Annual Report 2013

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

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Back Cover: “AC Magnetic Field Simulation around Overhead Power Line.”, Bulletin SEV/VSE, Matthias Walti in cooperation with ETH Zurich, High Voltage Lab.
Dear friends of the laboratory!

This year, we would like to inform you once again about the activities of the Power Systems and High Voltage Laboratories with this annual report. It is our pleasure to look back to our extensive and successful work in research and teaching.

The topic of power engineering in general, and electrical energy in particular, is still in the focus of public and political discussions. The future strengthening of the electric power system is generally considered to be a key element in the planned “Energy Strategy 2050” of the Swiss Federal Council and Parliament, and similarly also in many other European countries. This has had a continued positive influence on our research and teaching activities. Numerous students have decided to put their focus of the final years in this area and several excellent theses have been written. New programs like the “Swiss Competence Centers for Energy Research (SCCER)” and the “National Research Programmes (NRP)” are launched and our laboratories are closely involved. On the European level our research groups are active in EU FP7 and the upcoming Horizon 2020 programs.

The department D-ITET and ETH Zurich also consider electric power engineering as one of the key areas and the search for a new professor in Electric Power Systems has started. We hope that a final decision can be announced later this year.

In 2013, six doctoral students finished their research and successfully defended their dissertations. We congratulate (in alphabetical order) Sedat Adili, Spyros Chatzivasileiadis, Dominik Dahl, Olli Mäkelä, Maria Vrakopoulou, and Michael Walter. Doctoral students of our laboratories have received in total eleven research awards for their excellent and dedicated scientific contributions. Researchers from our lab have also successfully presented their work at the top international conferences and meetings; in total with more than 60 contributions. In addition, sixteen articles have been published in peer-reviewed journals.

A sad news reached us just after the turn of the year: Prof. Walter Zaengl, our much respected colleague who worked as professor for high-voltage engineering at our laboratory from 1969 to 1996, passed away in early January.
2014. We will always hold him and his work in the highest esteem.

We want to thank all researchers and other personnel working at our laboratory, as well as the external lectures. Without the dedicated and competent work of all co-workers of our laboratory, it would have not been possible to present all the interesting projects and important achievements from 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: Rita Heigert
Scientific Staff:

- MSc ETH Hubert Abgottspon
- Dr. Luis Baringo (November 2013 -)
- Dipl.-Ing. Theodor Borsche
- MSc ETH Matthias Bucher
- Dr. sc. ETH Spyros Chatzivasileiadis
- 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
- MSc ETH Markus Imhof
- Dr. sc. ETH Stephan Koch
- Dr. sc. techn. Thilo Krause
- Dr. sc. ETH Olli Mäkelä
- Dr. Johanna L. Mathieu
- MSc EPF Olivier Mégel
- Dr. sc. ETH Frauke Oldewurtel
- MSc ETH Line Roald
- Dr. sc. ETH Monika Ruh (June 2013 -)
- Dipl.-Ing., M.Sc. Andreas Ulbig
- Dr. sc. ETH Maria Vrakopoulou
- Dipl.-Ing. Evangelos Vrettos
- MSc ETH Roger Wiget

External PhD

- MSc ETH Christof Bucher

Students:

- MSc ETH Raffael La Fauci
- MSc ETH Marc Scherer

Scientific Associate:

- Prof. em. Dr. Hans Glavitsch

External Lecturers:

- Dr. Rainer Bacher, Bacher Energie, Baden
- Dr. Dieter Reichelt, Axpo, Baden
- Dr. sc. ETH Gaudenz Koeppel, Axpo, Baden
- Dr. sc. ETH Marek Zima, Swissgrid, Laufenburg
1.2 The High Voltage Laboratory

Head: Prof. Dr. rer. nat. Christian M. Franck

Secretary: Karin Sonderegger Zaky

Scientific Staff:
- Dipl.-Ing. Sedat Adili (- August 2013)
- MSc ETH Matthias K. Bucher
- MSc ETH Pascal B. Buehlmann (Oktober 2013 -)
- MSc Alise Chachereau (November 2013 -)
- MSc Physics Dominik A. Dahl (- June 2013)
- MSc ETH Pascal Häfliger
- MSc ETH Moonjo Kang
- Dipl. Ing. Myriam Koch
- MSc ETH Martin D. Pfeiffer
- Mag.rer.nat. Mohamed Rabie
- MSc ETH Andreas Ritter
- Dipl.-Ing. Michael Schüller
- MSc RWTH Malte Tschentscher (June 2013 -)
- MSc ETH Michael M. Walter (- July 2013)

Technical Staff:
- David Brühlmann, Electr. Technician (- March 2013)
- 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

Scientific Associates:
- Prof. Dr.-techn. em. Klaus Fröhlich
- Dr. sc. ETH Nicolas E. Karrer
- Dr. rer. nat. Timm H. Teich
- Prof. em. Dr. Ing. Walter Zaengl

Academic Guest:
- PhD Laura Ramirez Elizondo, Delft University/Netherlands (September 2013)
- PhD Student Ankan De, NSF FREEDM System Center, NC State Univ./USA (June-November 2013)
- PhD José Rodriguez Alvarez (October 2013 -)
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.
2.1 Lectures

**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 elektr. Energieversorgung
Lecturer(s): G. Andersson and M. Zima


**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

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.
2.2 Student Excursions

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

**Power Markets II**  
Thusis, Switzerland  
April 16-17, 2013

**High Voltage Technology**  
Alstom Grid, Gas-insulated high-voltage switchgears  
Oberentfelden, Switzerland  
April 19, 2013

**Technology of Electric Power System Components**  
ABB Surge Arrester Production Wettingen, Switzerland  
April 25, 2013

**Technology of Electric Power System Components**  
EWZ Hydro Power Plant and Substation Letten Zurich, Switzerland  
May 23, 2013

**High Voltage Technology**  
ABB Micafil Zurich-Altstetten, Switzerland  
May 24, 2013

**Power System Analysis**  
Axpo Baden, Switzerland  
Dec 4, 2013

**Electric Power Systems**  
EWZ Substation ”Sempersteig”  
Zurich, Switzerland  
Dec 6, 2013
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.

(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 Group Projects

Bachelor students are required to complete one group work. A group project includes at least 120 hours of study, the work can be divided into two small projects, each of an expense of at least 60 hours. A group project includes an oral presentation, a written report and is graded.

Viktor Lenz
*Koordination von Stahlwerken*  
Supervisors: E. Iggland, Marc Scherrer

René Sonderegger, Manuel Mühlebach
*Entwicklung eines automatisierten Messverfahrens für Korona-Einsatz-Spannungen und -Ströme an HGU Freileitungen*  
Supervisor: N. Karrer, M. Pfeiffer
2.5  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.

2.5.1  System Oriented Semester Projects

Ari Artinian  
*Multilateral Remedial Actions in Multi-Area Power Systems using the Dantzig-Wolfe Decomposition*  
Supervisor: O. Mäkelä

Seraina Buchmeier  
*Development of Short Term Solar Forecasts*  
Supervisor: O. Megel

Cem Eren  
*Assessing Time Control in Different Power Systems*  
Supervisors: E. Iggland, M. Scherrer

Carsten Heinrich  
*Markov Chain Modeling of Aggregations of Electric Water Heaters for DR*  
Supervisor: E. Vrettos, M. Kamgarpour

David Krammer  
*Estimation of Balancing Capabilities of Hydro Power*  
Supervisor: M. Bucher

Matej Masojedec  
*Marginal Price Forecast for Secondary Control Power*  
Supervisor: H. Abgottspoon

Felix Moritz  
*Stochastic Model Predictive Control of Residential Buildings for Price-based Demand Response Applications*  
Supervisor: E. Vrettos
Manuel Mühlebach
Contingency Screening for Power Flow Calculations
Supervisor: E. Iggland

Jonas Schmutz
Primary Frequency Control provided by Battery
Supervisor: T. Borsche, M. Koller

Jaka Strumbelj
The Influence of PSTs on the Power Flow Under Consideration of Uncertainty
Supervisor: L. Roald

Loukas Theodoulou
Using plug-in electric vehicle fleets to support the integration of increasing photovoltaic capacity
Supervisors: M. González Vayá, O. Mégel

Feodor Tobler
Markov Chain Monte Carlo for Spot Price Process Estimation
Supervisor: M. Hildmann

Christoph Trabert
Passivity-based Stability and Performance Constraints for Power Nodes Storage Units
Supervisor: A. Ulbig

Christina Tzanetopoulou
Impacts of High Penetration of PV in Distribution Grids and Mitigation Strategies Based on Storage
Supervisor: E. Vrettos, O. Mégel

Philipp Wittlinger
Charging scheduling of plug-in electric vehicle fleets under driving behavior uncertainty
Supervisor: M. González Vayá

Alexandra Zigkiri
The Role of Plug-in Electric Vehicles in System Restoration after Black-out
Supervisor: M. González Vayá
2.5.2 Technology Oriented Semester Projects

Oleg Valgaev
*Modelling of a Passive Resonance CB for HVDC Networks*
Supervisor: M. K. Bucher

Maiike Ortibus
*Influence of local weather conditions on OHL temperature distribution*
Supervisor: C. M. Franck

Tobias Wellerdieck
*Identification of time delays, characteristics field strengths and corona charges during partial discharge of SF6 in weakly inhomogeneous fields*
Supervisor: M. Koch

Lei Yang
*Influence of OHL tension and current on radial temperature distribution*
Supervisor: M. Kang
2.6 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.

2.6.1 System Oriented Master Projects

Farid Comaty
*Modelling and Simulation of the European Power System using Power Nodes - Assessing the Value of Flexibility*
Supervisor: A. Ulbig

Jiri Havran
*Forward Curve Modeling for Natural Gas*
Supervisor: M. Hildmann

Kari Hreinsson
*Centralized and Distributed Algorithms for Stochastic Unit Commitment*
Supervisor: M. Vrakopoulou

Avramiotis Falireas Iason
*Re-Design of Automatically Activated Control Reserves in the Swiss Power System*
Supervisor: T. Haring

Stavros Karagiannopoulos
*On geographical allocation of ancillary services in multi-area power systems: case primary control reserves in continental Europe*
Supervisors: E. Vrettos, F. Oldewurtel, M. Vrakopoulou

Andreas Kettner
*Modeling, Simulation and Analysis of the Swiss Electric Power System for high PV and Wind power scenarios*
Supervisor: A. Ulbig
Bing Li  
*Evaluation of cascading risk in optimal power flow*  
Supervisor: L. Roald, F. Oldewurtel

Matej Mesojevec  
*Balance Group Management*  
Supervisor: H. Abgottspon

Dona Mountouri  
*Electro-thermal Energy Storage for the City of Zurich*  
Supervisor: S. Koch

Karl Njalsson  
*Risk adjusted stochastic dynamic programming: A new method for hydro optimization*  
Supervisor: H. Abgottspon

Anthoula Panagou  
*Developing market models to evaluate new power system technologies*  
Supervisors: J. L. Matthieu, M. Vrakopoulou and M. Zima

Ganbayar Puntsagdashes  
*Stability Analysis with Decentralized Control of Photovoltaic Systems*  
Supervisor: M. Bucher

Stephen Raptis  
*SC-OPF in a Mixed HVDC-HVAC Grid*  
Supervisors: E. Iggland and R. Wiget

Luis Briones Roselló  
*Market-based control of plug-in electric vehicles*  
Supervisor: González Vayá

Jan Schlesier  
*Valuation and Revenue Driving Factors of Gas Turbine Power Plants*  
Supervisor: M. Hildmann

Anubhar Ratha  
*Optimal Wind Power Plant Bidding under Consideration of Storage*  
Supervisor: T. Haring, M. Hildmann

Xiaoya Tan  
*Toward higher Net Transfer Capacity values using corrective security control*  
Supervisor: M. Vrakopoulou
2.6 Master Projects

Athanasios Troupakis
Integrated Market for Manually Activated Ancillary Services Energy Products in Switzerland
Supervisor: M. Vrakopoulou

Danijel Veljkovic
Kalman-Filtering Approach for Wind/PV In-Feed Forecasts
Supervisor: A. Ulbig

Bolun Xu
Application-based Optimization for Li-Ion Battery Energy Storage Systems with Degradation Modeling
Supervisor: A. Ulbig

Fengtian Zhu
Secondary frequency control with aggregations of controllable commercial buildings
Supervisors: E. Vrettos, F. Oldewurtel, M. Haller

2.6.2 Technology Oriented Master Projects

Thomas Guillod
Simulation of AC/DC Hybrid Overhead Lines
Supervisor: C. M. Franck
3. Completed PhD Theses

Measurements and evaluation of electron transport in electronegative gas mixtures

Candidate: Dominik A. Dahl  
Thesis: ETH No. 21285  
Date of oral exam: 20 June 2013  
Examiner: Prof. Dr. Christian M. Franck  
Co-examiner(s): Prof. Dr. Zoran L. Petrovic, University of Belgrad

Abstract  Within the framework of this thesis, a swarm parameter experiment (SParX) is designed, built, and operated. It implements the pulsed Townsend (PT) electrical method with a high degree of automatization. SParX is applied to investigate the electrical properties of gas mixtures containing strongly electronegative molecules, and the electron attachment parameters of selected molecules. Above all, the goal is to provide reliable and efficient techniques for characterizing and assessing gases considered as additives for gaseous insulation in high voltage applications.

A key component of SParX is the custom made pulsed electron source. It is built by a thin metal film photocathode in transmissive configuration, which is illuminated by short pulses of an ultraviolet laser system. Photocathodes of various metals have been produced, and they are investigated for their transmission spectra, photocurrent spectra, and quantum efficiencies. For the SParX setup, Palladium films are chosen as they perform most efficiently and stable in the presence of gases.

Intrinsic parameters of the measured PT swarm currents are identified. They comply with a temporal growth model of electron swarms. It is then possible, for the first time, to apply regression methods for obtaining the electron swarm parameters from PT measurements. These evaluation methods produce mutually independent parameters: Bulk drift velocity $w$, effective ionization rate constant $v_{\text{eff}}/N$, and the gas density normalized diffusion time constant $N\tau_D$.

The experimental setup and evaluation methods are tested with measurements in Ar, N$_2$ and CO$_2$, where the present results are found to satisfactorily match reference data. The operating regime of SParX is 1 to 11 kPa.
total gas pressure at 293 to 300 K, with an electric field strength between 10 Td and 170 Td in N$_2$ (1 Td = $10^{21}$ Vm$^2$ is the gas density normalized field strength $E/N$). SParX can provide high accuracy and $(E/N)$-resolution around $(E/N)_{\text{crit}}$, where $(v_{\text{eff}}/N)$ is zero.

Measurements are made in binary mixtures with small amounts ($\leq 1.5\%$) of a strongly electronegative sample gas (SF$_6$ or C$_3$F$_8$) added to a buffer gas (Ar, N$_2$ or CO$_2$). A linear relation between the mixing ratio and $v_{\text{eff}}/N$ is apparent, and it is feasible to evaluate the sensitivity of $v_{\text{eff}}/N$ to changes of the mixing ratio. This analysis technique produces the linear response parameters as a function of $E/N$. These parameters characterize gas mixtures by representing the influence of the electron energy distribution of a buffer gas on the electron attachment rates of a sample gas.

The PT method and the linear response technique are applied to investigate octafluorotetrahydrofuran (c-C$_4$F$_8$O), a gas with previously unknown swarm parameter values. The measurements provide swarm parameters and $(E/N)_{\text{crit}}$ for mixing ratios of c-C$_4$F$_8$O $\leq 1.2\%$ in buffer gases. It is feasible to estimate preliminary electron attachment cross sections of c-C$_4$F$_8$O, which are consistent with the presently measured attachment parameters.

Two criteria are used to assess the electrical performance of gas mixtures: The linear response parameters as a function of $E/N$, and $(E/N)_{\text{crit}}$ as a function of the mixing ratio. For all the sample gases tested, their mixtures with N$_2$ can provide higher $(E/N)_{\text{crit}}$ than the mixtures with CO$_2$. It is found that $(E/N)_{\text{crit}}$ of N$_2$/c-C$_4$F$_8$O reaches 85% of the benchmark N$_2$/SF$_6$ for small mixing ratios. High attachment rates can appear in N$_2$/c-C$_4$F$_8$O because the attachment cross sections of c-C$_4$F$_8$O overlap with densely populated intervals of the electron energy distribution in N$_2$. However, in this mixture we see indications of delayed electron production with concurrent dissociation processes for $(E/N) > (E/N)_{\text{crit}}$. 
Abstract  The partial discharge (PD) measurement technique is a non destructive diagnostic method for high voltage insulation apparatus. Partial discharges are breakdown phenomena in gas occlusions of an insulation which may lead to a total breakdown of the dielectric.

The detection of PDs during post-production quality check of an insulation is difficult mainly because of the statistical time lag, which results from a lack of a start electron. The use of short X-ray pulses (duration 50 ns) has shown to eliminate the statistical time lag by providing start electrons for the partial discharge (PD) development, which makes it possible to detect very small voids at low electric field levels.

This work shows PD measurements on self-produced epoxy samples containing single spherical voids of defined size. The main aim of the experiments was to show how reliable pulsed X-ray induced PD (PRXPD) measurements are on detecting all relevant voids in insulation. Further, the effect of the X-ray dose on the phase resolved PD pattern (PRPD) characteristics through comparing it to natural PD inceptions was investigated. The minimum X-ray dose for PD inception was determined experimentally and general guidelines were given how to implement a PRXPD setup on any HV equipment.

To study the PD mechanism by analyzing the shape of the discharge pulse a time-resolved PD detection circuit was developed (TRXPD). TRXPD measurements with an ultra-wideband detection circuit and a photomultiplier tube allow the comparison of individual PD current pulses from naturally incepted and X-ray incepted voids at different doses and different field strengths.

It is concluded that the method of using ultra-short X-ray pulses to trigger PD is generally applicable and only those voids are triggered that would have incepted naturally with longer waiting times. No particular overvoltage stress is needed to test the insulation system.
Furthermore the minimum PD inception field for a spherical cavity in transparent epoxy is determined very precisely by applying a single X-ray pulse at different phase angles of the applied ac voltage. It is also shown how this measurement procedure can be used for a deterministic approach of modeling PD activity in spherical voids and determining parameters like statistical time delay and residual field after PD inception.
Power System Planning and Operation Methods Integrating the Controllability of HVDC

Candidate: Spyros Chatzivasileiadis
Thesis: ETH No. 21460
Date of oral exam: 13 September 2013
Examiner: Prof. Dr. Göran Andersson
Co-examiner(s): Dr. Brian Stott

Abstract  Aging power system infrastructure and increasing integration of renewable energy sources call for substantial investments in power systems, in order to ensure power system security and competitiveness. Investments on new lines, such as AC or High-Voltage Direct Current (HVDC) lines, are among the options. This thesis develops methods in order to incorporate HVDC lines based on the Voltage-Source Converter technology (VSC-HVDC) in power system operation and planning.

The main contributions lie in the introduction of new algorithms and the derivation of analytical relationships in response to questions regarding power system planning and operation in case of contingencies. In this respect, a new concept is also introduced.

Focussing on VSC-HVDC lines, two Security Constrained OPF formulations are introduced which can be used either for planning or for operation studies. Both take into account the VSC-HVDC lines and their ability to react fast after a contingency offering corrective control actions. The “Cost of Security” index is also introduced for ranking different expansion measures in planning studies.

In order to identify which form of transmission expansion is more preferable, analytical relationships are derived so as to examine if an overlay network with long lines, or local reinforcements by shorter AC line segments result in higher utilization. Relationships are also extracted in order to estimate (and appropriately model) reactive power series compensation of AC lines, when dealing with simplified networks.

The need for increased power flow controllability in highly meshed systems, such as the European network, is identified in several case studies in this thesis. In this respect, the concept “Towards a Fully Controllable Power System” is introduced, which aims at decoupling the market operations from the security considerations. A lower bound on the number of controllers needed in order to make a system fully controllable is derived and the “controllability vector” is introduced as a controllability index. Focussing on HVDC lines, two placement algorithms are developed in order to maximize
power system controllability and maximize social welfare. The first is based on the “controllability vector” introduced in this thesis, while the second makes use of properties of the Karush-Kuhn-Tucker optimality conditions for a DC-OPF problem.

This thesis concludes with yearly simulations on a simplified European power network. The goal in these is to identify the cost of operation and the Cost of Security of different expansion measures. Our results show that controllable flows and the capability of VSC-HVDC lines to offer corrective control actions can significantly reduce both the cost of operation and the Cost of Security.
Abstract  This work aims to systematically and accurately investigate switching arc characteristics in passive resonance high voltage direct current (HVDC) circuit breakers. The replacement of classical band energy with fluctuating wind and solar power from peripheral locations in Europe will significantly challenge the European transmission grid in the future. Energy must be transferred via cables for distances > 50km and via overhead lines for distances > 1000km with low losses. Voltage-Sourced-Converter (VSC) HVDC is considered to be superior to the classical alternating current (AC) transmission for long distance energy transfer, because it has significantly smaller losses and requires no reactive power compensation.

Mechanical circuit breakers are standard fault protection devices in AC networks but do not yet exist for HVDC with sufficient interruption performance. The current zero crossing, essential for arc extinction in mechanical breakers, is not inherently available in DC systems. This makes DC interruption more challenging than AC interruption. Passive resonance breakers excite an unstable current oscillation and create artificial current zero crossings by interaction the switching arc with an LC-commutation circuit. This principle has been successfully applied for Metal-Return-Transfer-Breakers (MRTB) in operation. It is, however, limited in maximal interruptible current, takes too long for current zero creation and uses a large capacitor, which significantly contributes to the breaker costs.

Significant improvement of the interruption performance is expected, if the arc chamber and nozzle design is optimized for passive resonant creation of current zero crossings in DC circuits. For this, the improvement of the switching arc characteristics is shown to be more effective and most probably also more economic compared to the passive L and C components of the resonance path. The main goal of this thesis is a systematic characterization of different arc configurations for use in black-box simulations.

For that purpose, a novel arbitrary pulsed current source has been developed. By creation of complex current waveforms, (eg. step currents and spikes superimposed on a current slope,) the transient and stationary arc

Switching Arcs in Passive Resonance HVDC Circuit Breakers

Candidate: Michael M. Walter
Thesis: ETH No. 21548
Date of oral exam: 22 November 2013
Examiner: Prof. Dr. Christian M. Franck
Co-examiner(s): Prof. Dr.-Ing. Volker Hinrichsen, TU Darmstadt
characteristics can be measured independently of each other. Thereby, a more accurate parameter determination and a better validation of blackbox models is achieved. In principle, the source could also be used to characterize the arc completely model-independent, by generation of step currents with various slope steepness. Furthermore, a novel improved method for arc characterization has been developed. A flexible model circuit breaker has been used to investigate the effect of blow pressure, nozzle geometry, nozzle material and blow gas type.

The investigations confirmed that a falling stationary UI-characteristic with decreasing arc voltage at increasing current is a necessary conditions for creation of passive resonance. A rising characteristic, the arc thermal inertia and high current gradients act as damping terms and inhibit passive resonance. For current amplitudes < 2 kA the following has been shown: a) an increase of blow pressure intensifies the falling slope of the stationary UI-characteristics and improves passive resonance, b) a narrow throat diameter and a large nozzle throat length exhibit a rising UI-characteristic and should therefore be avoided, c) nozzle material and blow gas type have shown only minor influence on the arc characteristics.

The results gained can be used to improve an existing HVDC MRTB in two ways: Firstly, if the time for current zero creation (and with it the total break time) is not important, the switching arc characteristic could be influenced that a) the size of the capacitance is minimized or b) the interruption current amplitude is maximized. Application for this are MRTB or HVDC load break switches. Secondly, the time for current zero creation can be minimized by suitable arc chamber design changes with consequent changes in the arc characteristic. By this, together with an increase in maximal interruption current, existing MRTBs could be improved for use as HVDC circuit breakers. Such a passive resonance HVDC circuit breaker would be a low loss and low cost alternative to the recently proposed hybrid breakers, which use expensive and inherently lossy solid state components.
Methods to Assess and Manage Security in Large Interconnected Electrical Power Systems

Candidate: Olli Heikki Feliks Mäkelä
Thesis: ETH No. 21608
Date of oral exam: 29 November 2013
Examiner: Prof. Dr. Göran Andersson
Co-examiner(s): Prof. Dr. Liisa Haarla

Abstract  The operating environment of power systems has changed in a fast pace during the last years and this change can be expected to continue in the future. Mainly this change can be explained by two major trends. First, the liberalization of the power market in Europe has led to a situation where the power flow pattern in the system changes from one hour to another. Second, an increasing share of electricity is produced using sources of electrical power that have a fluctuating nature. Examples of such production types are wind power and photovoltaics.

The transmission system operators are responsible for secure and reliable operation of their own network that is a part of an interconnected power system. The two above mentioned trends set new challenges for transmission system operators from the security and reliability point of view. In this dissertation, methods are presented that help the transmission system operators to face the challenges better in interconnected systems.

This dissertation contributes to the assessment and management of security in interconnected power systems by proposing additional data exchange among transmission system operators to account for fluctuations of in-feed in the assessment. Moreover, this dissertation contributes to the classification of power system security states by proposing a method that is particularly useful in systems with fluctuating in-feed. The dissertation contributes to analysis and handling of contingencies by considering the probability and severity of events in the systems. Also, this dissertation presents results on execution of the security assessment in interconnected power systems and this issue has been studied from the computational complexity point of view. Additionally, the dissertation proposes a method to handle uncertain power flows of lines in the system by robust re-dispatching of generators. Also, a method to estimate the optimal level of security and reliability needed in the robust re-dispatch method has been presented.

The methods have been illustrated with simulations using the IEEE RTS-96 test system.
Optimal decision making for secure and economic operation of power systems under uncertainty

Candidate: Maria Vrakopoulou
Thesis: ETH No. 21636
Date of oral exam: 3 December 2013
Examiner: Prof. Dr. Göran Andersson
Co-examiner(s): Prof. Dr. Antonio J. Conejo, Prof. Dr. John Lygeros

Abstract Operating power systems in a secure way constitutes a critical task for ensuring a well functioning society. However, security comes at the expense of additional investment and operational cost. The additional costs incurred to maintain a desired security level are expected to increase further due to the integration of Renewable Energy Sources (RES). This highlights the necessity to revisit certain operational concepts and construct novel design methodologies to achieve a better trade-off between a secure and an economic operation of the power network.

This dissertation concentrates on quantifying this trade-off and proposes a mechanism for optimal decision making in the presence of uncertainty. Building on a DC power flow set-up, we introduce the concept of probabilistic security, where the system and security constraints are allowed to be violated with a pre-specified probability. We formulate an optimal power flow problem with N-1 security constraints and wind power uncertainty as a chance constrained optimization program. To obtain a solution to this problem sampling based techniques with guaranteed performance are employed. We then incorporate a generation-side reserve decision mechanism in the developed security constrained optimal power flow framework. The reserves are represented as piecewise linear functions of the uncertainty and we optimize with respect to the coefficients of these functions. Therefore, a by-product of our production and reserve scheduling algorithm is the construction of a reserve strategy that can be deployed in real time operation.

Analogously to the generation-side reserves, we also provide a representation for the reserves offered by demand response. Exploiting demand-side capabilities for reserve provision allows a more economic operation of power systems since it results in lower total cost compared to the case where only generation-side reserves are taken into account. In view of reducing the total cost, the potential of certain network components other than demand response to provide corrective control actions are also exploited. Emphasis is given to HVDC links, and it is shown that, by appropriately modeling their post-disturbance operating point, the desired security level can be achieved at a lower operational cost. Finally, we extend the framework of
probabilistic security to an AC optimal power flow set-up which is based on semi-definite programming. To enhance the flexibility of the system we introduce a corrective control scheme that imposes post-disturbance control of the AVR set-point.

In all cases uncertainty is present and all proposed algorithms are formulated as chance constrained optimization programs. To solve the resulting problems we employ recently developed algorithms based on uncertainty sampling that offer a-priori guarantees regarding the probability of constraint satisfaction.
4. Research Activities

4.1 Power System Dynamics and Control

G. Andersson is academic advisor for the projects in section 4.1.

MARS – Security of Multi-Area Power Systems

Emil Iggland, Olli Mäkelä, Advisor: Göran Andersson, Marek Zima

Project Outline The project is a collaboration between the Power System Laboratory at the ETH Zürich and the corresponding group from the EPFL in Lausanne. System security in interconnected electric power systems is the main topic of research.

Abstract The primary concern of power system planning and operation is ensuring a secure supply of electric power. The N-1 criterion, which dictates that the system shall be able to withstand the unexpected outage of any single component, is commonly used for both operation and planning. Unfortunately, some deficiencies can be seen already in single-area operation. In multi-area operation, where a single transmission system operator (TSO) is responsible only for a part of the system, the N-1 criterion does not provide a clearly defined security criterion. Two main paths are prevalent in the operation of interconnected power systems. These are the centralized and decentralized approaches. Where-as the former proposes a globally responsible entity in charge of supervision, the latter is dependent on coordination and information exchange between the interested parties. The MARS project is domiciled within the decentralized domain, considering the requirements which must be fulfilled in order to increase security of operation while maintaining autonomy of the participants. Strong industry interest in the problem of multi-area security can be seen in commitments such as Coreso [1] and TSC [2]

The goal of this project is to propose new way of defining security, taking into account the desire to fairly share responsibility and costs for maintaining a secure state between the stake-holders. The allocation of cross-border transmission capacity should not be needlessly reduced in an attempt to separate the networks from each other, thereby removing the many benefits given by interconnection.
**Project Goals**  Defining security in multi-area systems is a very challenging task, aggravated by a need to share responsibility and costs of security measures among the stake-holders. The MARS-project addresses some of the topics associated with this question. Specific targets are the adequacy of current operating practices from a security perspective, reducing system vulnerability while maintaining trading capacity and methods for complementing security assessment in multi-area systems.

The project goals can be summarized by the points below:

- Propose needed data exchange and coordination among TSOs.
- Extensions to the current security criteria to account for deficiencies due to fluctuating wind and photovoltaic in-feed.
- Propose a security index that takes the level of security into account.
- Develop methods to consider severity of contingencies in the security assessment.
- Definition of a security criteria for multi-area systems, applicable to single area-systems.
- Allocation of responsibility, and cost, for security between the participants in multi-area systems.

The economic provision of control resources is therefore a crucial aspect. In addition to the system security, the possibility of trading of control reserves in multi-area systems is considered. Current practices dictate that each area is responsible for the provision of sufficient reserves to cover its own needs (secondary and tertiary control reserves), as well as a proportional amount of the demand of neighboring systems (primary frequency control reserves). With the integration of power network, generators with a comparative advantage in the provision of control reserves should be used for this task. In order to allow inter-system control reserve trading, the principles governing reserve sizing and allocation must be investigated in more depth.

The project does not strive towards a complete integration of TSOs into a so-called super-TSO, rather supporting a co-operative approach.

**Progress in 2013**

- Development of a multi-area power flow calculation with reduced data exchange.
- Extension of multi-area power flow to include multiple technologies, in particular HVDC.
- Development of methods to reduce the contingency set which must be considered by external neighbors.
• Development of a method to consider the risk of contingencies by accounting for probabilities and severities of contingencies in systems with fluctuating in-feed.

• Development of a probabilistic method to classify the system security state.

• Extension of a re-dispatch method to consider fluctuations of power flows of lines.

• Successful finalization of project with reporting to project sponsor.

References

[1] www.coreso.eu

Partnership: *swiss electric research, EPF Lausanne, Swissgrid*
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.
Progress in 2013

- The prototype software tool was handed over to the project partner.
- Research visit at NTNU and Sintef in Trondheim, Norway.
- Strategic bidding of ancillary services [1] and hydro power scheduling for a price maker [2] were presented at conferences.
- Detailed evaluation of different methods of how to consider short-term flexibility in a medium-term optimization was performed and will be presented at the PSCC conference.
- Risk-aware operation was considered where stochastic dual dynamic programming was applied to the resulting non-convex problem as well as risk measures were introduced in stochastic dynamic programming. The outcomes of this work will be presented at the PMAPS conference.

References


Smart Grid State Estimation for Fully Transparent Distribution Management Systems

Monika Ruh, Advisor: Göran Andersson

Introduction The advancement of distribution networks towards smart grids (SG) with decentralized energy sources will considerably impact the operation, monitoring and control of those networks. A future distribution management system (DMS) assigned with the task to control and monitor a smart distribution grid has to meet high requirements in order to guarantee secure, reliable and economical grid operation [1]. Particularly, the deployment of an advanced metering infrastructure (AMI) with smart meters (SM), intelligent electronic devices (IED), high-precision phasor measurement units (referred to as micro-synchrophasors or $\mu$PMUs [2]) and other telemetered measuring instruments will cause a huge amount of real-time data that has to be processed, checked and verified before being passed to the application functions of the DMS. 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 smart grid-capable DMS.

Project Description In order to cope with the new challenges that emerging smart grids will bring up, a joint research and development project was started with the aim to enhance the DMS of the industrial partner with smart grid applications. Thereby, the main goal is the development of a smart grid state estimator, which will be the core component of this future DMS. More precisely, the aim is not only to develop a smart grid state estimator but also to find an innovative solution how the latter can establish an efficient link between the base system functions and the application functions of such a smart grid-capable DMS.

Previous Work This project is a continuation of previous work with the objective of developing a DMS with a fully transparent data architecture [3]. The developed algorithms were implemented and tested in the partner’s process control software what proved their industrial feasibility and showed some promising results [4], [5].

Progress in 2013 To gain a deeper understanding of DSSE methods and algorithms, an extensive literature research was carried out during the initial phase of the project. The second phase of the project was then started with the building of a test grid using Excel as data base. This test grid can now be loaded into the MATLAB test bed by means of a simple procedure. During
the later test phase of the project, test grids which are exported from the data base of the industrial partner’s DMS can be loaded into the MATLAB test bed by using the same or a similar procedure. In addition, a generic visualization method has been programmed: By utilizing the coordinates stored in the Excel data sheet, the test grid gets automatically drawn by the visualization procedure. This kind of visualization is very advantageous when at a later date larger test grids have to be loaded into the MATLAB test bed. First careful considerations about how measuring devices have to be linked with the grid topology were done and discussed with the project partner.

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

References


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 (HVDC-VSC) 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**  In the last year, a dynamic VSC-HVDC was developed for dynamic studies [1]. The model includes all components of the HVDC link, like step down transformer, AC reactance, converter and the DC-cable, as well as the underlying control structure of the converters. This model allows an analytical tuning of the underlying PI-controllers according to an industry benchmark model. The developed model can be used in electromechanical dynamic studies.
Together with Alexander Fuchs (ifa, ETHZ) a large simulation study was performed testing the Model Predictive Control (MPC) based global grid controller with the dynamic VSC-HVDC model in the European network. It has been shown in [2] that inter-area oscillations can be damped efficiently by modulating the power injections of the VSC-HVDC lines with the proposed control method.

Currently the introduced control method is extended to be able to be used for voltage stability control. The next steps also includes the development of an placing strategy where to build VSC-HVDC lines in an optimal way for power transmission as well as for power system stability control. Another goal is to develop a decentralized power modulation controller which controls the injected power of the VSC-HVDC terminals.

Partnership: ABB, Automatic Control Laboratory ETH Zurich (ifa), swiss-electric research, swissgrid

References


Development of a Distribution System Simulation and Optimization Platform

Stephan Koch, Advisor: Göran Andersson

Abstract   The objective of this project is the development of a distribution grid simulation and optimization software for Distribution System Operators (DSOs) and SmartGrid researchers. The main purpose is to enable detailed time series simulations down to the customer level in order to provide novel planning and design methods for distribution systems comprising SmartGrid elements. Later, field software components will be created that implement SmartGrid control and optimization methods in real distribution systems.

Project Context   This project is a follow-up to the research conducted within the project Local Load Management [1] and presented in the PhD thesis of Stephan Koch [2]. The project is funded by ETH Zurich through a so-called Pioneer Fellowship [3] which runs from August 2012 to January 2014. It will lead to the foundation of the spin-off company Adaptricity [4] in early 2014. Co-founders will be Andreas Ulbig and Francesco Ferrucci.

Software Product   The software DPG.sim (Distributed Prosumer and Grid Simulation) will be composed of the following modules:

• **DPG.sim Base Product**: Base simulation software, enabling the simulation of so-called Prosumers containing mathematical models of generation, load, and storage units in the power system.

• **DPG.sim.meter**: SmartMetering data analysis toolbox, enabling system operators to gain an understanding of the lower grid levels by analyzing data obtained from SmartMetering.

• **DPG.sim.dispatch**: Predictive dispatch of controllable units in the power system according to wind, solar, and load forecasts. Basis for the DPG.sim.plan toolbox and a dispatch field application.

• **DPG.sim.plan**: Innovative methods for distribution grid planning including SmartGrid elements, building on DPG.sim.dispatch.

• **DPG.sim.renewables**: Evaluation of the impact of renewable energy expansion on the distribution grid, taking into account the local renewable energy potentials based on geographical maps.
Two Graphical User Interface screenshots of a prototype version of *DPG.sim* are shown in Figure 4.2.

![Screenshot of DPG.sim software prototype](image)

Figure 4.2: Screenshots of the *DPG.sim* software prototype

References


Distributed Load Management

Theodor Borsche, Advisor: Prof. Göran Andersson

Introduction  It has been shown in previous projects that Load Management can be used to shift consumption peaks, to level load prediction errors or even to offer ancillary services. Adjusting the load to the production, as opposed to the current paradigm of adjusting production to the load, will be necessary when solar and wind are major sources of power generation. A grid, in which consumers and producers of electric power communicate with each other in order to guarantee a more reliable, highly flexible, automatized operation, can truly be called a smart grid.

Research in Load Management has so far assumed perfect communication between the controller and the loads. Limitations imposed by bandwidth and latency of the communication channels may make adjustments of the control strategy and design necessary. A second focus of the project is in understanding the impact of Load Management on the distribution grid – while it can have adverse effects, when used properly Load Management may be able to reduce strain on transformers and power lines as well as to help integrate distributed stochastic generation.

Results  During the first phase of the project Distributed Load Management, a control topology relying only on aggregated measurements at substation level and on broadcast to the loads was devised. Non-linear estimation techniques were implemented to identify the number of switchable loads. Constraints on switching and temperature of the individual devices are ensured locally. As only unidirectional, low-bandwidth communication is required, communication costs are minimized.
Using the ability to track a reference consumption achieved by the above described control scheme, different business models were investigated. While loads can offer additional flexibility, activating loads during hours with high electric energy prices might increase the cost to the balance group.

One business case for energy balance groups (BG’s) is schedule compliance. Each balance groups submits a day-ahead schedule, and is penalized for deviations from this schedule. As the amount of flexibility needed to avoid deviations is not known in advance, a stochastic optimization based on load scenarios was defined. This optimization then weighs the cost of energy against penalties for schedule deviations. Figure 4.3 shows the full control scheme, including the observer developed in the first phase.

A second use case, this time on the side of the grid operator, is integration of photo-voltaic (PV) generation in low-voltage grids. If production is higher than demand, voltages may rise to unacceptably high levels. Activating loads during these times might alleviate such problems. Preliminary results show, how a simple control architecture can achieve voltage compliance even with high levels of PV penetration.

**Outlook** Future work will focus on optimal dispatch strategies for the loads. Using the high spatial resolution that can be achieved, the optimization may take into account overloading of single low-voltage transformers, local peaks of distributed generation and varying load profiles at different points in the distribution grid. On the other side, forecasts not only for consumption but also for wind and PV infeed are associated with an uncertainty, leading to a stochastic optimization problem.

Partnership: *Landis+Gyr, EKZ, KTI*

**References**

**Research Activities**

Smartgrid-Polysun: Design Tool for Local Load Management

Evangelos Vrettos, Advisor: Göran Andersson

**Introduction** The increasing share of renewable energy Sources (RES) in the electricity grid requires the active participation of demand in power system control tasks, i.e. demand response (DR) [1], and the integration of energy storage systems (ESS). This is expected to significantly increase the operational flexibility of power systems in various time scales.

**Project Description and Objectives** The goal of this project is the development of a software prototype for planning of DR and small-scale ESS at the building level, and evaluation of their effects on power system and power markets. The project objectives are summarized as follows:

- Modeling of controllable loads and storage devices in residential and commercial buildings.
- Optimal control of buildings with controllable loads, storage and local electricity production in a dynamic price environment.
- Effects of large RES shares on distribution networks and solutions based on DR and ESS.
- Provision of ancillary services (frequency and voltage control) by DR with emphasis on control and communication.
- Cost minimization in electricity markets using load shifting and balance group optimization.

Figure 4.4: The algorithm for robust frequency reserve provision with radiative heating, and the resulting room temperature.
Progress  In 2013, the following tasks were accomplished:

- Development of a stochastic model predictive controller (MPC) for optimal building control under weather and occupancy uncertainty.
- Development of algorithms for PV self-consumption maximization in buildings, and integration into the commercial software Polysun [2].
- Balance group optimization using the flexibility of large office buildings based on a deterministic MPC controller [3].
- Optimal battery placement and sizing in distribution networks to mitigate overvoltages and cable/transformer overloadings.
- Development of a scheduling/control algorithm to enable multitasking with thermal loads, i.e. combined frequency and voltage control [4].
- Moving horizon estimation of individual thermal loads’ states for frequency control with minimal investment in new communication infrastructure [5].
- Development of a scheduling/control algorithm based on robust MPC for provision of frequency reserves by office building aggregations [6].

Outlook  Looking forward into 2014, several avenues for further research are foreseen. For example, (a) the algorithm for balance group optimization will be extended considering a stochastic setup; (b) the algorithm for multitasking will be improved applying recent results in convex relaxation of optimal power flow; (c) the moving horizon estimation algorithm will be compared against existing approaches based on Kalman filtering; and (d) the dynamics of thermal loads in office buildings will be modeled more realistically to better estimate the potential for frequency reserve provision.

References


Partnership: BFE, Vela Solaris AG, swisselectric research
Secure Operation of Sustainable Power Systems (SOSPO)

Johanna Mathieu, Advisor: Göran Andersson

Abstract With increasing penetrations of intermittent renewable resources such as wind and solar, new methods are needed to assess power system security and control the grid. This project focuses on security assessment and control at the transmission level. Its aim is to develop new methods for real-time assessment of unsafe operating conditions and control mechanisms that will quickly return the grid to safe operation.

Project Description This project is conducted in collaboration with the Technical University of Denmark (DTU). ETH’s focus is modeling and control of “prosumers” defined as aggregations of consumers and producers at the transmission level. The goal is to use prosumers to provide remedial control actions when the system is approaching unsafe operating conditions. Prosumers control will not be used during normal grid operation. Moreover, we assume that fast control is available for emergency conditions. Therefore, prosumer control can be thought of as a way to gracefully steer systems that have headed into alert states back into normal states.

Goals

- Develop models of prosumer aggregations at the transmission level. The models should be suitable for optimization/control.
- Develop methods to identify the parameters of the prosumer models.
- Work with DTU to develop methods to control consumers in ways that enhance power system security.

Progress We have focused on developing models of aggregations of two types of residential loads: thermostatically controlled loads such as space heaters, refrigerators, and water heaters, and deferral loads such as washing machines and plug-in electric vehicles. Using previously established aggregate load models that treat aggregations of loads as virtual energy storage units, we have investigated the causes and magnitude of uncertainty in these types of models [1]. Additionally, we have just completed a study to estimate the technical resource potential of residential demand response in Denmark [2]. Future work will focus on using these models within control strategies.
References


4.2 Power Markets

G. Andersson is academic advisor for the projects in section 4.2.

Realistic Models for Liberalized Power Markets

Marcus Hildmann, Advisor: Göran Andersson

Research Overview  In the early 1990s many power markets in Europe were transformed from monopolies which are dominated by publicly owned companies into liberalized power markets. For the valuation of contracts and derivatives, electricity risk management and the valuation of virtual power plants (VPP) and pump storage plants, to name just a view, a new set of models is necessary to describe load and price behavior. Statistical models can be used to explain the formation of prices and price movements and also for estimation statistical properties such as volatility. In particular, the following aspects of energy prices will be modeled: Hourly spot prices, long term contract prices and the hourly price forward curve (HPFC).

1. Quality Management of the HPFC In order to trade profitable in energy markets, especially with non-standard over-the-counter (OTC) and structured contracts, it is necessary to capture the yearly, weekly and intra-day seasonality of the hourly prices and the price dynamics in the forward curve term-structure. Since power is not a storable good, the seasonality cannot be arbitrages by the market as it would be the case for a storable good. The standard method for determining the hourly price profile is the arbitrage-free HPFC. Based on the HPFC, all non standard products will be priced therefore the quality of the HPFC is an important aspect of the modelling. Since the HPFC on the other side will never be realized as a product, the quality of the HPFC cannot be estimated by backtesting. This project focuses on the development of quality criteria for the HPFC to ensure quality of the HPFC.

2. HPFC with Market Coupling Constraints
All construction methods of the HPFC are useable only for single price areas. None of the models in literature incorporate several pricing zones of coupled markets / nodal and implicit capacity auctions. While in the beginning of the power market liberalisation, cross border capacity was auctioned explicit independent from the actual power, nowadays many electricity markets show different price zones with implicit capacity auctions for cross borderer trading, such as the Nordpool market or the French/German cross
boarder trading. As a result, the volume of transferred power and possible congestion of the different price zones (national and international) have a direct impact on the electricity price level, structure of the neighbouring price zones and on the HPFC. In this project we work on construction methods for the HPFC which incorporate market coupling mechanics.

3. Valuation of Hydro Pumped Storage Plants
Based on statistical models, algorithms for the stochastic valuation of assets with storage under risk constraints are developed including the option value. The main focus is on hourly valuation including deterministic effects such as day-ahead spot market, intra-day market spread as well as stochastic characteristics like price volatility. For plants such as hydro pumped storage plants, external constraints like water availability has to be included in the valuation.

Current Project Activities In the area of the HPFC calculation current research activity is the development of an HPFC with non linear learning techniques to ensure a better capture of the seasonality. The second focus is the estimation of the integration costs of renewable energy sources (RES) in-feed.

Partnership: KTI, swissQuant Group AG Zürich
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 2013 investigated three different aspects: firstly, a general method to model the relations between forecasts and actually realized measurements, e.g. from power infeed from a wind farm, is proposed. Correlations between different geographic locations are also considered. The method is applied in an operation framework
that makes use of dynamic line ratings [1]. Secondly, in [2] we present a probabilistic power flow formulation that integrates uncertain infeed as well as the operation of reserves and HVDC interconnections. The formulation is applied in a strategy for the procurement and operation of reserves that considers the available transmission capacity and forecasts of uncertain sources. Finally, another research question addresses the cross-border coordination of re-dispatching measures, or more general: flexibility, between TSOs and the added flexibility from corrective control measures in this regard. This research is ongoing and preliminary results are found in [3].

**Future Tasks** Planned research tasks are a twofold: firstly, we attempt to define a general framework for the characterization and management of operational flexibility and secondly we investigate the potential of additional operational flexibility from adept use of HVDC and dynamic line ratings.

**References**


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

Abstract  The aim of the MoVeS project is to propose methods for modelling, analysis and control of complex, large scale systems. We adopt 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 key aspects 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 [3], [4], [5]).

The implementation of market designs on a retail level which enhance the provision of ancillary services through (aggregated) demand units (see also [2], [1]) and deal with issues of privacy and competition.

Current tasks

• The development of an approach to enable market-based renewable energy support and investments in demand response,

• The development of balancing market designs which allow the efficient allocation of costs for system balancing,

• The development of a simulation framework for contract design on a retail level which enable efficient exploitation of DR resources.
Future Outlook

- The identification of the role of competition for aggregation units on a retail level,
- The development of a descriptive simulation framework to investigate different specific balancing settlement design issues.

References


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 4.3 as indicated.

HeatReserves — Demand response for ancillary services: thermal storage control

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

**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, which pump water to high altitudes in case of power surplus and release water through turbines in case of power shortage. Although in Switzerland the electricity production of wind and solar is currently limited, the need for ancillary services is significant also here, because of the nuclear phase-out as well as business opportunities with neighboring countries having substantial renewable generation, such as Germany.

We propose to use thermal loads as additional means for ancillary services to account for the expected increase in renewables. To achieve this, we develop
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).

appropriate demand response schemes for the thermal loads. One advantage of thermal loads is their ability to react locally, whereas control reserves from hydro power plants can lead to congestions in the transmission network. 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 aggregation of several office buildings (c.f. Fig.4.5(a)); second, control of a large number of household appliances (c.f. Fig.4.5(b)). These two options share a number of challenges, which can be categorized as follows:

**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 (currently) very limited measurement possibilities for household appliances.

**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.
4.3 Future Electric Energy Systems

For household appliances communication infrastructure still needs to be developed considering the trade-off between performance and investment 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 (Transmission System Operator) 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.

Demand response options for both office buildings and for household appliances will be addressed by developing appropriate methodologies, tackling the computational complexity of the large-scale aggregated systems, validating the proposed methods in large-scale simulations, and finally case study implementations on a modular test building (c.f. Fig.4.5(c)). The demand response schemes developed will provide additional ancillary services to the grid while optimizing energy use of each building/household unit. The expected outcome of the project is guidelines for Switzerland on the methodology and costs for implementation of demand response schemes for ancillary services and incentives for user participation in the schemes.

Partnership: *Automatic Control Laboratory, ETH Zurich, Swissgrid, EMPA Dübendorf, Laboratory of Building Science & Technology, University of St. Gallen, Institute of Economy and the Environment*
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  Figure 4.6 gives an overview of the tools that have so far been developed by the PSL for the project. Work in 2013 has focused on finalizing and preparing the tool for final simulations of future mobility and power system scenarios, as well as on extending the existing methods.

Market-based control for smart-charging: Previously, a smart-charging scheme based on the direct management of vehicle charging by an aggregator, and another one based on the response of electric vehicles to exogenous prices had been developed. Recently, a scheme building on market-based control was developed. In this framework, vehicles are active market participants, each placing bids in the market. With the help of the reinforcement learning algorithm known as Q-learning, vehicles learn how to setup their bids optimally. Results show that this scheme can also be used effectively to reduce the negative impacts of uncontrolled charging, with a performance close to that of the centralized aggregator-based scheme.

Synergies between electric mobility and renewable energies: We have studied how PEVs could be used as distributed storage resources to help integrate fluctuating energy sources into the power system. In [1] PEV batteries are used to compensate the forecast error of a wind power plant. We developed a day-ahead charging scheduling strategy that minimizes system generation costs, enforces network and PEV end-use constraints, and at the same time enables the fleet to compensate deviations of wind power output from
its day-ahead forecast. For this purpose, a probabilistic wind power fore-
cast model is integrated into an Optimal Power Flow (OPF) based smart-
charging scheme. In other studies we also showed that thanks to the PEV 
charging flexibility, less power from renewable sources would need to be 
curtailed in the case of a high penetration of renewables in the generation 
mix.

**Impact assessment on distribution networks:** Studies were performed for 
the network of the utility BKW, comprising the 16kV distribution network 
and four exemplary 400V distribution networks (rural, mountain, city, and 
suburb).

**Impact assessment on transmission networks:** Based on scenarios for the 
evolution of electricity supply and demand in Switzerland in the future, 
models of the future power system according to the different scenarios were 
developed. This is an important input for the tools assessing the impact of 
electric mobility on transmission networks, which are based on OPF simu-
lations.

![Figure 4.6: Overview of the tools developed by PSL for the project 
THELMA.](image)

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cast uncertainty in smart-charging approaches for plug-in electric ve-
PlanGridEV – Distribution grid planning and operational principles for EV mass roll-out while enabling DER integration

Marina González Vayá, Thilo Krause, Luis Baringo, 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 2013, the first task of Workpage 4 (WP4) has been launched. The global objective of WP4 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 first task of this WP4 aims at formally defining operational and planning process of the distribution grid as an optimization problem. The definition of this optimization problem includes the identification of the objective to be reached, the constraints, the variables and the degrees of freedom, including storage opportunities offered by EVs. The specific role of the PSL is the modeling of EV fleet aggregations and their flexibility.

The next step of WP4 is to develop new methods for representing storage capabilities offered by EVs to optimize the distribution grid operation. This poses several challenges such as the modeling of the coupling between states/hours of the system and the charging profile. The methods to be developed will be applied on typical simulation case studies including different network architectures and EV charging scenarios.
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 centres.

Progress  In 2013, 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 main focus has been to find a representation of risk related to cascading events for use within an OPF. The focus has been on the probability of cascade initiation, i.e., the probability that a first outage leads to a further outage. The severity of the post-contingency operating point is defined as the probability that a second line trip will take place (and thus a cascade is initiated). As opposed to the deterministic N-1 criterion, which assumes that a line trips as soon as the line thermal capacity is exceeded,
the probability of a secondary trip is calculated based on both the extent of post-contingency line overload and the change in line loading between the pre-contingency and the post-contingency condition. 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 [2] and [3].

Another objective within the UMBRELLA project for the past and coming year is the further development of the probabilistic security-constrained OPF (pSCOPF) presented in [4] to include state-of-the-art technological means like PSTs and FACTS devices.

Further, we are working on the development 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 [5].

**Future Tasks**

- Further development of the risk-based security criteria
- Inclusion of state-of-the-art technological measures, like FACTS devices, in the risk-based tool
- Evaluation of different market designs and determination of operational rules and cooperation procedures among TSOs

**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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Control-Based Grid Adaptation & Operational Flexibility of Power Systems

Andreas Ulbig, Advisor: Göran Andersson

Introduction  Power system dispatch optimization and real-time operation are becoming more and more driven by several major trends which include notably 1) the wide-spread and large-scale deployment of variable Renewable Energy Sources (RES), i.e. wind turbines and photovoltaics (PV) units, with highly fluctuating and not perfectly predictable nor fully controllable power generation, 2) the growing power market activity, which has led to deterministic frequency deviations caused by transient power imbalances and more volatile power flow patterns due to more frequent changes power plant set-points, and 3) the emergence of a smart grid notion or vision as a driver for change in power system operation. This constitutes a major paradigm shift in the management of power generation and load demand portfolios. Managing the interaction of conventional power system units, e.g. fully dispatchable, fuel-fired thermal generation as well as bulk hydro storage and non-controllable loads, with new power system units, e.g. variable RES (wind turbines, PV), non-hydro storage and controllable loads, which are only time-variant dispatchable, becomes a more challenging task.

Operating power systems optimally in this more complex environment requires a more detailed assessment of the available and needed operational flexibility. It is an important property of electric power systems and essential for mitigating disturbances in a power system such as outages or forecast deviations of either power in-feed, i.e. from wind turbine or PV units, or power out-feed, i.e. load demand. The availability of sufficient operational flexibility is a necessary precondition for the effective grid integration of large shares of fluctuating power in-feed from variable RES.

Main Research Objective  These grid operation challenges motivate the development of new modeling, control and assessment frameworks that allow the exploitation of yet untapped sources for providing operational flexibility, e.g. via ancillary services. Such sources are, for example, wind turbine and PV units, thermal electric load units in the residential and industrial sector and the distributed electric storage capacity of plug-in (hybrid) electric vehicle fleets.

- Control-based Grid Adaptation  Through better usage of existing flexibility sources via more accurate modeling and more effective control schemes, otherwise deemed necessary investments into grid adaptation for coping with high RES shares, could be deferred. This
is an essence a trade-off between employing more computation & communication is power systems operation, which are cheap (and getting cheaper), and physical grid investments, which are expensive. One example of this is the usage of Dynamic Line Rating (DLR) for improving transmission grid utilization and, thus, also RES integration [7].

- **Power Nodes Modeling Framework** This recently introduced framework [1], [2] can be used for modeling deterministic and stochastic power generation, storage and demand processes and their interaction. Further development of the theoretical foundation of Power Nodes, i.e. its relationship to existing energy modeling frameworks such as the well-known Energy Hub concept [8], its practical application, i.e. the modeling of more complex units (hydro storage lakes & cascades) and their interactions, i.e. aggregation/pooling of power system units and the assessment of the aggregate’s properties, are being pursued.

- **Operational Flexibility in Power Systems** Assessment methods for operational flexibility in power systems are being developed. Of particular importance is the additional operational flexibility that can be obtained from power system units that feature only partially and/or time-variant controllable and observable power generation and demand processes, i.e. variable RES units [3], [4] and traditional load units.

- **Control Schemes for Power System Units** Control methods for the exploitation of increased controllability over power generation, demand and storage units with time-variant availability for ancillary service provision are developed. A fast Model Predictive Control (MPC) scheme has been developed for frequency control and inertia provision from generic energy storage units [6].

**Current Activities**

- Grid adaptation in power systems with large shares of variable RES (hardware-based versus control-based grid adaptation). Key results are illustrated in Fig. 4.7.

- Analysis of operational flexibility in power systems (quantification and visualization). Key results are shown in Fig. 4.8 and published in [4].

- Impacts of inverter-based RES deployment on power system stability and operation [5].

- Work on the role of storage in power & energy systems, including extensions of the Power Nodes and Energy Hub modeling frameworks.
Figure 4.7: RES Curtailment in Power Systems with high variable RES shares.
(a) Hypothetical German Power System (25x today’s storage capacity) with varying RES energy share (0%–50% each, x-axis: PV, y-axis: Wind). Curtailment in % of available RES energy.
(b) Forced curtailment for different IRENE-40 scenario families.

References


Figure 4.8: Aggregation of maximum operational flexibility of individual power system units. Flexibility of conventional unit with no energy constraint (yellow), flexibility of energy-constrained storage (blue) and aggregated flexibility of both units (green).


Distributed Energy Storage, Control, and Allocation (DESCA)

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

Abstract  The rapidly growing share of fluctuating Renewable Energy Sources (RES) in the electricity mix will change 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 the high investment costs associated with energy storage, the units should provide multiple services to increase their utilization factors [1]. 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 is conducted in cooperation with the company Ampard. Our project partner provides a software framework for controlling and coordinating distributed storage in the grid. The project is divided into three work streams (WS) described as follows:

• WS 1: Modeling of resources
  We model flexible assets (e.g. energy storage, demand response, distributed generation), which can provide services to the customer or to the power system. Simplified models are needed to incorporate these resources into a control framework that is able to extract system services while providing local services. We primarily focus on developing a battery model that can describe battery degradation associated with battery usage. By quantifying battery degradation, it will be 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 local services. Moreover, we can manage the additional flexibility of resources to provide system service that enhance profitability. This work stream focuses 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 service are estimated through historical data and predictions while considering the technical and regulatory requirements of each service. The technical capabilities of different resource types will be analyzed and the cost-to-go will be estimated from the degradation model developed in WS1. The goal is to provide the customers with different allocations strategies to be selected based on their own interests and other portfolio assets. The allocation schedules will be passed on to the control algorithms developed in WS2.

Progress

In the scope of WS1, we developed methods that identify both fast battery dynamics and slow battery degradation processes [2] for arbitrary battery usage patterns, such as those seen in real applications. For optimal control design, we developed 1) simple linear battery models that capture non-linear fast battery dynamics and 2) a methodology to obtain an economically-motivated control objective from the identified degradation process. Additionally, a combined heat and power plant model was developed for use within control algorithms. This model also includes thermal storage and the possibility to co-optimize heat and electricity production. We also identified different models from the literature suitable for modeling the dynamics of demand response resources.

Regarding WS2, the interaction between the local and central control algorithms was defined, as shown in Fig. 4.9, as well as the communication and computational requirements. In addition to the battery models, [2] also proposed some initial local control algorithms, focusing on peak shaving. A first version of the central control algorithm was developed [3] and focuses on the co-optimization of storage allocation for distribution network support and frequency control provision. We use an MPC approach with receding limited time horizon and consider perfect forecasts.

The milestone report of WS3.1 characterized the requirements for the different local and system services. Ref. [4] analyzed energy/power requirements for a batteries providing frequency control, including methods to offset the frequency response to manage battery states of charge. Furthermore, the central control algorithm developed for WS2 also helps define optimal allocation strategies.
Future Tasks

- Development of strategies to dispatch individual resources under uncertainty using an aggregated schedule from a central scheduler;
- Implementation of load and PV forecasting methods;
- Expansion of the central scheduler from a deterministic to a stochastic algorithm;
- Recommendations regarding improvement to markets and tariffs that would better leverage the flexibility of storage resources.

References


4.3 Future Electric Energy Systems

HVDC Networks

G. Andersson, C. M. Franck

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 need to be solved or further elaborated before actual planning, design, and implementation of an actual HVDC network can commence. The aim of this research project is to address some of the most salient questions in order to establish a more solid basis of knowledge and results on which system planners, manufacturers, regulators, and others can base their future decisions and planning activities.

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?” In this proposed first phase, the overall system aspects will be studied both from (A) the power system and (B) the component point-of-view. The project is addressing only pre-competitive research topics.

Within the project, the following points will be addressed:

- Develop methods and tools to study the interaction, joint planning, and joint operation of AC and HVDC networks. Control strategies in different modes will be investigated. Studies of benchmark systems will also be made.

- Develop methods and tools to study the transient behavior of the system under different fault conditions. Network topologies with and without circuit breaker will be investigated.
• Study and formulate common rules for the operation of converter terminals ("grid code") and specify the technical requirements on the main components of the HVDC network.

Currently, two subprojects are worked on:

• Interaction between AC and HVDC system
• Specification of main components

Partnership: ABB, Alstom Grid, Siemens, Swiss Federal Office of Energy (BfE)

Subproject A - 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 [1].

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 overlapping 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 [2]. 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 a final step the economic aspects of the network has to be considered as well.

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 2013** The main goal of this year was the investigation of the OPF problem. The linearized model of the power for AC grids was expanded to incorporate HVDC grids [3]. The base OPF dispatches the generator in the HVAC and HVDC grid and finds optimal power set points for all terminal stations. The second step was to introduce a security assessment into the OPF model. The N-1 criterion was used to guarantee a secure operation in case on any possible outage. Two different control schemes for the HVDC terminals were investigated. Preventive control can adjust the terminal power set-points prior to operation and keeps it at a constant level for all contingencies. Post contingency corrective control uses the fast controllability of the HVDC terminals and changes the power set-points of the terminal stations for different system states. The results shows that the operation cost can be significantly reduced when using corrective control compared to for preventive control.

**References**


Subproject B - Specification of Main Components

Matthias K. Bucher, Advisor: Christian M. Franck

Aim  The maximum currents and voltages during faults are important dimensioning criteria for the network equipment. The goal of this project is to investigate transient currents and voltages in order to derive requirement specifications for the network components such as circuit breakers (CB).

Approach  Analytic calculations in simplified models are derived for the deeper understanding of transient processes and simulations in PSCAD are used for the fully detailed models and for the validation of the analytical and numerical calculations.

Activities 2013  In the first half of the year, the main focus was on the derivation of analytic expressions for the individual fault current contributions from the different network components during pole-to-ground faults. Simulations of the fault current through the CB and the analysis of the influence of the network parameters on the individual contributions had been published before [1]. The aim of the analytic approximations is to ease the CB specification without simulations and to serve as basis for the preparation of future standards on short-circuit current calculations in HVDC networks. The limitations of the existing IEC61660 standard for auxiliary DC networks are shown and alternative equations are proposed for the HVDC network and compared with PSCAD simulations of a benchmark model. The first results for the capacitive contributions were submitted for review.

In parallel, an investigation of the influence of the transmission technology (cable or overhead lines) on the time development of the CB current during pole-to-ground faults in a 3 terminal HVDC network (Fig. 4.10) was conducted and the results were presented at the IPST in Vancouver [2].

In the second half of the year, different grounding practices for multi-terminal HVDC networks were compared in terms of maximum fault current through the CB and maximum overvoltage at the healthy pole during pole-to-ground faults. Therefore, simulations in PSCAD of monopolar and bipolar configurations with different grounding points were performed and
analyzed. Low-ohmic and high-impedance earthing concepts were considered.

At the same time, the next work package on HVDC CB modeling was initiated and a student semester project started with the task of modeling the passive resonance CB.

Outlook 2014 The main focus in 2014 will be on the HVDC CB modeling. Resonance, solid-state, and hybrid CBs will be modeled in PSCAD and the performance in terms of maximum breakable current and transient recovery voltage will be investigated. Besides, the second publication on analytic fault current calculations regarding the contribution from the AC side will be prepared. Moreover, a joint publication of subproject A and B is planned. The previous investigations on the influence of the DC network layout on the pre-fault steady-state losses, the transient overcurrents during the fault, and the post-fault contingencies [3] will be continued and completed by an OPF study considering also security aspects.

References


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

Moonjo Kang, Pascal B. Buehlmann, José Rodriguez Alvarez, Advisor: Christian M. Franck

Introduction and Background Challenging goals of the climate and energy policy of governments and deregulated electricity markets involve a growth of distributed renewable electrical energy generation and an increasing electrical energy transfer, thereby asking for more transmission capacity and optimal load utilization.

As restrictions and public acceptance practically prevent utilities from building new overhead lines (OHLs) a capacity up-grading of existing lines becomes an important option.

Approach for Thermal Analysis The transmission capacity of Europe’s OHLs is commonly determined by limitations on the conductor temperature, characterized by the ampacity. Historically, system operators base their ampacity calculations on conservative and fixed values in terms of weather, ambient and conductor conditions [1], leading to static thermal line ratings.

Since static thermal ratings apply adverse worst-case weather conditions, transmission capacities of OHLs are often limited artificially. Breaking up these conservative default values immediately enables an increase of the transmission capacity on existing OHLs. On the other hand, on days with unusually warm weather conditions, there is a risk of overloading the lines. Dynamic rating may improve operational security under these conditions.

Implementing Dynamic Thermal Rating (DTR) may be regarded as one of the few possibilities to increase transmission capacity as well as operational security of existing transmission networks [2]. Because DTR uses real-time (or forcasted) weather, ambient and/or conductor data, the OHLs may be operated closer to their thermal limits, where the associated radial temperature gradients can reach noticeable values. With the optimized current capacity, consideration of DTR helps the operators to monitor and control the OHLs without thermal violation.

Approach for Coupling Effects In order to predict the lifetime of conductors as precisely as possible, the material strength reduction due to fretting corrosion and creep must be taken into account. These symptoms are strongly influenced by the electrical-thermal-mechanical coupling effects which are simulated with finite element methods (FEM) and verified by laboratory experiments.
Tension clamps and conductor joints are critical zones due to compressing the conductor. Analyzing these cases first lead to a better understanding of the coupling effects. This leads to a better understanding of the boundary conditions be implemented in further investigation of a conductor with a homogeneous temperature and stress distribution.

**Activities 2013**

- Experimental investigation of the relationship between line tension, carrying current and radial thermal conductivity
- Influence of local wind blowing and solar radiation onto axial temperature distribution
- Steady-state and transient simulations based on relevant ambient and conductor parameters
- Weather and conductor data evaluation of on-field lines at two different locations
- Comparison of on-field measurement data to 1D model predictions
- Simplified 3D FEM simulations for the clamping mechanism
- Setup of computed tomography (CT) equipment

![Figure 4.11: On-field measurement system (Left), lab test setup including the high-current source and the conductor tensioning system (Center), simplified 3D conductor FEM-model for clamping mechanism and CT equipment (Upper and lower right)](image)
Outlook 2014

- Evaluate temperature distribution and structural change around the tension clamps
- Influence of humidity and precipitation onto temperature distribution
- 3D FEM simulations with the electrical-thermal-mechanical coupling effects in clamping zones
- Optimization of the physical parameters for the 1D model using field measurements
- Definition of a reliable current rating procedure using 1D models
- Evaluation of the importance of radial temperature gradients in transmission lines using field data

Partnership: swiselectric research, CCEM, Axpo AG, Pfisterer Sefag AG, swissgrid

References


Hybrid AC/DC Overhead Lines

Martin D. Pfeiffer, Advisor: Christian M. Franck

Introduction and Background  In order to meet the challenges related to integrating an increasingly higher share of renewable energy sources, significant improvements are needed with regard to the transmission infrastructure. Since the construction of new high voltage overhead lines (OHL) is subject to significant opposition, there is a strong interest in increasing the transmission capacity of existing OHLs. This project has continued the investigation of the possibility of increasing the transmission capacity through the conversion of existing double circuit AC lines to hybrid AC/DC OHLs. The primary focus is currently on the ground level ion current density as well as the ion current coupling into nearby conductors.

Activities 2013  In 2013 significant progress has been made in the computational as well as experimental aspects of the project. With regard to the simulation of the ion flow environment around hybrid lines, the following points stand out:

- In the framework of a master thesis, Thomas Guillod developed a new ion flow simulation method based on solving the space charge enhanced electric field and the ion transport problem iteratively[1]. The method has significant advantages with regard to computational cost and stability. A publication describing the method is pending acceptance in the IEEE Transactions on Power Delivery.

- The effect of a conversion of an existing AC double circuit line to a hybrid AC/DC overhead line with respect to its impact on the AC magnetic field environment has been analyzed and presented in a cooperative effort with Swissgrid AG in the SEV Bulletin[2].

- A cooperation project with RWTH Aachen and Amprion GmbH was launched in which the HVL will contribute with simulations of the ion current environment around full-scale tower geometries.

Meanwhile in the laboratory, the following activities took place:

- The experimental setup was improved to allow automatic control and measurements (total corona current and spatially resolved ion current profiles on the ground) of HVDC conductors.

- A previously developed rain simulation setup was re-activated and practical aspects improved.
• A cooperation project with Amprion GmbH was launched. Investigations have included the impact of rain intensity on the corona onset gradient and corona intensity of HVDC conductors as well as the impact of the conductor surface type on the corona behavior. The results are presented in two technical reports.

Figure 4.12: Top view of the laboratory setup showing a suspended bundle-conductor and ion current probes to the side of the bundle.

Outlook 2014 The plan for 2014 is to experimentally validate the developed ion flow simulation method and apply it to assess conversion options for real tower geometries. Two master students are contributing to this by detailed investigations of the corona production model and the ion current coupling into nearby conductors. A significant aspect of the work in 2014 will furthermore be the evaluation and publication of experimental data.

Partnership: Amprion GmbH, RWTH Aachen (IfHT)

References

4.3 Future Electric Energy Systems

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. Current research focuses on a number of challenges which have been identified in recent years, such as the charging of solid insulation or the breakdown of gaseous insulation by moving particles [1]. 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 disconnector and earthing switches. Using the international standards and the research performed on traditional AC disconnector and earthing switches 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 [2]. 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 4.13: Capacitive bus-charging (l) and bus-transfer (r) currents calculated for 420 kV GIS under AC and DC stress of various ripple content, published in [3].](image-url)
**Progress**  In 2013, previous research on AC disconnectors and DC bus-transfer in GIS was used as a basis for analyzing the influence of varying magnitudes of current and voltage ripple prevalent in future HVDC multi-terminal networks onto the main disconnector switching cases. The results published in [3] revealed a significant influence of the ripple magnitude and phase angle which can give rise to demands similar or even more difficult than the well-known AC cases. Additionally, a non-standardized proof of concept AC disconnector test facility was set up in order to prepare for the verification of a novel test method proposed for future HVDC applications. Initial operation of the setup has revealed promising results which are expected to be published in 2014.

**Partnership:** ABB Switzerland AG

**References**


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 influence of x-rays on discharges, the insulation of dc 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  The aim of this project is to provide and validate a model for the breakdown in strongly electronegative gases. It is the goal to predict the breakdown voltage of SF$_6$ replacement gases for all technical relevant geometries and voltage waveshapes. The experiment provides an electrode arrangement to test partial discharge and breakdown behaviour of gases and gas mixtures.

Activities 2013  The setup – consisting of a step voltage source and a homogeneous field electrode arrangement with a small protrusion placed inside a pressure vessel – was improved to measure discharge pulses during voltage application with high resolution (figure 4.14). Measurements in SF$_6$ were performed to prove the setup and to acquire data for comparison to future experiments.

The setup is extended to perform experiments with application of short X-ray pulses to precisely evaluate the voltage level of partial discharge inception. The X-ray source provides start electrons inside the critical volume, thus the statistical time lag will be overcome and the inception level can be determined with high accuracy. The experiments will be completed within the next year.

Further, a model of partial discharge and breakdown behaviour in SF$_6$ described in literature [1] was implemented and extended to other electronegative gases, such as tetrafluormethan (CF$_4$) and octofluoropropane (C$_3$F$_8$). These two gases will now be experimentally investigated and the results will be compared to the model simulations.
Figure 4.14: Discharge sequence leading to breakdown at 0.9 $\mu$s

Outlook 2014

- Completion of the X-ray experiments to investigate the exact inception level of partial discharges in SF$_6$.
- Measurements in CF$_4$ and C$_3$F$_8$ to obtain the experimental parameters for discharge and breakdown behaviour.
- Adaptation of the existing model for SF$_6$ to describe the experimental results for electronegative gases other than SF$_6$.
- Construction of a setup for breakdown experiments and proving of breakdown prediction based on the adapted model.

References

4.4 Gaseous Insulation

**DC Insulation**

**Introduction**  Gas insulated equipment is quite common for different high voltage AC applications today. Gas insulated switchgear (GIS) is well-known but also gas insulated lines (GIL) will become more important. An advantage of gas insulated equipment is that it can be installed very space saving compared to air insulated equipment. That is especially interesting for substations in densely populated areas where land use must be minimized.

As DC has advantages in transmitting a large amount of power over long distances with low losses, also DC gas insulated applications will be required in the future. However the field of DC gas insulation is not well established and not much operational experience exists today. The main problem with respect to insulation seems to be identified today, which is charge accumulation on the surface of the spacer [1].

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. Three sources are supposed to feed the surface charging [2].

- Ion drift in the gas
- Conduction through the solid insulation material
- Conduction along the insulator surface

The aim of this project is to get a better understanding of these charging processes and the DC field distribution and electrical strength.

**Partnership:** ABB Switzerland Ltd.

**References**


Gas phase insulator charging

Michael Schueller, Advisor: Christian M. Franck

Project Goal  Main focus of this project is to investigate and quantify the influence of charge accumulation origin from the gas volume. Charge sources in the gas phase are natural ionisation or micro discharges at electrode surfaces.

Figure 4.15: View in the test chamber with high voltage electrode with defined active gas volume and epoxy sample [2].

Activities 2013  In 2013 the influence of the active gas volume was investigated in detail. It was proven that surface charges only originate from those regions of the gas volume that are connected to the insulator surface via field lines. This volume is called active gas volume [1].

Further, the influence of the roughness of the electrodes and the spacer is studied. It is shown that on rough electrodes micro discharges take place that cannot be measured by traditional PD measurement. But still, these micro discharges have a significant impact on the surface charging of gas insulated HVDC spacers because additional ions are created that accumulate over long times.
4.4 Gaseous Insulation

Outlook 2014  The most important material property for DC insulation systems is the electric conductivity. As the conductivity is strongly dependent on the temperature, the influence of different temperatures of the insulation material is going to be investigated. For this, heatable electrodes were constructed inside the test vessel. In 2014 experiments with different temperature gradients inside the insulation material are going to be conducted to study this influence in detail. Further, the research shall be concluded by writing and defending the PhD thesis.

References


Influence of material properties on insulator charging in HVDC GIS

Malte Tschentscher, Advisor: Christian M. Franck

Project Goal  The goal of this project is to investigate the conductivity along the insulator surface and its influence on the field distribution and electrical strength. The scope contains investigations of homogeneous surface properties as well as of local surface inhomogeneities.

Figure 4.16: High voltage electrode arrangement
Experimental setup  An ultra low noise measurement setup has been designed and constructed to investigate the temperature and field dependency of the electrical surface conductivity. The gas insulated set-up enables current-voltage measurements of high resistive materials, in a wide range of electric field strengths and temperatures.

Outlook 2014

- The measurement setup will be characterised and the control system improved.
- Established homogeneous GIS insulation materials will be investigated.
SParX - Swarm Parameter Experiment

Alise Chachereau, Dominik A. Dahl, Pascal Haefliger, Mohamed Rabie, Advisor: Christian M. Franck

Abstract  Discharge properties of electron attaching gas mixtures are investigated in our swarm parameter experiment (SParX) [1]. We provide fundamental data for assessing high voltage insulation gases and gas mixtures.

The experiment implements the pulsed Townsend electrical method. SParX is a semi-automated setup and permits 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.

Progress 2013  Previous measurements of electron attachment rates to c-C$_4$F$_8$O, C$_3$F$_8$ and SF$_6$ in buffer gases: Ar, N$_2$, CO$_2$, were analyzed [2]. For c-C$_4$F$_8$O a first set of attachment cross sections have been estimated. Further the following binary mixtures of natural gases were measured: Ar-O$_2$, N$_2$-O$_2$, N$_2$-CO$_2$. The objective is to find an optimal mixture of natural gases. Although the Ar-O$_2$ mixture was investigated for a theoretical purpose, an unexpected nonlinear behavior in the reduced critical field strength as a function of the mixing ratio of argon and oxygen, was observed [3]. For the binary mixture N$_2$-O$_2$, detailed measurements were made with different mixing ratios to optimize the critical field strength. Figure 4.17 shows the reduced critical field strength \((E/N)_{\text{crit}}\) as a function of the mixing ratio of

![Figure 4.17: The reduced critical field strength \((E/N)_{\text{crit}}\) as a function of the mixing ratio of oxygen and nitrogen with 0% equal to pure nitrogen and 100% to pure oxygen.](image)
oxygen and nitrogen. Furthermore, a novel method for deriving attachment cross sections of strongly attaching gases with small mixing ratios in buffer gases was developed.

On a more technical side, the safety in operating the experiment was enhanced. The laser beam is now guided in a shielded cage. Besides, the range of operation was analyzed, and the dependency on the experimental parameters such as voltage, electrode displacement, pressure and temperature was investigated carefully [4].

**Outlook 2014**

1. We will extend the mixtures analysis of natural gases to gas mixtures with three components.

2. Further measurements are planned for c-C_4F_8O mixtures in Ar, N_2 and CO_2, and new measurements for HFO-1234 mixtures. The main output will be the swarm parameters and the critical electric field strength of these mixtures. In addition we aim to obtain preliminary attaching cross sections of these gases.

Partnership: *Alstom (Schweiz) AG*

**References**


Pre-Screening Insulation Gases by Quantum-chemical Methods

Mohamed Rabie, Advisor: Christian M. Franck

Abstract Considerable effort has been undertaken to find SF6 replacement gases with high electric strength. Characteristics sought in high voltage insulation gases are mainly chemical stability, low toxicity, low flammability, high electric strength and boiling point ranges that are suitable for high voltage applications. Considering the enormous number of all conceivable molecules, the determination of their properties in individual experiments is highly inefficient. Thus, a systematic search using computer programs is desirable to filter out promising candidates.

Figure 4.18: Estimated electric strength relative to SF6 vs estimated boiling point for carbonyl compounds containing 3, 4 and 5 carbon atoms. The region of promising candidates is the upper-left corner [2].

Goal of the project It is effective to estimate the electric strength of new gases by computational methods alone before testing their electric and chemical behavior in experiments. Such a filtering technique, known as virtual screening, is necessary to find from a very large library of compounds a few most promising compounds with the desired properties.

Activities 2013 We developed a method for estimating the electric strength and the boiling point of electronegative gases [1]. This method was combined with the systematic structure generation of compounds and was applied to the large chemical group of carbonyl compounds [2]. Further, out of a large library of 56000 compounds from the PubChem database a few
most promising gaseous dielectrics were identified, based on environmental, thermodynamic and dielectric criteria [3].

**Outlook**  A quantitative investigation of the electric strength should follow for the top-candidates, e.g. by swarm parameter measurements and the derivation of the critical electric field strength (see SParX project description).

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5. Publications

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M. Vrakopoulou, S. Chatzivasileiadis, E. Iggland, M. Imhof, T. Krause, O. Mäkelä, J. L. Mathieu, L. Roald, R. Wiget, G. Andersson
*A Unified Analysis of Security-Constrained OPF Formulations Considering Uncertainty, Risk, and Controllability in Single and Multi-area Systems*
IREP Symposium-Bulk Power System Dynamics and Control IX (IREP), August 25 - 30, 2013, Rethymnon, Greece

M. A. Bucher, G. Andersson
*Balancing Reserve Procurement and Operation in the Presence of Uncertainty and Transmission Limits*
48th International Universities’ Power Engineering Conference (UPEC), September 2 - 5, 2013, Dublin, Ireland

M. Imhof, G. Andersson
*Dynamic Modeling of a VSC-HVDC Converter*
48th International Universities’ Power Engineering Conference (UPEC), September 2 - 5, 2013, Dublin, Ireland

O. Mäkelä, G. Andersson
*Risk-Based Security Assessment and Effects of Fluctuating In-Feed on Risk*
48th International Universities’ Power Engineering Conference (UPEC), September 2 - 5, 2013, Dublin, Ireland
O. Mäkelä and G. Andersson
*Classification of Power System Security State in Presence of Fluctuating In-Feed in Operational Planning*
North American Power Symposium Conference, September 22 - 24, 2013, Manhattan, KS, USA

E. Vrettos, A. Witzig, R. Kurmann, S. Koch, G. Andersson
*Maximizing Local PV Utilization Using Small-scale Batteries and Flexible Thermal Loads*
28th European PV Solar Energy Conference and Exhibition, September 30 - October 4, 2013, Paris, France

T. Borsche, F. Oldewurtel, G. Andersson
*Balance Group Optimization by Scenario-based Day-ahead Scheduling and Demand Response*
IEEE PES Innovative Smart Grid Technologies (ISGT) Europe, October 6 - 9, 2013, Copenhagen, Denmark

O. Méigel, J. L. Mathieu, G. Andersson
*Maximizing the Potential of Energy Storage to Provide Fast Frequency Control*
IEEE PES Innovative Smart Grid Technologies (ISGT) Europe, October 6 - 9, 2013, Copenhagen, Denmark

M. Vrakopoulou, S. Chatzivasileiadis, G. Andersson
*Probabilistic Security Constrained Optimal Power Flow Including the Controllability of HVDC Lines*
IEEE PES Innovative Smart Grid Technologies (ISGT) Europe, October 6 - 9, 2013, Copenhagen, Denmark

B. Xu, A. Ulbig, G. Andersson
*Impacts of Dynamic Line Rating on Power Dispatch Performance and Grid Integration of Renewable Energy Sources*
IEEE PES Innovative Smart Grid Technologies (ISGT) Europe, October 6 - 9, 2013, Copenhagen, Denmark

E. Vrettos, G. Andersson
*Combined Load Frequency Control and Active Distribution Network Management with Thermostatically Controlled Loads*
IEEE International Conference on Smart Grid Communications (SmartGridComm), October 21 - 24, 2013, Vancouver, Canada
J. L. Mathieu, M. González Vayá, G. Andersson
*Uncertainty in the Flexibility of Aggregations of Demand Response Resources*
IEEE Industrial Electronics Society Annual Conference (IECON), November 11 - 13, 2013, Vienna, Austria

S. Pfaffen, K. Werlen, S. Koch
*Evaluation of Business Models for the Economic Exploitation of Flexible Thermal Loads*
2. D-A-CH Energieinformatik Konferenz, November 12 - 13, 2013, Vienna, Austria

N. Addy, J. L. Mathieu, S. Kiliccote, D. S. Callaway
*Understanding the Effect of Baseline Modeling Implementation Choices on Analysis of Demand Response Performance*
ASME 2013 International Mechanical Engineering Congress and Exhibition, November 15 - 21, 2013, San Diego/California, USA

J. Liu, S. Li, W. Zhang, J. L. Mathieu, G. Rizzoni
*Planning and Control of Electric Vehicles Using Dynamic Energy Capacity Models*
IEEE Conference on Decision and Control (CDC), December 10 - 13, 2013, Florence, Italy

J. A. Taylor, J. L. Mathieu
*Index Policies for Demand Response Under Uncertainty*
IEEE Conference on Decision and Control (CDC), December 10 - 13, 2013, Florence, Italy

F. Oldewurtel, D. Sturzenegger, G. Andersson, M. Morari, R. Smith
*Towards a Standardized Building Assessment for Demand Response*
IEEE Conference on Decision and Control (CDC), December 10 - 13, 2013, Florence, Italy

A. Ulbig, T. Rinke, S. Chatzivasileiadis, G. Andersson
*Predictive Control for Real-Time Frequency Regulation and Rotational Inertia Provision in Power Systems*
IEEE Conference on Decision and Control (CDC), December 10 - 13, 2013, Florence, Italy
5.4 Technology Oriented Conference Papers

D. A. Dahl, C. M. Franck  
*Attachment cross sections of C4F8O estimated from swarm measurements in Ar, N2 or CO2 buffer gas*
Fruehjahrstagung DPG, 25 Feb - 2 March 2013, Jena, Germany

N. E. Karrer, B. Hudoffsky  
*Waveforms, Current Sensors and Their Bandwith in Power Electronics*
Internat. Exhibition and Conference for Power Electronics, Intelligent Motion, Power Quality PCIM Europe 2013, 14 - 16 May 2013, Nuremberg, Germany

M. K. Bucher, C. M. Franck  
*Analysis of Transient Fault Currents in Multi-Terminal HVDC Networks during Pole-to-Ground Faults*
IPST International Conference on Power Systems Transients, 18 - 20 July 2013, Vancouver, Canada

M. D. Pfeiffer, M. K. Bucher, C. M. Franck  
*The Effect of Grid Topology on Transient Fault Currents in Multi-Terminal VSC-HVDC Offshore Networks*
IPST International Conference on Power Systems Transients, 18 - 20 July 2013, Vancouver, Canada

P. Haefliger, C. M. Franck  
*Ar - O2 mixtures*
POSMOL 2013, 19 - 21 July 2013, Kanazawa, Japan

D. A. Dahl, C. M. Franck  
*Attachment cross sections of C4F8O estimated from swarm measurements in Ar, N2 or CO2 buffer gas*
POSMOL 2013, 19 - 21 July 2013, Kanazawa, Japan

M. Rabie, C. M. Franck  
*Predicting the electric strength of proposed SF6 replacement Gases by means of DFT*
International Symposium on High Voltage Engineering ISH 2013, 25 - 30 August 2013, Seoul, South Korea
M. Schueller, C. M. Franck
*Influence of the gas volume size on spacer charging in SF\textsubscript{6} under DC stress*
International Symposium on High Voltage Engineering ISH 2013, 25 - 30 August 2013, Seoul, South Korea

M. Kang, C. M. Franck
*Radial Temperature Distribution of AAAC Overhead Line in Stationary and Transient Conditions*
International Symposium on High Voltage Engineering ISH 2013, 25 - 30 August 2013, Seoul, South Korea

A. Ritter, U. Straumann, C. M. Franck
*Derivation of requirements for small current switching in future HVDC substations*
International Symposium on High Voltage Engineering ISH 2013, 25 - 30 August 2013, Seoul, South Korea

M. M. Walter, M. Kang, C. M. Franck
*Arc cross-section determination of convection stabilized arcs*
International Symposium on High Voltage Engineering ISH 2013, 25 - 30 August 2013, Seoul, South Korea

M. M. Walter, C. Leu, C. M. Franck
*Optimizing the arc characteristics for improved designs of passive resonant HVDC circuit breakers*
FSO 2013, 2 - 6 September 2013, Brno, Czech Republic
6. Presentations

S. Chatzivasileiadis, T. Krause
_Erfahrungen und Ergebnisse aus dem EU-Projekt IRENE-40_
Swissgrid AG, Laufenburg, Switzerland, January 22, 2013

C. M. Franck
_Radio Interview ”Die Geschichte des Stromnetzes”_
Radio Interview SRF3 Input, Zurich, Switzerland, February 24, 2013

C. M. Franck
_An efficient procedure to identify and quantify new molecules for insulating gas mixtures_
Spring Meeting of the German Physical Society, DPG, Jena, Germany, February 25, 2013

J. L. Mathieu
_Harnessing distributed flexible resources for sustainable electric energy systems_
York University Lassonde School of Engineering, Toronto, Canada, February 28, 2013

C. M. Franck
_High Voltage Insulation Gas Mixtures alternative to SF₆_
IC London, London, UK, March 5, 2013

J. L. Mathieu
_Harnessing distributed flexible resources for sustainable electric energy systems_
University of Vermont School of Engineering, Burlington, VT, USA, March 21, 2013

C. M. Franck
_Short-circuit current calculation in HVDC networks and their interruption_
Delft University of Technology, Delft, Netherlands, March 25, 2013

J. L. Mathieu
_Harnessing distributed flexible resources for sustainable electric energy systems_
University of Michigan, Ann Arbor, USA, March 25, 2013
J. L. Mathieu
Harnessing distributed flexible resources for sustainable electric energy systems
University of California, Santa Barbara, USA, April 2, 2013

K. Froehlich
Keynote speech: Electric power transmission challenges - solutions
International Colloquium on Ultra High Voltage Systems, New Delhi, India, April 3, 2013

J. L. Mathieu
Harnessing distributed flexible resources for sustainable electric energy systems
Dartmouth College Thayer School of Engineering, Hanover, NH, USA, April 4, 2013

J. L. Mathieu
Controlling electric loads to manage energy imbalances in power systems
Institut National de Recherche en Informatique et en Automatique (INRIA), Paris, France, April 17, 2013

K. Froehlich
Opening speech
International CIGRE-CIRED symposium on Smart Grids, Lisbon, Portugal, April 22, 2013

J. L. Mathieu
Harnessing distributed flexible resources for sustainable electric energy systems
University of Washington, Seattle, USA, April 23, 2013

H. Abgottspon
Multi-horizon decision trees applied to self-scheduling of hydro power
NTNU, Trondheim, Norway, May 3, 2013

G. Andersson
Cyber-Physical System Security of the Power Grid
University of Michigan, Ann Arbor, USA, May 3, 2013

K. Froehlich
Keynote speech: The electric power system - challenges and solutions
CIGRE China Colloquium, Lijiang, China, May 8, 2013
C. M. Franck
**Increasing the transmission capacity of existing overhead power lines**
PSI Paul Scherrer Institut, Villigen, Switzerland, May 16, 2013

K. Froehlich
*Opening speech and keynote: CIGRE’s role in the dynamic change of the electric power system*
31st International CIGRE session, Zlatibor, Serbia, May 26, 2013

G. Andersson
*Models and Tools for the Analysis of Future Electric Power Systems*
European PhD School in Power Electronics, Electrical Machines, Energy Control & Power Systems, Gaeta, Italy, May 29, 2013

G. Andersson
*Energy Hubs and Controls*
European Control Conference, Tutorial Session on Power System Controls, Zurich, Switzerland, July 18, 2013

C. M. Franck
*Short-circuit current calculation in HVDC networks and their interruption*
Institute of Technology, Tokyo, Japan, July 22, 2013

G. Andersson
*Automatic Generation Control & State Estimation: potential attack vectors, impacts, and countermeasures*

S. Chatzivasileiadis
*Interaction between AC and DC Power Systems: The Need for Controllability*
IEEE PES Swiss Chapter Workshop, Baden, Switzerland, September 4, 2013

K. Froehlich
*Opening speech*
CIGRE Joint Colloquium SC A2/C4, Zurich, Switzerland, September 8, 2013

C. M. Franck
*Introduction to ETHZ*
CIGRE Joint Colloquium SC A2/C4, Zurich, Switzerland, September 10, 2013
C. M. Franck
_Ein neuer Anlauf zur alten Frage nach alternativen Isoliergasmischungen fuer gekapselte Schaltanlagen_
ETG - FKH Fachtagung, Baden, Switzerland, September 25, 2013

K. Froehlich
_CIGRE in the dynamic change of the electric power sector_
CIGRE 7th Southern Africa Regional Conference 2013, Somerset, South Africa, October 7, 2013

T. W. Haring
_Market Designs for Reserve Capacity in the Presence of Renewable in-feed and Demand Response_
California Institute of Technology, Pasadena, Los Angeles, USA, November 4, 2013

T. W. Haring
_On Ancillary Service Market Design_
Renewable Energy Lab, University of Washington, Seattle, USA, November 9, 2013

J. L. Mathieu
_Planning and control of demand response resources given partial information and uncertainty_
University College Dublin, Ireland, November 26, 2013

M. Vrakopoulou
_Optimal decision making for secure and economic operation of power systems under uncertainty_
IBM Zurich Research Laboratory, Zurich, Switzerland, December 5, 2013

J. L. Mathieu
_Demand response today_
Control & Decision Conference (CDC), Workshop on Flexible loads as ancillary services, Florence, Italy, December 9, 2013

M. González Vayá
_Optimal Bidding Strategy of a Plug-in Electric Vehicle Aggregator in Day-ahead Electricity Markets_
7. Awards and Events

7.1 Awards

Dominik A. Dahl
Posterpreis des Fachverbandes Plasmaphysik, Germany
"Attachment cross sections of C4 F8O estimated from swarm measurements in Ar, N2 or CO2"
February 2013

Sedat Adili
John Neal Award 2013
"Theory and Application on Pulsed X-Ray Induced Partial Discharge Measurements for HV Equipment"
June 2013

Marina González Vayá
High Quality Paper Award, IEEE Powertech Conference, Grenoble, France
“Integrating Renewable Energy Forecast Uncertainty in Smart-Charging Approaches for Plug-in Electric Vehicles”
June 2013

Michael Koller, Theodor Borsche, Andreas Ulbig
High Quality Paper Award, IEEE Powertech Conference, Grenoble, France
Defining a Degradation Cost Function for Optimal Control of a Battery Energy Storage System
June 2013

Theodor Borsche, Andreas Ulbig, Michael Koller
Best Paper Award on Integration of Wind, Solar and Storage, IEEE Power & Energy Society General Meeting, Vancouver, Canada
“Power and Energy Capacity Requirements of Storages Providing Frequency Control Reserves”
July 2013
Mohamed Rabie
Young Researcher Award of the 18th International Symposium on High Voltage Engineering
"Predicting the Electric Strength of Proposed SF6 Replacement Gases by Means of Density Functional Theory"
September 2013

Stephan Koch, Andreas Ulbig, Francesco Ferrucci (spin-off project “Adaptricity”)
Finalist of Axpo Energy Award
October 2013

Myriam Koch
2013 DEIS Graduate Fellowship
IEEE Organisation, USA
November 2013

Stephan Koch, Andreas Ulbig, Francesco Ferrucci (spin-off project “Adaptricity”)
Winning Team of the startup competition Innovate4Climate, Stage 1
November 2013

Thomas Guillod
Second place at the ”ETG Innovation Prize” for his Master Thesis “Simulation of hybrid AC/DC Overhead Power Lines”
November 2013

Stephan Koch
Hans-Eggenberger-Preis (shared)
December 2013
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

Corrective Power Flow Control: Computational Aspects and Benefit Analysis
Dr. sc. ETH Gabriela Hug, Carnegie Mellon University, USA
April 23, 2013

Trends in ancillary services, market for primary control reserves in Alpine region
Andreas Mueller, Business Engineer & Marek Zima, Dr. sc. ETH - Swissgrid
April 30, 2013

Simulation game for bidding of ancillary services based on experimental economics
Dipl-Ing. Iason Avramiotis-Falireas & Dipl-Ing. Athanasios Troupakis - Swissgrid
Mai 7, 2013

Hochspannungsgleichstromschalter fuer die Energienetze der Zukunft
Dipl.-Ing. Markus Bujotzek, ABB Research Center
Mai 14, 2013

Mischspannungsbeanspruchung bei Isoliermaterialien
Dr.-Ing. Carsten Leu, TU Ilmenau, Germany
Mai 28, 2013

Very Fast Transients in GIS: Modeling, Simulation and Mitigation
Prof. Jasmin Smajic, University of Applied Science, Rapperswil
October 8, 2013
Synergies Between Storage, Transmission and Balancing Across a Fully Renewable Pan-European Power System
Prof. Martin Greiner, Aarhus University, Denmark
October 29, 2013

Ancillary service to the grid from deferrable loads: the case for intelligent pool pumps in Florida
Prof. Sean Meyn, University of Florida, USA
December 17, 2013
7.3 Other Events

LIMES Schülerinnen-Tag
Presentation of the High Voltage Laboratory to approx. 70 visitors
ETH Zurich, January 16, 2013

Visit of Leo Club Rapperswil
Presentation of the High Voltage Laboratory to 15 visitors
ETH Zurich, March 6, 2013

D-ITET Schnuppertage 2013
Presentation of the High Voltage Laboratory to 20 visitors
ETH Zurich, March 15, 2013

Studieninformationstage für Maturandinnen und Maturanden 2013
Presentation of the High Voltage Laboratory to student groups
ETH Zurich, September 4 - 5, 2013

Cigré Joint Colloquium SC A2/C4
in cooperation with Electrosuisse and ewz
ETH Zurich, September 8 - 19, 2013

Visit of Energie Brig Aletsch AG, EnBAG AG
Presentation of the High Voltage Laboratory to 25 visitors
ETH Zurich, September 20, 2013

Technikwoche Gymnasium Appenzell
Presentation of the High Voltage Laboratory to 20 students
ETH Zurich, November 6, 2013
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. 8.1):** 22 m length, 21 m width, 9.3 m height
- **Secondary high voltage laboratory:** 21 m length, 11 m width, 10 m height
- **several Faraday cages:** 4.5 m length, 4 m width, 2.4 m height
- **Impulse testing**
  - Lightning Impulse: 1500 kV, 80 kJ
  - Switching Impulse: 1500 kV, 80 kJ
- **AC Testing**
  - (dry, short time) 800 kV/400 kVA; 50 Hz
  - (dry, permanent): 400 kV/200 kVA, 15 Hz – 200 Hz
  - (SF₆-encapsulated, 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. In 2012 we have successfully passed the reaccreditation of our accredited Laboratories.
Accredited calibration laboratory  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  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.
Die ETH Zürich nimmt Abschied von

Prof. Dr. Walter Zaengl


Die Angehörigen der ETH Zürich, seine ehemaligen Studierenden wie auch seine Kolleginnen und Kollegen werden ihm ein ehrendes Andenken bewahren.

Der Präsident der ETH Zürich

Ralph Eichler