. No significantly superior mixture was found. The potential for improving the critical field strength is limited to an increase of around 5% compared with synthetic air [**??**]. To broaden the criteria for an optimal mixture, we started considering as well the slope of the effective ionization rate around the critical field, which is a measure of the sensitivity to protrusions. Plotting the slope in function of the critical field strength led to interesting graphs but the same result.
Through the results of the binary mixtures, the question arose if the critical field strength could be increased by adding a third gas component. N_2-O_2-CO_2, N_2-O_2-Ar, N_2-CO_2-Ar and CO_2-O_2-Ar mixtures were simulated with Bolsig+ and Magboltz. The most promising mixtures were measured with the Pulsed Townsend experiment. No significantly higher critical field in combination with a low sensitivity to protrusions were found. Encouraging increase in critical field strength were reported in literature for mixtures at higher pressures. Unfortunately, such high pressures and concentrations of oxygen could not up to now be measured with our setup. The role of detachment has to be better understood to be able to predict swarm parameters in the higher pressure regime.

Investigating strongly attaching gases and gas mixtures. The electron attaching properties of the gases Octafluorotetrahydrofuran (c-C_4F_8O), 1,3,3,3-Tetrafluoropropene ($C_3H_2F_4$), advertised under the commercial name HFO-1234ze, and Octafluorobutene (2-C_4F_8) were investigated. c-C_4F_8O mixtures with N_2 or CO_2 showed a pressure dependent effective ionization rate. This effect can be seen in the displacement current measurements performed at different pressures in figure **??**.

The measurements of HFO-1234ze and 2-C_4F_8 are still under analysis. The critical electric field of HFO-1234ze proved strongly pressure dependent. HFO-1234ze

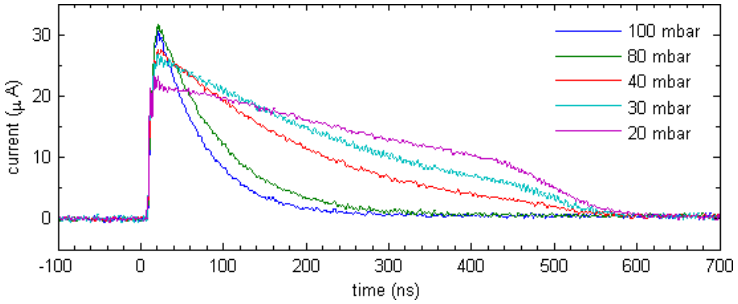

Figure 4.14: Displacement current measured in the mixture of 0.5% c-C_4F_8O in N_2 for a constant distance of 17 mm, a constant reduced electric field of 20 Td, and various pressures.

does not show desired synergy effects in mixture with N_2 or CO_2. 2-C_4F_8 mixtures show a strongly attaching behaviour. The measured effective ionization rate was not pressure dependent in the investigated pressure range.

Deriving attachment cross-sections of strongly attaching gases. A well defined routine was introduced for the investigation of electron attachment cross sections of electronegative gases from swarm parameters [**??**]. Within this method, the attachment cross section of a strongly attaching gas can be obtained from the attachment rate by means of linear inversion. A preliminary attachment cross section was derived for the c-C_4F_8O [**??**]. A collaboration was set up with the University of Fribourg, Dept. of Chemistry, which independently investigated the attachment cross-sections of c-C_4F_8O with a beam experiment, for comparison with our results.

Evaluating ion currents. We developed a method of measuring and analyzing simultaneously electron and ion currents in our pulsed Townsend experiment in order to determine important discharge parameters for both electrons and ions [**??**]. The ionization and attachment rates as well as the drift velocities of positive and negative ions in CO_2 are shown in Figure **??**.

Improving the experimental setup. We investigate various thin film materials for use as an electron source. Preliminary tests in nitrogen showed for one material that the quantum efficiency was ten times higher than the efficiency of palladium which we currently use. Additionally, this new material enabled to extend the measurement range in pure oxygen to higher pressures.
A second experimental setup is under construction to achieve a higher accuracy and an easier handling. The first experiment has been restructured in a more compact way.

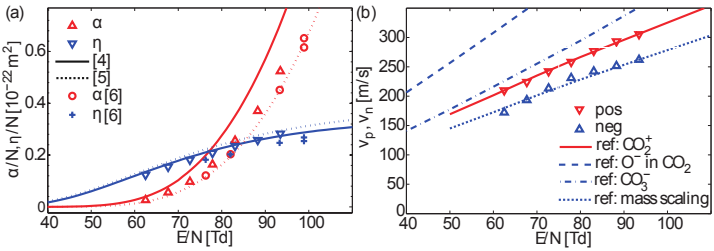

Figure 4.15: **(a)** Measured density reduced reaction coefficients (triangles) in CO_2 vs reduced field E/N, and reference data. **(b)** Measured drift velocities of positive v_p and negative v_n ions (triangles) in CO_2 vs E/N, and reference data.

Outlook

- Data of binary and ternary mixtures of natural gases will be published. To further quantify gas mixtures, a physical model combining the critical electrical field and the slope of the effective ionization rate will be developed.
- Further investigations of natural gas mixtures will be performed at higher pressures and higher oxygen concentrations. For that purpose, the model used for the evaluation will be extended to take detachment into account.
- The data on c-C_4F_8O will be published, and the measurements of HFO-1234ze and 2-C_4F_8 will be further analyzed. Other strongly attaching gases will be investigated.
- A Monte Carlo code for the simulation of electron transport on the basis of fundamental collision cross sections will be developed for the comparison and the interpretation of our measurement results.
- The second experimental setup will be delivered at the beginning of the next year. This will be followed by benchmark measurements.

Partnership: *ABB Switzerland Ltd, Alstom Switzerland, Pfiffner Instrument Transformer*

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DC Insulation

Malte Tschentscher, Advisor: Christian M. Franck

Introduction DC Insulation Due to the growing demand for long distance connections and large transmission capacities, high voltage direct current (HVDC) systems have become an increasingly important element of high power networks. Gas insulated components will play a major role as high power connections, as well as distribution, switching, and transmission devices.

The development and design of reliable gas insulated equipment for HVDC differs significantly from that optimized for HVAC. Phenomena such as surface charge accumulation along with temperature and field dependent material properties are dominant in determining the electric field gradient [**??**]. It is well known that DC stress on GIS causes charging phenomena in the solid insulators as well as on their interfaces to the neighbouring materials. The presence of accumulated charges is considered to reduce the system breakdown voltage. Operating conditions as polarity reversal or voltage transients may lead to a harmful field distribution which exceeds the breakdown voltage [**??**].

The goal of this project is to investigate the solid-gas interface properties along the insulator surface and its influence on the field distribution and electrical strength. The scope contains investigations of homogenous surface properties as well as of local surface inhomogeneities.

Activities 2014 A highly precise measurement setup has been constructed, to determine surface and volume properties of solid insulation under HVDC stress. It is possible to perform up to four isothermal polarisation or depolarisation current measurements in parallel. The setup has been designed for voltages up to $\pm$20kV and temperatures between -20°C and 100°C. The configuration enables current measurements ranging down to 10^{-15}A.

Outlook 2015

- Investigation of interface properties of different materials under HVDC stress.
- Simulation of the effects of surface conductivity on HVDC insulator charging to quantify the accessible range of material properties for achieving robust operation of gas insulated systems (GIS).
- Construction of a measurement setup to verify the findings by surface charge measurements on small scale insulator models.

Partnership: *ABB Switzerland Ltd*

Figure 4.16: High voltage electrode arrangement

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Effects of mixed-frequency voltage stress on dry-type insulation materials

Raphael Färber, Advisor: Christian M. Franck

This is a joint project with the Power Electronic Systems Laboratory (PES).

Motivation The role of power electronic converters in energy transmission and distribution networks is bound to increase due to their unprecedented flexibility in electrical power conversion and conditioning (e.g. HVDC or flexible AC transmission systems). 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 aging 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 compact yet reliable insulation concepts, e.g. for solid-state transformers [**??**].

Activities 2014

- Identification of experimental scenarios (breakdown and aging)
- Dimensioning and manufacturing of an electrode-specimen configuration which permits testing under controlled laboratory conditions
- Acquisition of processing equipment and know-how for in-house production and adequate storage of epoxy specimens
- Identification of Arbitrary Waveform Impedance Spectroscopy (AWIS) as an interesting diagnostic tool for mixed-frequency stress testing

Goals 2015

- Finalization of the electrode-specimen design and its validation with diagnostic tests (see figure **??**)
- First breakdown test results with the pulse generator test bench (developed in collaboration with the PES laboratory)
- Materialization of a low voltage AWIS setup with implementation of the digital signal processing algorithms
- Development of a current measurement scheme allowing the integration of AWIS in the high voltage pulse generator setup

Acknowledgement This project is part of the Swiss Competence Centers for Energy Research (SCCER) initiative which is supported by the Swiss Commission for Technology and Innovation (CTI).

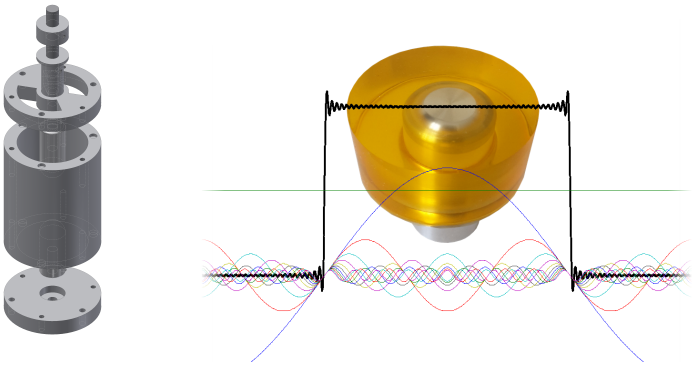

Figure 4.17: Mold allowing adjustable electrode gap separation (left) and epoxy test cast subject to as of yet artistic mixed frequency stress (right)

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[1] P. Wang et al.; "The Influence of Repetitive Square Wave Voltage Parameters on Enameled Wire Endurance"; IEEE Transactions on Dielectrics and Electrical Insulation, 2014.

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Hybrid AC/DC Overhead Lines

Sören Hedtke, Martin Pfeiffer, Tim Schultz, Advisor: Christian M. Franck

Introduction and Background This project investigates the idea of converting existing multi-circuit AC transmission towers to hybrid AC/DC systems (AC and DC on the same tower). The goal is to maximize the capacity of existing infrastructure and reduce the need for new transmission corridors.

Activities 2014 The hybrid AC/DC overhead lines project has gained significant momentum in 2014. New research cooperations that were signed this year confirm the strong interest by industry as well as governmental decision makers. As a result, the HVL team working on the project grew by 2 members (Sören Hedtke as a PhD student and Tim Schultz as a temporary scientific assistant). The following list summarizes the progress made in 2014:

- In a cooperation with RWTH Aachen and Amprion GmbH funded by the German Federal Ministry for Economic Affairs and Energy under funding identifier 03ET7502A, the previously developed ion flow simulation framework ("IMoC") was applied to the investigation of several full-tower geometries found on "Corridor A" of Germany's current Grid Development Plan. This is the world's first specific plan for hybrid AC/DC transmission on the same tower. A comparison of simulated data with full-scale field measurements carried out by Amprion in Germany is planned for a joint publication in 2015.
- The influence of conductor spacing and bundle geometry on the ion current coupling from a DC bundle into a grounded bundle was investigated experimentally and summarized in a technical report.
- Detailed laboratory studies were carried out to benchmark the performance of the IMoC framework with respect to its predictive ability for ground level ion currents and total corona losses for pure DC energization scenarios [**??**].
- Hybrid AC/DC energization scenarios were investigated in the laboratory. The results showed that the role of corona on AC conductors in hybrid AC/DC systems may be more significant than previously anticipated. Implications of these findings for the modeling assumptions used in the IMoC framework are currently being investigated [**??**].
- An in-depth analysis of the connection between the conductor surface characteristics and the resulting corona behavior during rain was launched using novel image processing methods.
- Funding was received from the Swiss National Research Programme NRP 70 ("Energy Turnaround") for a project intended to investigate hybrid AC/DC conversions with respect to the Swiss context. While the HVL will focus on technical aspects, the project is embedded in a research consortium that will also shed light on economic, social and power-systems aspects of a conversion. Partners in this project are: ABB, Axpo, FKH, KWO, Pfisterer Sefag and Swissgrid.

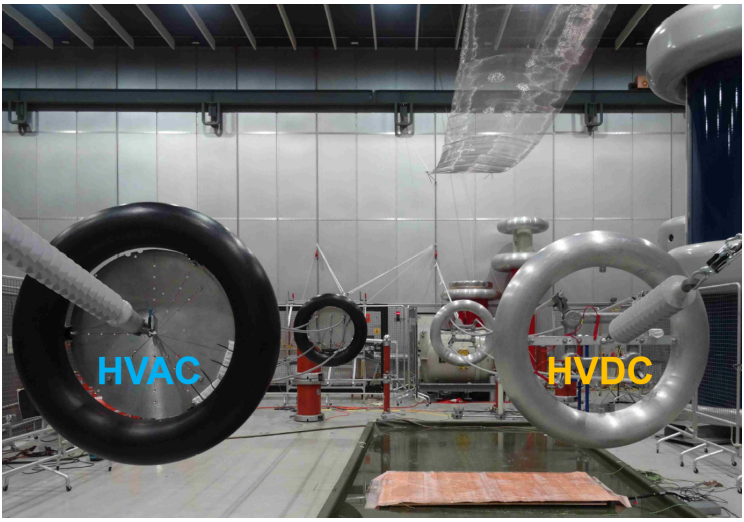

Figure 4.18: Laboratory setup for hybrid AC/DC investigations

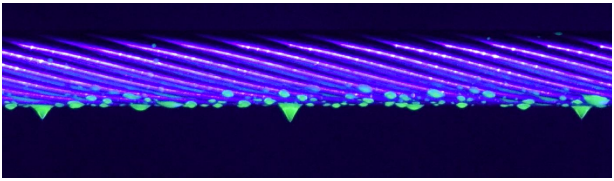

Figure 4.19: Optical investigation on rain drop deformation during corona

- Additionally a cooperation agreement with TransnetBW was signed. The research focus of this project is on audible noise of hybrid AC/DC systems and ion flow simulations.
- In this context a first series of measurements was started to investigate the audible noise emission of DC overhead lines during different weather transitions.
- Also a simulation tool is in development for the asessment of conductor placement in hybrid tower arrangements regarding audible noise emission based on existing semi-empirical formulas. Therefore the conductor surface gradients of hybrid overhead lines are to be evaluated by the charge simulation method (CSM).

Outlook 2015 In 2015 one of the main goals is to conduct outdoor tests aimed at answering questions related the ion current coupling of AC and DC conductors and audible noise production. This work will be accompanied by further indoor laboratory measurements. The ultimate goal is to improve the modeling of these effects and make the results available to the relevant stakeholders.

Partnership: *ABB, Amprion, Axpo, FKH, KWO, Pfisterer Sefag, RWTH Aachen (IfHT), Swissgrid, TransnetBW*

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5.1 Journal Papers

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M. Bucher, R. Wiget G. Andersson, C. M. Franck
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T. Borsche, U. Markovic, G. Andersson
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M. Vrakopoulou, J. L. Mathieu, G. Andersson
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M. Kamgarpour, E. Vrettos, G. Andersson, J. Lygeros
Population of Thermostatically Controlled Loads for the Swiss Ancillary Service Market
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Exploring the Potential of Buildings in the Swiss Ancillary Service Market
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An Optimal Power Flow Formulation Including Risk of Cascading Events
XIII Symposium of Specialists in Electrical Operation and Expansion Planning (SEPOPE), 18-21 May 2014, Foz do Iguassu, Brazil

S. Karagianopoulos, E. Vrettos, G. Andersson, M. Zima
Scheduling and Real-time Control of Flexible Loads and Storage in Electricity Markets under Uncertainty
International Conference on the European Energy Market (EEM), 28-30 May 2014, Krakow, Poland

E. Vrettos, J. L. Mathieu, G. Andersson
Demand Response with Moving Horizon Estimation of Individual Thermostatic Load States from Aggregate Power Measurements
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18th Power System Computation Conference (PSCC), 18-22 August 2014, Wroclaw, Poland

P. Fortenbacher, J. L. Mathieu, G. Andersson
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M. González Vayá, L. Briones Roselló, G. Andersson
Optimal bidding of Plug-in Electric Vehicles in a Market-based Control Setup
18th Power System Computation Conference (PSCC), 18-22 August 2014, Wroclaw, Poland

T. Haring, D. Kirschen, G. Andersson
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S. Karagiannopoulos, E. Vrettos, P. Centeno Lopez, M. Vrakopoulou, F. Oldewurtel, G. Andersson, M. Zima
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O. Mégel, J. L. Mathieu, G. Andersson
Scheduling Distributed Energy Storage Units to Provide Multiple Services
18th Power System Computation Conference (PSCC), 18-22 August 2014, Wroclaw, Poland

T. Qiu, T. Haring, D. Kirschen
Cost Recovery in a Rolling Horizon Unit Commitment with Energy Storage
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A. Ulbig, G. Andersson
Analyzing Operational Flexibility of Electric Power Systems
18th Power System Computation Conference (PSCC), 18-22 August 2014, Wroclaw, Poland

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Control of Thermostatic Loads Using Moving Horizon Estimation of Individual Load States
18th Power System Computation Conference (PSCC), 18-22 August 2014, Wroclaw, Poland

R. Wiget , E. Iggland, G. Andersson
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R. Wiget, M. Vrakopoulou, G. Andersson
Probabilistic Security Constrained Optimal Power Flow for a Mixed HVAC and HVDC Grid with Stochastic Infeed
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Scenario-based MPC for Energy Schedule Compliance with Demand Response
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Impact of Frequency Control Reserve Provision by Storage Systems on Power System Operation
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BESS Control Strategies for Participating in Grid Frequency Regulation
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M. Bestehorn, T. Borsche
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T. Borsche, G. Andersson
A Review of Demand Response Business Cases
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M. Bucher, R. Wiget, G. Hidalgo-Barquero Pérez, G. Andersson
Optimal Placement of Multi-Terminal HVDC interconnections for increased Operational Flexibility
IEEE PES Innovative Smart Grid Technologies Europe (ISGT), 12-15 October 2014, Istanbul, Turkey

P. Fortenbacher, A. Ulbig, S. Koch, G. Andersson
Grid-Constrained Optimal Predictive Power Dispatch in Large Multi-Level Power Systems with Renewable Energy Sources
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T. Haring, G. Andersson
Contract Design For Demand Response
IEEE PES Innovative Smart Grid Technologies Europe (ISGT), 12-15 October 2014, Istanbul, Turkey

M. González Vayá, G. Andersson, S. Boyd
Decentralized Control of Plug-in Electric Vehicles under Driving Uncertainty
IEEE PES Innovative Smart Grid Technologies Europe (ISGT), 12-15 October 2014, Istanbul, Turkey

5.4 Technology Oriented Conference Papers

D. A. Dahl, M. Rabie, C. M. Franck
Electron attaching properties of c-C4F8O derived from swarm parameter measurements in buffer gases
Gas Discharges 2014, 6-11 July 2014, Orleans, France

M. M. Walter, C. M. Franck
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Gas Discharges 2014, 6-11 July 2014, Orleans, France

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A. Ritter, U. Straumann, U. Riechert, C. M. Franck
Investigation of LC-Resonance Driving in Disconnector Bus-Transfer Testing
Cigre Session 2014, 24-29 August 2014, Paris, France

P. Haefliger, C. M. Franck
Critical electric field strength and effective ionization coefficient measurements of nitrogen-oxygen mixtures with variable mixing ratio
Cigre Session 2014, 24-29 August 2014, Paris, France

M. Rabie, P. Haefliger, C. M. Franck
Obtaining electron attachment and ionization rates from simultaneous analysis of electron and ion swarms in a pulsed Townsend setup
SPIG 2014, 26-29 August 2014, Belgrade, Serbia

T. Guillod, J. Huber, G. Ortiz, A. De, J. Kolar, C. M. Franck
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M. Schueller, R. Gremaud, C. M. Franck
Accuracy of surface potential measurements of HVDC spacers
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M. Koch, M. Bujotzek, C. M. Franck
Inception Level of Partial Discharges in SF6 Induced with Short X-Ray Pulses
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G. Andersson
Future Energy and Power Systems – Challenges and Solutions
Los Alamos National Laboratory, New Mexico, USA, 29 Januar 2014

T. Borsche, A. Ulbig
Grid Operation and Flexibility with Energy Storage and Demand Response – Implementation and Economics
EES-UETP Course on Energy Storage in Power Systems: Technologies, Applications and Future Needs, EPFL Lausanne, Switzerland, 6 February 2014

R. Wiget
HVDC Networks: Interaction between AC and HVDC Systems
KTH Royal Institute of Technology, Automatic Control Group, Stockholm, Sweden, 20 February 2014

G. Andersson
The Electric Power Grid - A Key Enabler for a Sustainable Energy System
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Japan - Switzerland Energy Technology Workshop, Gstaad, Switzerland, 12 March 2014

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Keynote Speech: Cigré in the dynamic change of the electric power sector
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HVDC Insulator Charging in SF6 Insulated Systems
Frühjahrstagung Deutsche Physikalische Gesellschaft DPG, Berlin, Germany, 18 March 2014

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Skoltech Workshop on Future Energy Systems, Moscow, Russia, 20 March 2014

T. Borsche
Scenario-based Optimization for Energy Schedule Compliance with Demand Response
Stochastic Optimization Winterschool, Bad Hofgastein, Germany, 24 March 2014

H. Abgottspon
Locally Valid Cuts for Solving Non-convex Problems with SDDP and Application to Hydro Power
Stochastic Optimization Winterschool, Bad Hofgastein, Germany, 24 March 2014

E. Vrettos
Residential and Commercial Demand Response for Provision of Power System Services at Various Time Scales
ABB Corporate Research, Baden-Dättwil, Switzerland, 9 April 2014

M. González Vayá
PEV aggregator's co-optimization of energy and regulation markets
University of Delaware, Delaware, USA, 28 March 2014

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Managing large aggregations of plug-in electric vehicles
Lawrence Berkely National Laboratory, Berkeley, USA, 25 April 2014

M. Pfeiffer, C. M. Franck
Hybrid AC-DC overhead power line research at ETHZ
Wissenschaftsforum HGÜ der TRANSNETBW, Forschungsaktivitäten zur Hochspannungsgleichstromübertragung im Kontext der Energiewende, Stuttgart, Germany, 20 May 2014

K. Fröhlich
Moderation and Opening Speech: Cigré Steering Committee Meeting
EPRI, Electric Power Research Institute, Charlotte, USA, 21 May 2014

M. Bucher
Balancing of Power Systems under Increasing Uncertainty
swissgrid, Laufenburg, Switzerland, 23 May 2014

M. Koch
A new approach to an old question: alternative insulation gas mixtures for GIS
Invited Speech at Customer Meeting MC Moser-Glaser AG, Kaiseraugst, Switzerland, 5 June 2014

H. Abgottspon
On How to Account for Short-term Flexibility in a Medium-term Optimization of Pumped Hydro Storages: a Multi-horizon Stochastic Programming Approach
Conference of the International Federation of Operational Research Societies, Barcelona, Spain, 15 July 2014

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K. Fröhlich
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Modeling Frameworks for Future Power Systems
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Cigré/CIRED Information-Day, Leizpig, Germany, 1 October 2014

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Welcome Speech and Interview
3rd International Colloquium on Transformer Research and Asset Management, Split, Croatia, 15 October 2014

G. Andersson
Felix Wu Distinguished Lecture in Power Systems: The Future Electric Power System – Developments and New Analysis Tools
The University of Hong Kong, Chair of Electrical Engineering, Hong Kong, SAR China, 10 November 2014

C. M. Franck
Opening Speech
Cigré Informationsnachmittag: Hochspannung - Rückblick auf die Cigré Session 2014, Zurich, Switzerland, 20 November 2014

A. Ritter
Alternative Testmethode von Trennschaltern
Cigré Informationsnachmnittag: Hochspannung - Rückblick auf die Cigré Session 2014, Zurich, Switzerland, 20 November 2014

M. Ruh
Technische Voraussetzungen für eine sichere und zuverlässige Stromversorgung
"ETH unterwegs" an der Kantonsschule, Rychenberg, Switzerland, 21 November 2014

H. Abgottspon
Modellierung kurzfristiger Flexibilität in mittelfristigen Optimierungen
Asset Optimization Day 2014, Bern, Switzerland, 12 December 2014

7. Awards and Events

7.1 Awards

Andreas Ritter
Ernst Bickle Studienpreis, SEW Eurodrive Foundation, Germany
Master Thesis "Disconnector and Earthing Switch Operation in HVDC GIS"
July 2014

Kári Hreinsson, Maria Vrakopoulou, Göran Anderson
Best Paper Award, Power Systems Computation Conference (PSCC), Wroclaw, Poland
"Spinning and Non-Spinning Reserve Allocation for Stochastic Security Constrained Unit Commitment"
August 2014

Olivier Mégel, Johanna L. Mathieu, Göran Andersson
Best Paper Award, Power Systems Computation Conference (PSCC), Wroclaw, Poland
"Scheduling Distributed Energy Storage Units to Provide Multiple Services"
August 2014

Line Roald, Maria Vrakopoulou, Frauke Oldewurtel, Göran Andersson
Best Paper Award, Power Systems Computation Conference (PSCC), Wroclaw, Poland
"Risk-constrained Optimal Power Flow with Probabilistic Guarantees"
August 2014

Matthias Bucher, Roger Wiget
Eurel International Management Cup
Winning Team
September 2014

7.2 Colloquia

These colloquia deal with topics on current problems in Power Engineering. The presentations are mostly held by external speakers from academia and industry. The colloquia are open to everyone. There is a regular newsletter informing about the topics and inviting to the next presentations. More information and registration to the newsletter can be found online:
www.eeh.ee.ethz.ch/kolloquium

The Australian Future Grids Project
Prof. Dr. David Hill, University of Hong Kong, SAR China
3 March 2014

Distributed Control of Multi-Terminal HVDC Systems
Martin Andreasson, Automatic Control Lab, KTH, Stockholm, Sweden
11 June 2014

Application of probabilistic constraints to problems of energy management under uncertainty
Dr. René Henrion, Weierstraß-Institut für Angewandte Analysis und Stochastik, Leibniz-Institut im Forschungsverbund Berlin e. V. (WIAS), Deutschland
30 September 2014

The virtual energy storage implemented by Swisscom Energy Solutions
Dr. Martin Geidl, Swisscom Energy Solutions, Switzerland
21 October 2014

A Business Model for Load Control Aggregation to Firm up Renewable Capacity
Prof. Dr. Shmuel Oren, UC Berkeley, California, USA
24 October 2014

7.3 Other Events

Taster Day for Schoolgirls
Presentation of the High Voltage Laboratory to approx. 10 visitors
ETH Zurich, 8 January 2014

Taster Day Electrical Engineering 2014
Presentation of the High Voltage Laboratory to 20 visitors
ETH Zurich, 14 March 2014

Campus Visit Kantonsschule Seetal, Lucerne
Visit of the High Voltage Laboratory, ETH Zurich, Switzerland
ETH Zurich, 25 June 2014

Studieninformationstage für Maturandinnen und Maturanden 2014
Presentation of the High Voltage Laboratory to student groups
ETH Zurich, 3-4 September 2014

Nationaler Zukunftstag 2014
Presentation of the High Voltage Laboratory to approx. 10 children
ETH Zurich, 13 November 2014

8. Infrastructure and services offered

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. **??**): 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)

The High Voltage Laboratory provided various services for several Swiss and European companies or institutions throughout the year.

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-tanδ 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 8.1: Picture of main high voltage laboratory.

Safety upgrade of the HV-Laboratories

Jonas Trüssel, Advisor: Christian M. Franck, Hans-Jürg Weber

Introduction The main focus of this project which is running since last year, is the upgrade of the safety infrastructure of the HV-Laboratories for the experimental setups. The HVL is willing to improve the system from an already safe state to a Safety Integrity Level 3 standard after machinery norm EN 62061 which is state of the art. This increase the safety for the user but also for the equipment.

Activities 2015 All Laboratories are now equipped with new fences and safety devices. Also the large HV-laboratory E31 has a new control unit for the safety for its 800 kV-AC- and 1.25-MV-Impulse-voltage-unit. First successful tests have already be done and the system can be taken into operation.
Eleven more failsafe control units, called Supercube, were build. They are already in use in several Experimental setups.
Our project was presented at the ISH 2015 in Pilsen (CZ) and in various technical journals. Moreover, we have been visited by several universities and companies interested in our new safety and control system. This novel technology is thus transferred to others labs and we expect to see a wider use in the near future.

Supercube.png Supercube.pdf
Supercube.jpg Supercube.mps
Supercube.jpeg Supercube.jbig2
Supercube.jb2 Supercube.PNG
Supercube.PDF Supercube.JPG
Supercube.JPEG
Supercube.JBIG2 Supercube.JB2

Figure 8.2: New safety fence in the big HV-Laboratory

Outlook 2016 Aim until spring 2016 is to finish the project, which contains following points:

- To improve the performance of the Supercube and fix last bugs.
- Create an interface for the new control unit for the existing AC-cascade in the large HV -Lab
- To finish the full and complete documentation.

References

[1] J. Trüssel; "Entwicklung, Aufbau und Test einer Standard-Steuereinheit für die modularen Hochspannungs-Baukastenprüfanlagen des HVL"; Masterarbeit; ETH Zürich-High Voltage Laboratory; 2014

Kametech AG, an ETH spin-off company of HVL

Dr. Nicolas Karrer

Introduction There are several well known methods to measure current but only few are applicable to measure current in the range of 10 A to several 1000 A at frequencies up to MHz for laboratory use. A promising method was developed at ETH and named HOKA-Principle. This principle combines a DC capable current measurement device with an AC only capable measurement device. This way it is possible to measure a current from DC up to the MHz range at nominal current, see figure **??**, while being galvanically isolated.

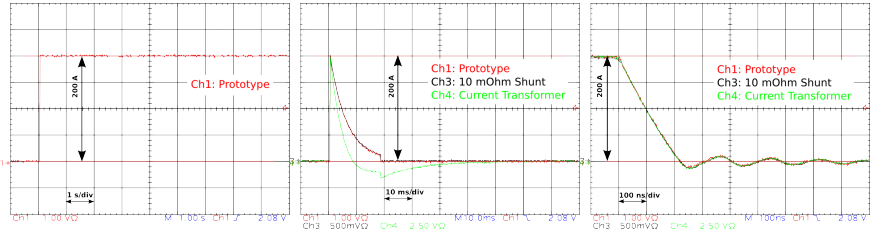


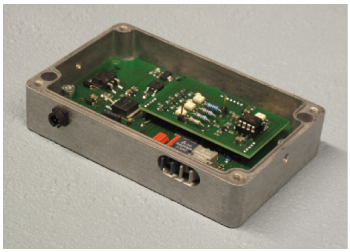
Figure 8.3: Comparison of the frequency range. Left: Constant current (1 s/div), Middle: slow changing current (10 ms/div), Right: a fast current transient (100 ns/div).

Several current measuring devices have been designed over the past years and have been tested at universities and industrial companies, always with positive feedback. Now the time has come to bring these devices, as well as a four-channel fiber optic data acquisition system (figure **??**, left), to the market. Therefore Kametech AG was founded.

Activities 2014

- End of April Kametech AG was founded as an ETH spin-off company of the High Voltage Lab by Dr. Nicolas Karrer.
- A new galvanically isolated current measurement device has been designed for a nominal current of 1000 A and peak currents up to 3000 A. Its bandwidth ranges from DC up to at least 1 MHz with a signal delay below 50 ns. Since our calibration system works only up to 400 A, a new method to calibrate this device was developed. This device has been compared with conventional current devices - the new device performs better than the conventional probes, especially at higher frequencies.
- Another promising development was the realization of an AC current measurement device capable of measuring ripple currents in the order of 10 mA to 500 mA on top of a switched 100 A DC current. The detectable ripple frequency stretches from 1 kHz up to 1 MHz.

- Development of a new calibration system for currents up to 1000 A.
- Towards the end of the year the homepage of **kametech** was finished and is now operational: www.kametech.com



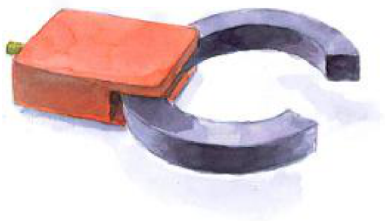
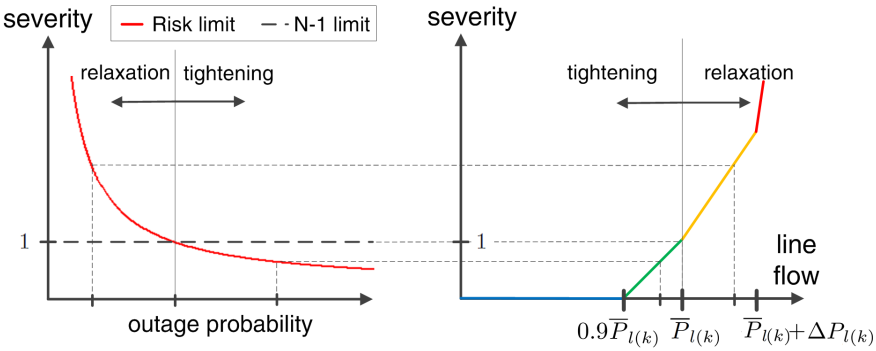


Figure 8.4: Left: Two of the four-channel fiber optic data acquisition system with USB interface for connection to PC.
Right: Sketch of the clamp-on current measurement device (in development).

Outlook 2015

- Small scale series production of different current measurement devices.
- Development of an clamp-on current measurement device (figure **??**, right).
- Participation at an industrial competition for a custom designed measurement device.
- Analysis of the saturation behavior of current-transformer measurement devices based on the data sheet values and lab measurements.
- Initiating sales activities.


severity
Risk limit
N-1 limit
relaxation
tightening
1
outage probability
severity
tightening
relaxation
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line
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