Power Systems and High Voltage Laboratories

Annual Report 2007
Annual Report 2007

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Power Systems and High Voltage Laboratories
(Institut für Elektrische Energieübertragung und Hochspannungstechnologie)

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Front cover: Illustration of the concept for a future DMS with fully transparent data architecture: The so called transparency matrix contains in each column one data object of the DMS.

Back side: Test of the lightning protection device of a full size nose radome in the High Voltage Laboratory of ETH Zürich. The peak value and time parameters of the lightning impulse voltage and the peak values of the impulse currents are measured in accordance with IEC 60060-1 using measuring systems calibrated according to IEC 60060-2.
Preface

Dear Friends of the Laboratory,

We can also this time look back on a very successful year. Most important to report is that the interest in power engineering among the electrical engineering students has been consolidated. We even had a slight increase in the number of students in the course “Electric Power Systems” to 67 and we see no signs of decreasing interest from the students. It is clear that many students have realized that the problems related to the energy supply are of utmost importance for our society in the future. Furthermore, it is also obvious that electricity will be the backbone of the future energy system, so our students will most certainly find challenging and interesting tasks in their professional careers. It is not only the course “Electric Power Systems” that have experienced a significant increase in attendance the last years. The other courses we offer have also seen a tripling or even more in number of attendees. This implies more work for us and for our assistants, but we are all pleased to have this additional inspiring burden.

The number of PhD students has decreased slightly during the year. There are two reasons for this. Firstly, we have had in total nine PhD examinations during the last year. This is probably a new record for our Laboratory. Secondly, the flourishing job market for electrical engineers makes it hard for us to recruit new PhD students. During the year we had several projects, which were already financed by external funds, that we could not start due to lack of manpower. It is clear that we must put more effort into recruitment of new PhD students during 2008. The research we do is highly appreciated by our external partners and half, or even more, of our projects are externally financed, and we see not signs of reduction of this funding.

During 2007 we got a number of confirmations that our work is of high quality. Members of the laboratory were recognised by various prestigious awards, both for teaching and research activities as can be seen in the appropriate sections of the annual report. Even if these awards were given to individuals, we see them also as recognition of the work performed in the whole Laboratory. Most of our teaching and research is a result of true teamwork.

Last but not least we want to thank all the personnel of the Laboratory for their enthusiastic and excellent work performance. The most important asset of an academic institution is its staff, and thanks to the good ideas and hard work of all our collaborators we can conclude once again that 2007 was another successful year of the Laboratory.

G. Andersson        K. Fröhlich
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Activities of the Power Systems Laboratory

1. Organisation

Head: Prof. Dr. Göran Andersson
Secretary: Rita Zerjeski
Dipl.-Ing. Martin Geidl leave April 2007
Dipl.-Ing. Turhan Demiray
Dipl.-Ing. Matthias Galus start June 2007
Dipl. El.-Ing. Florian Kienzle
Dipl. El.-Ing. ETH Gaudenz Koeppel leave March 2007
Dipl.-Ing. Stephan Koch start October 2007
Dipl.-Ing. Martin Kurzidem
Dipl.-Ing. Antonios Papaemmanouil start January 2007
Dipl. El.-Ing. ETH Monika Ruh
Dr. sc. ETH Marek Zima
Scientific Associates: Prof. em. Dr. Hans Glavitsch
External Lecturers: Dr. Rainer Bacher, Bundesamt für Energie, Bern
Dr. Dieter Reichelt, Technische Betriebe, Kreuzlingen
Dr. Marek Zima, Atel, Olten
Academic Guests Dr. Zhiyong Li
Central South University
Changsha, China
External PhD Students: Dipl.-Ing. Malte Thoma leave March 2007
1. Organisation
2. Teaching

The lectures and laboratory classes listed in the following section are part of the standard curriculum of the Electrical Engineering Department and are conducted by the staff of the Power Systems Laboratory. Details of the entire electrical engineering curriculum can be provided on application (list of lectures, option proposals).

2.1 Lectures

1st Semester  
Networks and Circuits I  
Andersson, G.  
Netzwerke und Schaltungen

The electric current and voltage; linear and non-linear resistive circuit elements; theory of meshed linear circuits (time variant and invariant); electric energy and power; ideal amplifier circuits with controlled current sources. Non-linear resistive systems, transistor amplifier as a non-linear system.  
As in the first semester the mathematical basics are not yet fully developed, the lecture is limited to direct current circuits. The knowledge to be achieved will be intensified by through exercises.

5th semester  
Electric Power Systems  
Andersson, G.  
Fröhlich, K.  
Elektrische Energiesysteme

Introduction to the theory and technologies of electric power systems. Overview of today’s and future structures of electrical power systems.  
Structure of electric power systems, Symmetrical three phase systems, Line, transformer, and generator models, Analysis of simple systems, Analysis of unsymmetrical three phase systems, Elements of current switching, Fundamental properties of important devices and subsystems in electric power systems, Elements of insulation coordination

6th semester & 7th semester  
Modelling and Analysis of Power Networks  
Andersson, G.  
Modellierung und Analyse elektrischer Netze

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 and non-linear calculation (NewtonRaphson), non-linear load flow (specification and solution methods), three-phase and 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.
2. Teaching

7th semester

Optimization of Liberalized Electric Power Systems

Bacher, R.

Optimierung liberalisierter elektrischer Energiesysteme

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.

7th semester

Power Market I - Portfolio and Risk Management

Reichelt, D.

Strommarkt I - Portfolio und Risk Management

Understand the worldwide liberalisation of electricity markets, the various markets models, pan-european power trading and the role of power exchanges. Financial products (derivatives) based on power prices, management of a portfolio containing physical production, contracts and derivatives, evaluation of trading and hedging strategies, methods and tools of risk management

8th semester

Power Market II - Modeling and Strategic Positioning

Reichelt, D.

Strommarkt II –Modellierung und strategische Positionierung

Pricing and modelling of derivatives based on electricity prices, power economies in open markets, development of the strategic position of utilities, evaluation of power plants and long-term contracts

8th semester

Power System Dynamics and Control

Andersson, G.

Zima, M.

Systemdynamik und Leittechnik in der el. Energieversorgung

### 2.2 Seminars

1st-4th semester

PPS: Economical and technical aspects of a sustainable energy supply
Wirtsch. und techn. Aspekte einer nachhaltigen Energieversorgung

Galus M.
Kienzle F.
Koch S.
Kurzidem M.
Papaemmanouil A.

In the past, electricity markets were characterized by vertically integrated utilities operating as regulated monopolies. However, the ongoing liberalisation process, the Kyoto-protocol as well as upcoming technologies are forcing a reorganisation and redirection of the electricity market. The offered seminar addresses several issues related to this reorganisation process. Main topics are distributed generation, particularly aspects of renewable energy sources (solar and wind power) as well as economical and ecological issues on liberalized markets. The students are writing and presenting a report covering single aspects, learning how to search for literature as well as how to write and present scientific reports.

### 2.3 Student Projects

To be admitted to the diploma examinations of the 7th and 8th semester, students of the electrical engineering department have to carry out two projects. Each student can freely choose his subject area, but usually the two projects have to originate from different subject areas. According to the curriculum, two days of the week during the semester period are to be devoted to this work. In general, the subjects are derived from topical research and development tasks.

- Pascal Kienast: “Reliability Analysis on the IEEE Three Area Test System with the Incorporation of Substation Outages”
- Jean-Pierre Rapenne: “Implementation of the UPFC Model in a MATLAB based Power System Simulator”
- Tobias Keel: “Medium time Scale prediction of Power System State for Ancillary Services Planning”
2. Teaching

2.4 Diploma Projects

Allocated time is six months. The majority of students devote their time to this work in the winter semester. The student has the option to carry it out either before or after the formal diploma examination (dates in spring and autumn).

Kasimir Egli "Analysis of Strategic Behavior in Combined Electricity and Gas Markets Using Agent-based Computation Economics"

Dominique Guth “Security and Vulnerability of Energy Supply”

Pascal Kienast “Optimal Overload Response in Electric Power Systems Applying Model Predictive Control”

Christof Duthaler “Power Transfer Distribution Factors: An Analysis of the Application in the UCTE-Network”

David Henzi “Entwicklung einer kundenorientierten Lastabwurfstrategie am Beispiel EWZ-Netz” (In German)

Pascal Stricker “Efficient Production and Purchasing Portfolio for BKW and Switzerland”

Tom Kessler “Reliability Analysis of the Swiss High Voltage Transmission System”

Johanna v. Lindeiner “An Investigation of the Conjectural Variations Approach in Oligopoly Electricity Markets”

2.5 Student Excursions

Portfolio and Risk Management II to RWE Trading, Essen, Germany
4-5 June 2007

Modeling and Analysis of Power Networks to swissgrid
Laufenburg, Switzerland
20 June 2007, 19 December 2007

Power Market I to Atel
Olten, Switzerland
10 January 2007, 19 December 2007
3. Research Activities

3.1 Completed PhD Theses

**RELIABILITY CONSIDERATIONS OF FUTURE ENERGY SYSTEMS: MULTI-CARRIER SYSTEMS AND THE EFFECT OF ENERGY STORAGE**

Candidate: Dipl. El.-Ing. ETH Gaudenz Alesch Koeppel  
Thesis: ETH No. 17058  
Date of Oral Examination: 9 February 2007  
Examiner: Prof. Dr. Göran Andersson  
Co-Examiner: Prof. Dr. Arne Holen, Norwegian University of Science and Technology, Trondheim

Author's Summary  
This thesis addresses two different reliability aspects of future energy systems, compiled in two different parts.

Part I of the thesis focuses on reliability calculations in multi-carrier energy systems, i.e. energy systems comprising not only electrical energy but also e.g. chemical and thermal energy. A model for reliability analyses is proposed, based on the energy hub modeling concept, suitable for analysing several energy systems simultaneously. With this model expected reliability of supply and expected energy not supplied, optionally considering load shedding can be calculated. Furthermore, the model can be applied both for systems without energy storage devices and for systems including energy storage devices. To include energy storage devices into the reliability model, a Markov model for energy storage devices was developed. The model allows to use the storage both for back-up supply as well as for peak load supply.

The multi-carrier reliability model is verified with alternative reliability calculation methods. Furthermore, the applicability of the storage model and the complete multi-carrier reliability model is demonstrated with several examples and sensitivity analyses.

Major findings are that interconnections between the different energy carriers are beneficial, in particular for reducing expected energy not supplied. This is true for all involved energy carriers, as long as the ratings of the loads and installed components are similar. Otherwise, the systems with larger ratings improve the reliability characteristics of the other energy carriers, however these systems do not benefit from the interconnections.

Part II of the thesis addresses the network infeed reliability of nondispatchable generators, in particular photovoltaic and wind based systems. A major issue with the generation from renewable energy sources is the limited accuracy of the production forecasts. It is proposed to combine the nondispatchable generator with an energy storage device at the point of network infeed, with the purpose of the energy storage device to compensate deviations between forecasted and actual generation. This
A time series based modeling procedure is proposed, suited for application with measurements from different types of non-dispatchable generators. This modeling procedure is applied in two case studies, using measurement data from a 500 kW photovoltaic installation as well as using wind speed measurements of a 2 MW wind turbine. The performance of the systems is analysed with a set of proposed analysis procedures. Both case studies show the applicability of the proposed methods. Moreover, both case studies identify that energy storage devices can considerably improve the network infeed reliability. The required energy capacities depend on the rated output of the generator and are thus comparatively high in the case of the wind turbine.

For the simulation of different forecast error magnitudes, both constant and forecast horizon dependent, a new approach for forecast simulations was chosen and successfully implemented. In addition, a procedure for determining the value of the energy storage device is proposed, based on reduced balancing penalties incurred. Furthermore, it is shown that price signals can be included to shift the infeed to high price periods. Closing, the validity of time series analyses is discussed.
OPTIMAL OPERATION OF DISTRIBUTION NETWORKS WITH HIGH PENETRATION OF DISTRIBUTED GENERATION

Candidate: Dipl.-Ing. Malte Christian Thoma
Thesis: ETH No. 17063 (In German)
Date of Oral Examination: 2 March 2007
Examiner: Prof. Dr. Göran Andersson
Co-Examiners: Prof. Dr.-Ing. Wolfram H. Wellssow, Siemens, Germany
Prof. Dr. Klaus Fröhlich, ETH Zurich

Author’s Summary
The importance of renewable energies and combined heat and power generation for electricity production will further increase in the next years, not only in Germany but all over Europe. Beside the conventional more or less centrally organized generation- and distribution structure more and more distributed generation (DG) units of different technologies will come to the forefront.

Today’s centrally organized electricity supply structure is comparatively stable, relatively simple to control and guarantees a high degree of supply quality. But it requests large investments with a long commitment, is less flexible and can barely use efficiency potentials. Distribution grids (low and medium voltage) are essentially passive, this means that the network management is carried out in the higher voltage levels. As more and more DG units feed in the grid, the distribution grids have to become more „active“. With a high share of wind power, combined heat and power as well as photovoltaic generation more duties of grid management have to be carried out at the point of common coupling of DG units. This requests for more communication and new control strategies in the distribution grids.

At the same time grids with DG have in the middle term the potential, to reduce the susceptibility for big scale black-outs, because on one hand with to a high number of smaller and individually controlled DG units the break down of one unit does not have a major impact and on the other hand with a specialised grid management the option exists, to build up islanded grids during interruptions on the higher voltage levels and to continue with supply of the connected customers.

In the European research project „DISPOWER“ 38 institutions from all over Europe dealt with these topics. In this context a new kind of energy management system for low voltage grids was developed: „PoMS“. PoMS is the acronym for “Power Flow and Power Quality Management System”. Major targets during development were, that the system is able to manage autonomously a selected low voltage grid including the installed (controllable) grid devices in order to improve power quality as well as to guarantee an economically optimized operation of the grid. Therefore this systems simplifies the integration of more and more DG units in already existing distribution grids and generates at the same time an economical and technical benefit for the affected grid operator. All essential algorithms for the operation of PoMS has been
3. Research Activities

developed within this Ph-D thesis. They will be explained in detail in the following. The approaches used in this work have been designed specially to fit for the application in limited low voltage grid segments, eg. area grids or industrial grids. It is a big advantage, that the algorithms are designed so general and so scalable, that they can be used in a slightly modified form also for the optimization of larger grids.

From the beginning it was the aim of the project, that the system is not only be theoretically designed but also tested under real conditions in a existing low voltage grid. For that a fix time slot was given, that had to be met under all circumstances. Therefore the big challenge in the framework of this Ph-D thesis was not only to develop appropriate algorithms, but also to do this in the given time. With the successful test of PoMS it could be demonstrated, that the developed algorithms are practical and allow an economically optimized grid management under real conditions. Further it could be shown, that PoMS can be used even for the operation of permanently islanded grids as well as for the operation of temporary islanded grids due to faults or interruptions on higher voltage levels („Fault Ride Through“).
INTEGRATED MODELING AND OPTIMIZATION OF MULTI-CARRIER ENERGY SYSTEMS

Candidate: Dipl.-Ing. Martin Geidl
Thesis: ETH No. 17141
Date of Oral Examination: 29 March 2007
Examiner: Prof. Dr. Göran Andersson
Co-Examiner: Prof. Dr. Olav B. Fosso, Norwegian University of Science and Technology, Trondheim

Author’s Summary
In the past, conman energy infrastructures such as electricity and natural gas systems were mostly planned and operated independently. Motivated by different reasons, a number of recent publications suggests an integrated view of energy systems including multiple energy carriers, instead of focusing on a single energy carrier. One incentive for that is given by the increasing utilization of gas-fired distributed generation, especially co- and trigeneration. The conversion of energy between different carriers establishes a coupling of the corresponding power flows resulting in system interactions. The investigation of such phenomena requires the development of tools for an integrated analysis of multiple energy carrier systems, which has become a recent field of research.

This thesis presents a generic framework for steady-state modeling and optimization of energy systems including multiple energy carriers. The general system model includes conversion, storage, and transmission of various energy carriers. The couplings between the different infrastructures are explicitly taken into account based on the concept of "energy hubs". Using this model, various integrated optimization problems are defined. For determining the optimal system operation, multi-carrier optimal dispatch and optimal power flow approaches are developed. A general optimality condition for optimal dispatch of multiple energy carriers is derived and compared with the standard approach for electricity networks. Besides operational optimization, two approaches for the structural optimization of multi-carrier energy systems are presented, which enable to estimate the optimal coupling of energy infrastructures. The models are demonstrated in a number of application examples, showing their basic characteristics and usefulness.
3. Research Activities

**ON THE CONTROL OF DISTRIBUTED GENERATION IN POWER SYSTEMS**

**Candidate:** Mirjana Milosevic, M.Sc. El.Eng.
**Thesis:** ETH No. 17277
**Date of Oral Examination:** 11 June 2007
**Examiner:** Prof. Dr. Göran Andersson
**Co-Examiner:** Prof. Dr. Math Bollen, STR I; Sweden

**Author’s Summary**

Many new primary energy sources in distributed generation systems are interfaced with the electric grid through power electronic inverters. If several of these are present in proximity of each other, interactions between them could arise. Part I of the thesis presents a study of the interaction between hysteresis controlled voltage source inverters connected to the same power network. The coupling between the inverters results in an interdependence of their switchings. It is shown that this interdependence is not detrimental, and a reduction of the ripple in the resulting current supplied to the network as compared to the single inverter case is obtained. The effects of various parameters of the inverters are analyzed.

Interest in isolated power systems is rapidly increasing. When the system operates in isolation then load tracking problem will arise which can cause voltage and frequency instabilities. Part II of the thesis presents a study of power generation control in a small isolated network with Photovoltaic (PV) panels as the main power generation. It is shown that a possible solution to keep power balance in the system and to have generation control is to use battery storage.

In small isolated power networks without storage units and with PV panels operating at their Maximum Power Points (MPPs), no frequency control is possible. Therefore, to control the grid frequency with PV panels only, a new algorithm was developed and simulated, where the PV panels bus is specified as a reference node. This algorithm allows operating the PV panels not only at their MPPs, but at an operating point where the needed power is produced. This operating mode is called “MPPT off mode”, in contrast to “MPPT on mode”, in which the PV panels always deliver the maximal possible power.
3.2 Current Projects

**FORMULATION OF AN OLIGOPOLISTIC POWER MARKET AS A MIXED LINEAR COMPLEMENTARITY PROBLEM (MLCP)**

Martin Kurzidem

Many oligopolistic price equilibrium models appeared in the literature with the purpose of studying strategic behavior among competing generating companies. In general, these models differ in terms of market design, network representation, the type of oligopoly game and the solution methodology. In order to understand the complexities of competition and to help analyze market designs and regulatory policies, computationally tractable models of strategic behavior are becoming increasingly important.

As a first approach, an integrated market design has been implemented for electricity trading in a transmission constrained network. The goal of each of the strategic generators is to choose a supply function bid in order to maximize its profit, which is a best response to the other generators’ bid. Thus, the generators are facing a two-level optimization problem in which they try to maximize their profit under the constraint that their dispatch and spot price are determined by the system operator. From the mathematical point of view the generators’ optimization problem is of the MPEC type (Mathematical Programs with Equilibrium Constraints), which is an optimization problem with a non-convex feasible region, and for that reason, such a model is generally difficult to compute for large systems. The resulting equilibrium problem among the generators is an EPEC (Equilibrium Problem with Equilibrium Constraints).

An alternative model to ease the problem is to include smooth functions for modelling the manipulation of the transmission prices. This has been done by introducing the Conjectured Transmission Price Response (CTPR) function which makes the problem to be treated as being convex and modelled as a MLCP. Unlike the MPEC-based formulation of each strategic generator’s profit maximizing problem, which results in an endogenous and correct determination of the transmission price, the CTPR is an exogenous assumption and represents the modeler’s judgment about how each generator might anticipate that the price will change.

**Goal of the project**

Since the liberalization of the electricity markets in several European countries, the demand for transmission capacity at some European transmission interconnections is sometimes much higher than the available capacity. Particularly regarding the Swiss-German cross border interconnections, the transmission capacity is often inadequate. The motivation of this work will be to study congestion management schemes with respect to the Swiss electricity cross-borders interconnection since Switzerland takes a major position in the UCTE-network as a result of its special geographical location.
3. Research Activities

References


Partnership: NOK
LOCAL LOAD MANAGEMENT AND DISTRIBUTED GENERATION

Stephan Koch

Initial considerations
The limited availability of fossil fuels and the necessity to mitigate climate change by reducing greenhouse gas emissions pose great challenges for the transformation of today’s electrical energy systems. In this context, the paradigm of Distributed Generation (DG) is gaining increasing weight in research and industrial activities. One of the reasons for a possible large-scale shift towards Distributed Generation in the nearer future is the growing penetration of the power system by infeeds from renewable energy sources, which are mostly decentralized by nature. Apart from that, substantial efficiency increases can be achieved by using Combined Heat and Power (CHP) generation, which often calls for fairly small units in order to supply local heat demand.

Nowadays, centralized generation schedules usually follow the stochastic but predictable demand for electricity. Conversely, infeeds from DG units essentially appear as a reduction of consumption because the installed capacity is relatively small compared to the load. Without communication equipment, DG units are not “seen” as generation units from a grid point of view.

If DG shall account for a high amount of the overall electricity production, a reliable joint dispatch of high numbers of diverse units has to be possible, as well as the provision of ancillary services such as active power reserves. With the introduction of large amounts of renewable energies that often fluctuate over time, questions about grid integration, backup and control concepts for a reliable power supply become more and more important. In this context, the role of the loads may also change substantially – from a source of stochastic disturbance to active contributors to grid stability and operation.

Outline of the project
During the course of the project, control concepts and coordination strategies for multiple decentralized generation units, small-scale storages and controllable loads are explored. One key focus is on algorithms for an automatic Demand-Side Management of household appliances. Thermal storage potentials in devices such as freezers, air condition units and water boilers can be used in order to influence the power consumption behavior over time in a controlled way. If coordinated properly, household loads with a suitable communication interface can make a contribution to grid stability, efficiency and the integration of intermittent renewable energy sources, while the user comfort shall remain unimpeded. Concretely, loads could participate in the optimization of schedule management or the provision of active power reserves. Apart from that, device-dependent load shedding in the case of a network disturbance can be a feasible option to prevent a full blackout of entire regions. A specific challenge is constituted by the fact that household appliances are relatively small and highly diverse in type, rated power, storage capacity and usual operation. Novel control algorithms will be have to be explored in order to take full advantage of the demand-side flexibility on different time scales, which may comprise several hours, minutes or
3. Research Activities

...even seconds. The possibilities for a unification of the load management concepts with the control of storages such as batteries and Distributed Generation units will be investigated. Apart from that, arising stability and control issues in low voltage grids are addressed.

References


Partnerships: 
Swiss Electric Research
ATEL
Landis & Gyr
University of Applied Sciences Northwestern Switzerland
Towards Future Electricity Networks

Antonis Papaemmanouil

Abstract
The European electricity system is undergoing, and will also in the future undergo, significant changes due to new requirements concerning environment, economy, security of supply, and technology. These new requirements will have implications both for the power production, i.e. generators, and for the transmission and distribution networks can be summarized in:

- Security of supply
- Environmental compatibility
- Economic viability

Traditionally the long term planning and analysis of electric power systems has put a lot of emphasis on the power production side of the electric power system. Quite often the main purpose has been to show that the annual energy balance can be satisfied, and for that purpose different expansion plans have been evaluated. This is still an important part of the power production planning, but the above requirements in Europe and other places in the world call for new methods and tools to analyze the development of the electricity system, including the transmission and distribution systems.

According to the project, the pathway to the future electricity networks crosses miscellaneous energy policies and strategies, generation forms and transmission constraints as depicted in the figure below (Fig. 1)

![Fig. 1 Pathway to the future electricity networks state](image-url)
3. Research Activities

Objective
The overall goal of this project is to develop an analysis and planning tool that takes into account the above discussed considerations. More explicitly the tool should, in addition to standard power planning tools, embrace

- Power plants of the future
- Load growth in the system
- Power transmission system
- Indirect costs caused by the electric power system
- Environmental and societal standards

From a Swiss perspective this project is particularly of interest of the following reasons:
1. The transmission capacity between Switzerland and Germany, and also the capacity between Switzerland and Italy are often exhausted and transmission congestion management has to be implemented to distribute the capacity among the different actors.
2. The shortage of power in the Swiss system forecasted by numerous studies, often referred to as the “Stromlücke” will be analysed from a European perspective. With the tools and models to be developed it can be seen whether this is a specific Swiss problem or other regions/countries will face similar situations.
3. The hydro power plants with storage will in the future play an important role as balancing and regulating power. This opens new possibilities for the Swiss hydro power that can be further studied and analysed in the project.

Project Activities 2007
During 2007 the following work has been done:

- Development of a DC Optimal Power Flow simulating market behaviour and topological issues
- Internalization of external costs in generation production
- Analysis of the European Interconnected System and collection of useful data needed to synthesize a simplified model of the European network.
- Combination of the required operational criteria in a multiobjective optimization

References
[3] Understanding how market power can arise in network competition: A game theoretic approach, C. A. Berry et al, 1999


Partnerships: Chalmers University of Technology, Sweden, Bundesamt für Energie, Switzerland
3. Research Activities

HYBRID SIMULATION OF ELECTRIC POWER SYSTEM DYNAMICS

Turhan Demiray

Introduction
The dynamic behavior of very large power systems are most often studied with the so-called transient stability programs. In these programs the traditional phasor model approach is used. Recent developments, particularly the introduction of more power electronics based equipment e.g. HVDC and FACTS components, show that there is a shortage in the analysis methods with phasor models. For such components a full time domain simulation is needed. Due to the limitation of computer storage and computation time, a complete representation of a large power system in an electromagnetic transients program is very difficult.

Goal of the project
The aim of the project is to develop a new simulation framework to increase the efficiency and accuracy of the simulations. One approach is to simultaneously perform the transient stability study on a large portion of the power system and the detailed electromagnetic transient on a small portion of the system of interest. So the advantage of this approach is to combine the „efficiency“ of the transient stability program and the „accuracy“ of the electromagnetic transient program [1]. Another approach is to use the concept of “time-varying Dynamic Phasors” as proposed in [2] to model power electronics based equipment. It has several advantages over phasor based methods. Firstly it has a wider bandwidth in the frequency domain than the slow quasi-stationary phasor. Secondly, dynamic phasors can be used to compute fast electromagnetic transients with larger time steps, so that it drastically reduces the simulation time compared to conventional time domain EMTP like simulation. Phasor Dynamics Approach provides a middle ground between the approximations inherent in a phasor based sinusoidal quasi-steady-state representation, and the analytic complexity and computational burden associated with representing network voltages and currents in time-domain.

Project Activities in 2007
- The prototype of the simulation tool was implemented in MATLAB. The basic steps have been taken to implement the developed models and algorithms also in the commercial simulation program NEPLAN [5] for power system analysis.
- Dynamic phasor model of the doubly-fed induction generator (DFIG) has been derived and implemented in the new simulation framework.
- A new numerical integration method based on the trapezoidal method has been derived which is optimized for the numerical integration of systems represented by dynamic phasors.
References:


Partnership: Busarello+Cott+Partner Inc.
3. Research Activities

**COORDINATED POWER FLOW CONTROL TO ENHANCE STEADY-STATE SECURITY IN POWER SYSTEMS**

**Gabriela Hug-Glanzmann**

**Introduction**
The electrical energy demand increases continuously leading to an augmented stress on the transmission system and higher risks for outages. In addition, electric power trades across borders have enhanced due to the liberalization of electricity markets. The resulting regularly changing load-flow patterns require a transmission grid which is able to cope with daily modified generation and load distributions. In several areas in Europe, the grid is not able to meet these demands any more and as a consequence, particular lines are often driven close to or even beyond their limits. But the extension of the system required to further guarantee secure transmission is difficult for environmental and political reasons. A promising and competitive alternative option is the usage of FACTS devices.

These devices are able to influence power flows and voltages and therefore provide the possibility to enhance the security of the system in manifold ways: increase of the transfer capacity, resolution of congestions by relieving overloaded lines, improvement of the voltage profile, reduction of power losses, enhancement of damping. But to benefit from such devices, their control settings have to be chosen appropriately.

**Proposed Solution**
In order to determine the optimal control settings of FACTS devices in a power system, an Optimal Power Flow problem is formulated with the objective to enhance the security of the system reducing the risk for system outages. But Optimal Power Flow problems for realistic power systems such as the UCTE grid involve thousands of variables and constraints resulting in an optimization problem of considerable size. A procedure is developed to formulate an Optimal Power Flow problem constrained to a limited area by using sensitivities to define the area and to approximate the influence of the FACTS devices at the border of the area.

With an increasing number of controllable devices in a power system, the border of such areas may coincide or the areas are even overlapping. In such cases, coordination among the areas and the corresponding devices is recommendable in order to improve the overall control performance necessitating the application of a Multi-Area Control technique. In this project, the Multi-Area Control method based on Approximate Newton Directions is extended for cases where the areas are determined independently from each other resulting in possibly overlapping areas and parts of the grid neglected in the optimization process.

**Progress in 2007**
- Extension and Implementation of the Multi-Area Control method based on Approximate Newton Directions
- Application of the developed methods (Sensitivity Analysis, Limited Area Control, Multi-Area Control) to the IEEE 57 bus system and the UCTE system
- Completing the PhD thesis
References


Partnerships:  
ABB
Swissgrid
3. Research Activities

**IMPROVED STATE AND TOPOLOGY ESTIMATION**

Marija Bockarjova

**Introduction**

State estimation is a widely used technique to provide a description of the power system state based on the available measurements. The state estimation result is a set of complex voltage phasors at every system bus at a given point in time and these phasors are referred to as the static state of the system [1]. It forms the basis for a number of other applications, such as: system observation, security assessment, optimal power flow, transmission system usage billing, and transmission system model verification.

![Fig. 1. Role of state estimation in supervision and control of power systems.](image)

Many SE systems have now been in use for decades; however, there are still some concerns and practical problems presenting challenges for further research. One example is the convergence problem of SE that may occur after topology changes or during disturbances. Another area to consider is the network topology processing.

Conventional power system SE algorithm uses switch-status inputs to construct the network topology after which the main estimation process commences. One of the primary sub-functions of the SE algorithm is to detect, identify and correct bad (measurement) data. The current bad data detection algorithms are designed to find analog measurement errors based on the assumption that the network topology is correct. When this assumption is false, these bad-data algorithms can produce an estimated model with an incorrect and potentially dangerous topology, or the main estimation procedure does not provide an answer.
This project investigates ways to better and more systematically handle the interaction between switch-status errors and traditional bad measurement data. The current activities are investigation of the new algorithms for wrong topology identification.

**Objectives**

The research objectives are to achieve robust and fast state estimation under changing conditions in power system, such as topology changes, unknown load and generation variations. The SE algorithm shall be based on the power system model and the redundant measurements provided by RTUs and a limited number of PMUs or other IEDs.

**References**


*Partnership:* ABB Corporate Research
DEVELOPMENT OF NEW ALGORITHMS, METHODS AND PROCEDURES FOR FUTURE DISTRIBUTION MANAGEMENT SYSTEMS

Monika Ruh

Introduction
Due to the advent of distributed generation, the liberalization of power markets and the enactment of new extensive environmental laws, distribution grid operators and municipal utilities are assigned with new complex tasks and have to fulfill more stringent requirements concerning security of supply and reliability, power quality, economy and environmental impact. To meet all these partly diverging requirements, not only economically planned and sufficiently dimensioned distribution grids are essential, but the distribution management system (DMS) with which the distribution grid will be controlled and monitored is almost as important.

To date, there exists no grid control system which could control the operation of an electric power system completely automatically. The human operator decides on many of the significant matters: Based on the received information from the control system and with his technical knowledge and working experience, he determines what has to be done or not. Thus, the operator “closes” the so called supervisory control loop, respectively he is very much “in the loop”. As a consequence, DMSs have to take the cognitive abilities in reception and processing of sensory stimuli of human beings into account. For instance, visualization has to be done by ergonomic principles.

Besides the human operator in the control center, the system engineer and his work have to be also considered when developing a future DMS. The system engineer, who is responsible for both the implementation work of the DMS and its configuration updates, needs a DMS architecture allowing to adapt to the specific customer installation with minimal effort. Such a user-friendly DMS needs to have a fully transparent data architecture.

Project Activities
The in 2006 developed first concept for a complete transparent DMS has been tested by means of real data provided by the company Rittmeyer. During this project phase, the transparency concept has been slightly modified and thereby improved concerning its implementation. Subsequently, a so called condensing algorithm linking data from the base system to application-oriented calculation tools has been developed and accurately tested.

Objective
The aim of this project is the development of new algorithms, methods and procedures, which should provide operators and system engineers with a better support. Hence, the development of this future DMS does not only focus on aspects concerning power systems but also on software architecture and ergonomic design questions.
References


Partnership: Rittmeyer AG
4. Publications and Presentations

4.1 Journal Papers

**M. Geidl, G. Andersson**
“Optimal Power Flow of Multiple Energy Carriers”

**M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klöckl, G. Andersson, K. Fröhlich**
“Energy Hubs for the Future”

**G. Andersson**
“Technische Vorraussetzungen des Stromhandels” (In German)
Im Stromhandel, Europa Institut Zürich, Band 77, 2007, pp 23-34

**F. Kienzle, M. Schulze, M. Arnold, P. Favre-Perrod**
“Energy Hubs als Lösung für die Zukunft” (In German)
Magazin “Umwelt Perspektiven”
URANG GmbH, Illnau, Switzerland, No.5/2007, pp 18-19

**M. Ruh**
“Grundlagen einer sicheren und zuverlässigen elektrischen Energieversorgung” (In German)
Schweizerische Gesellschaft für Automatik
SGA Bulletin Nr. 47, 2007
4.2 Conference Papers

M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klöckl, G. Andersson, K. Fröhlich
Pittsburgh, Pennsylvania, USA
13-14 March 2007

P. Korba, M. Larsson, B. Pal, R. Majumder, G. Andersson
“Towards Real-time Implementation of Adaptive Damping Controllers for FACTS Devices“
Proceedings of IEEE PES General Meeting
Tampa, Florida, USA
24-28 June 2007

M. Milosevic, P. Rosa, M. Portamann, G. Andersson
“Generation Control with Modified Maximum Power Point Tracking in Small Isolated Power
Network with Photovoltaic Source”
Proceedings of IEEE PES General Meeting
Tampa, Florida, USA
24-28 June 2007

M. Arnold, S. Knöpfli, G. Andersson
“Improvement of OPF Decomposition Methods Applied to Multi-Area Power Systems”
Paper 371, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007

M. Kurzidem, G. Andersson
“A Study of the Transmission Price Conjecture in an Oligopolistic Power Market”
Paper 360, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007

M. Ruh, G. Andersson, A. Borer
“A New Concept for a Fully Transparent Distribution Management System”
Paper 345, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007

A.G. Beccuti, T. Demiray, M. Zima, G. Andersson, M. Morari
“Comparative Assessment of Prediction Models in Voltage Control”
Paper 230, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007

M. Bockarjova, A. Dolgicers, A. Sauhats
“Enhancing Fault Location Performance on Power Transmission Lines“
Paper 334, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007
4. Publications and Presentations

T. Demiray, F. Milano, G. Andersson
“Dynamic Phasor Modeling of the Doubly-fed Induction Generator under Unbalanced Conditions”
Paper 230, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007

G. Hug-Glanzmann, R. Negenborn, G. Andersson, B. De Schutter, H. Hellendoorn
“Multi-Area Control of Overlapping Areas in Power Systems for FACTS Control”
Paper 277, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007

M. Bockarjova, G. Andersson
“Transmission Line Conductor Temperature Impact on State Estimation Accuracy“
Paper 338, Proceedings of PowerTech Conference
Lausanne, Switzerland
1-5 July 2007

R.R. Negenborn, A.G. Beccuti, T. Demiray, S. Leirens, G. Damm, B. De Schutter, M. Morari
“Supervisory Hybrid Model Predictive Control for Voltage Stability of Power Networks”
Proceedings of American Control Conference
New York City, USA
13 July 2007

A. Hajimiragha, C. Canizares, M. Fowler, M. Geidl, G. Andersson
Proceedings of IREP Conference, Charleston, S.C., USA
19-24 August 2007

G. Hug-Glanzmann, G. Andersson
“Coordinated Control of FACTS Devices in Power Systems for Security Enhancement”
Proceedings of IREP Conference, Charleston, S.C., USA
19-24 August 2007

F. Kienzle, G. Koeppel, P. Stricker, G. Andersson
“Efficient Electricity Production Portfolios Taking into Account Physical Boundaries”
Proceedings of 27th USAEE/IAEE North American Conference, Houston, USA
17 September 2007

F. Kienzle, T. Krause, K. Egli, M. Geidl, G. Andersson
“Analysis of Strategic Behaviour in Combined Electricity and Gas Markets Using Agent-based Computational Economics”
Proceedings of 1st EMMACE Workshop, Karlsruhe, Germany
26 October 2007
4.3 Conference, Seminar and Workshop Presentations

G. Hug-Glanzmann
“Coordinated Control of FACTS Devices”
HYCON Meeting
Zurich, Switzerland
20 February 2007

G. Andersson
“Vision of Future Energy Networks”
Invited Lecture of Third Annual Carnegie Mellon Conference on the Electric Industry
Pittsburgh, Pennsylvania, USA
13 March 2007

G. Andersson
“The Energy Hub; A Key Concept for the Future”
Seminar, University of Wisconsin
Madison, Wisconsin, USA
16 March 2007

G. Hug-Glanzmann
“Supervisory Water Level Control for Cascaded River Power Plants”
MPC Seminar, ETH Zurich,
Zurich, Switzerland
29 March 2007

M. Ruh
“A New Concept for a Fully Transparent Distribution Management System”
9th International Workshop on Electric Power Control Centers
Ullensvang, Norway
13 June 2007

G. Andersson
“Simulation of Power Systems Dynamics using Dynamic Phasor Models”
University of Manitoba
Winnipeg, Canada
22 June 2007

G. Andersson
“Towards Real-time Implementation of Adaptive Damping Controllers for FACTS Devices”
IEEE PES General Meeting
Tampa, Florida, USA
28 June 2007

M. Milosevic
“Generation Control with Modified Maximum Power Point Tracking in Small Isolated Power Network with Photovoltaic Source”
IEEE PES General Meeting
Tampa, Florida, USA
28 June 2007
4. Publications and Presentations

M. Arnold
“Improvement of OPF Decomposition Methods Applied to Multi-Area Power Systems”
PowerTech Conference
Lausanne, Switzerland
2 July 2007

M. Kurzidem
“A Study of the Transmission Price Conjecture in an Oligopolistic Power Market”
PowerTech Conference
Lausanne, Switzerland
2 July 2007

M. Bockajova
“Enhancing Fault Location Performance on Power Transmission Lines”
PowerTech Conference
Lausanne, Switzerland
4 July 2007

T. Demiray
“Comparative Assessment of Prediction Models in Voltage Control”
PowerTech Conference
Lausanne, Switzerland
4 July 2007

M. Bockajova
“Transmission Line Conductor Temperature Impact on State Estimation Accuracy”
PowerTech Conference
Lausanne, Switzerland
5 July 2007

M. Ruh
“A New Concept for a Fully Transparent Distribution Management System”
PowerTech Conference
Lausanne, Switzerland
5 July 2007

T. Demiray
“Dynamic Phasor Modeling of the Doubly-fed Induction Generator under Unbalanced Conditions”
PowerTech Conference
Lausanne, Switzerland
5 July 2007

G. Hug-Glanzmann
“Multi-Area Control of Overlapping Areas in Power Systems for FACTS Control”
PowerTech Conference
Lausanne, Switzerland
5 July 2007
G. Hug-Glanzmann
“Coordinated Control of FACTS Devices in Power Systems for Security Enhancement”
IREP Conference
Charleston, South Carolina, USA
23 August 2007

G. Andersson
“Power Systems Industry and Universities - A Successful Cooperation for More than Century”
15th Anniversary of EES-UET, Comillas Pontifical University
Madrid, Spain
13 September 2007

G. Andersson
“Congestion Management in Electric Power Systems”
University of Fribourg
Fribourg, Switzerland
17 September 2007

F. Kienzle
“Efficient Electricity Production Portfolios Taking into Account Physical Boundaries”
27th USAEE/IAEE North American Conference
Houston, Texas; USA
17 September 2007

G. Hug-Glanzmann
“Coordinated Control of FACTS Devices in Power Systems for Security Enhancement”
Next Generation Seminar
Manchester, United Kingdom
18 September 2007

M. Arnold
“Multi Source Energy Systems”
HYCON Annual Conference
L’Aquila, Italy
28 September 2007

F. Kienzle
“Analysis of Strategic Behaviour in Combined Electricity and Gas Markets Using Agent-based Computational Economics”
1st EMMAC Workshop
Karlsruhe, Germany
26 October 2007

G. Andersson
“Control in Electric Power Systems”
Automatic Control Group, KTH
Stockholm, Sweden
3 December 2007
5. Conferences, Visits and Workshops

G. Andersson
“Simulation of Power Systems Dynamics using Dynamic Phasor Models”
Seminar TU Delft
Delft, The Netherlands
18 December 2007

5. Conferences, Visits and Workshops

5.1 Conference and Workshop Participations

F. Kienzle, M. Kurzidem
IEWT 2007
Energy Systems of the Future: Technologies and Investments between Market and Regulation
Vienna University of Technology
Vienna, Austria
14-16 February 2007

M. Kurzidem, A. Papaemmanouil
Electricity Markets at the Crossroads-Fostering Market Integration
Brussels, Belgium
1–2 March 2007

G. Andersson
Third Annual Carnegie Mellon Conference on the Electric Industry
Pittsburgh, Pennsylvania, USA
12–15 March 2007

G. Hug-Glanzmann
MPC Seminar
ETH Zurich
Zurich, Switzerland
29 March 2007

M. Ruh
FGH-Seminar
Lastfluss- und Kurzschlussberechnungen in Theorie und Praxis
Schwetzingen, Germany
8-10 May 2007

M. Ruh
9th International Workshop on Electric Power Control Centers
Ullensvang, Norway
10-13 June 2007

G. Andersson, M. Milosevic
IEEE PES General Meeting
Tampa, Florida, USA
28 June 2007
IEEE PowerTech Conference
Lausanne, Switzerland
2-5 July 2007

G. Andersson, M. Bockarjova, G. Hug-Glanzmann
IREP Conference
Charleston, South Carolina, USA
19-24 August 2007

F. Kienzle
First Swiss Forum for Energy Technology
University of Bern
Bern, Switzerland
21 August 2007

F. Kienzle
27th USAEE/IAEE North American Conference
Houston, Texas, USA
17 September 2007

G. Hug-Glanzmann
Next Generation Seminar
Manchester, United Kingdom
16-19 September 2007

M. Bockarjova, M. Zima
Towards an European Centre for Electrical Networks
Ljubljana, Slovenia
21 September 2007

M. Arnold, M. Galus
HYCON Annual Conference
L’Aquila, Italy
17-29 September 2007

F. Kienzle
1st EMMAC Workshop
Karlsruhe, Germany
26 October 2007

S. Koch
Infotag Regelenergie (VDEW)
Frankfurt-Mörfelden, Germany
8 November 2007

M. Kurzidem, A. Papaemmanouil
Summer School on Physical Constrained Electricity Markets as Complex Systems
Torino, Italy
4-8 December 2007
5. Conferences, Visits and Workshops

5.2 Visits

G. Hug-Glanzmann
Delft Center for Systems and Control
Delft, The Netherlands
4–6 April 2007

M. Arnold, F. Kienzle
Politecnico di Torino
Torino, Italy
28-31 May 2007

G. Andersson
Evaluation Panel for
Deutsche Forschungsgemeinschaft (DFG)
Frankfurt/M
5-6 July 2007

M. Bockarjova
ABB Corporate Research
Raleigh, USA
24 August – 7 September 2007

G. Andersson
PhD Examination
Chalmers University of Technology, Sweden
20 September 2007

G. Andersson
PhD Examination
Norwegian University of Science and Technology
Trondheim, Norway
20 November 2007

A. Papaemmanouil
Project Meeting
Chalmers University of Technology
Gothenburg, Sweden
3-4 December 2007

G. Andersson
PhD Examination
TU Delft, The Netherlands
18 December 2007
6. Events and Awards

6.1 Events

**Computational Techniques for Power Infrastructure Defense Systems**
Prof. Chen-Ching, Iowa State University, USA
ETH Zürich, Switzerland
9 July 2007

6.2 Awards

**G. Andersson**
Outstanding Power Engineering Educator Award
IEEE Power Engineering Society
2007

**G. Koeppel**
ETG Innovationspreis 2007
Zürich, Switzerland

**M. Geidl**
"High Quality Paper Certificate" for presentation of the paper "Optimal coupling of energy infrastructures"
PowerTech Conference
Lausanne, Switzerland
2-5 July 2007

**M. Kurzidem**
PowerTech Conference
Lausanne, Switzerland
2-5 July 2007
Activities of the High Voltage Laboratory

1. Organisation

Head: Prof. Dr.-techn. Klaus Fröhlich
Secretary: Karin Sonderegger Zaky

Scientific Staff: Dipl.-Ing. Josep Aniceto Calero
Dipl.-Ing. Stefan Berger leave 31 March 2007
Dipl.-Ing. Andreas Bitschi
Dipl. El.-Ing. ETH Andreas Ebner
Dipl. El.-Ing. ETH Patrick Favre-Perrod
Dipl. El.-Ing. ETH Lukas Graber
Dipl.-Ing. Manfred Grader leave 31 March 2007
Dipl.-Ing. Martin Hinow
Dipl. El.-Ing. Evgeny Murtola
Dott. Fis. Claudia Roero leave 31 March 2007
Dipl. El.-Ing. ETH Philipp Simka
Dipl.-Ing. Matthias Schulze
Dr. Ulrich Straumann

Former staff working on PhD: Dipl.-Ing. Stefan Berger
M.Sc.El.Eng. Mike Chapman
Dott. Fis. Claudia Roero
Dipl.-Ing. Manfred Grader

Permanent Staff: El. Ing. FH Hans-Jürg Weber High Voltage Laboratory
Charles Sigrist Electronics Group
Heiko Vögeli Electronics Group
Henry Kienast Workshop

Scientific Associates: Tit.-Prof. em. Dr. sc. techn. Habibo Brechna
Dr. Nicolas Karrer
Dr. rer. nat. Timm H. Teich
Prof. em. Dr. Ing. Walter Zaengl

Visiting Lecturers: Dr. Werner Hofbauer, ABB High Voltage Techn. Ltd.
2. Teaching

The lectures and laboratory classes listed in the following section are part of the standard curriculum of the Electrical Engineering Department and are conducted by the staff of the High Voltage Laboratory. Details of the entire electrical engineering curriculum can be provided on application (list of lectures, option proposals).

2.1 Lectures

5th Semester
Electric Power Systems  
*Elektrische Energiesysteme*

Andersson, G.  
Fröhlich, K.

Introduction to the theory and technologies of electric power systems. Overview of today's and future structures of electrical power systems. Structure of electric power systems; Symmetrical three phase systems; Line, transformer, and generator models; Analysis of simple systems; Analysis of unsymmetrical three phase systems; Elements of current switching; Fundamental properties of important devices and subsystems in electric power systems; Elements of insulation coordination.

6th or 8th Semester
High Voltage Technology  
*Hochspannungstechnik*

Fröhlich, K.

Basic phenomena related to gaseous, fluid and solid dielectrics; dielectric breakdown mechanisms; dimensioning of high voltage components by employment of theoretical considerations and computer modelling tools (small project); sources of overvoltages (switching and lightning); overvoltage protection; investigation of dielectric stresses by computer modelling (small project); insulation coordination.

7th Semester
Technology of Electrical Power Systems  
*Technologie elektrischer Energiesysteme*

Fröhlich, K.  
Schulze, M.

Emerging technology in distribution and transmission systems (super conductivity, fault current limitation, energy storage, HVDC); electromagnetic compatibility for system and personnel; intelligence of power system equipment (control, model based diagnosis); decentralised, renewable energy sources; project work; excursion to a utility and to a manufacturer; innovation management.
7th Semester  
**Engineers Work – Technique and Economics**  
*Ingenieurarbeit - Technik und Wirtschaft*  
*Hofbauer, W.*

After a short introduction to purpose of an enterprise, its control and the role of the engineer will be explained by the example of surge arresters. By some examples the accounting principles will be presented focusing on the meaning and goal of the financial statement, the income statement and the balance sheet. The importance of the capital expenditure accounting is explained which considers besides product related cost factors like functionality, design and variety of variants, also process related cost factors like personnel, infrastructure and make or buy decisions. By specific consideration of the engineers’ work the importance of the Research and Development process and its impact on the success of an enterprise will be explained.

5th - 8th Semester  
**Computer Science Oriented Project Work**  
*EDV-orientierte Projektarbeit*  
*Fröhlich, K.*

Using information technology tools, the students, operating in teams and with only limited supervision, have to find solutions to topical problems chosen from the research or teaching activities of the high voltage group. Depending on the tasks, existing programme packages may be applied or, if necessary, new programmes or programme subsections have to be compiled.
2. Teaching

2.2 Student Projects

To be admitted to the diploma examinations of the 7th and 8th semester, students of the electrical engineering department have to carry out two projects. Each student can freely choose his subject area, but usually the two projects have to originate from different subject areas. According to the curriculum, two days of the week during the semester period are to be devoted to this work. In general, the subjects are derived from topical research and development tasks.

P. Bader  „Effektivmessgerät mit grosser Bandbreite“
R. Cortesi  „Messung des Ein- und Ausschalteverhaltens von Leistungs- transfomtoren“
K. Dejakum  „Beschichtung von Leiterseilen“
B. Fässler  „Realisierung einer Schrittmotorsteuerung“
A. Hauser/ D. Höhener  „Langzeitstabile Druck- und Temperaturmessung in einer gas- isolierten Schaltanlage“
J. P. Rapenne  „Forschung im Bereich von solartechnischen Anwendungen“
D. M. Schneider  „Thermoelektrische Energiewandlung in Gebäuden“
A. Steiner  „Multistress-Alterung elektrischer Maschinenisolierungen“
T. Märki / D. Leuenberger  „Elektrische Modellierung der Schaltkammer eines Hoch- spannungschalters“
M. Schnellmann  „Elektronische Schnellabschaltung mittels Mikroprozessorsystem“
V.-Q. Tran  „Effekte der Sonnenstrahlen auf die Gasströmungen in SF₆ isolierten Schaltanlagen“
M. Walter  „Möglichkeiten zur Bestimmung des Remanenzflusses von Leistungstransformatoren bei verschiedenen Unterwerks- konfigurationen“
R. Dörig / F. Günther  „Untersuchung des Einflusses verschiedener Unterwerks- komponenten auf das Ausschaltverhalten von Leistungstransformatoren“
A. Buhr  „Bestimmung der Entladungsaktivität von Wassertropfen“

P. Zgraggen  „Electromagnetic Simulation of a Drilling Cable“

E. Iggland  „Untersuchung des Durchschlagverhaltens gemäss dem Hochfrequenzmechanismus“

J. De Capitani  „Erfassung der temperaturbedingten Volumenänderung bei gasisolierten Schaltanlagen“

2.3 Diploma Projects

Allocated time is six months. The majority of students devote their time to this work in the winter semester. The student has the option to carry it out either before or after the formal diploma examination (dates in spring and autumn).

R. Gmünder  „Peltier Wäschetrockner“

M. Bösch  „Messung und Simulation des dreiphasigen Ein-, und Ausschaltverhaltens von Leistungstransformatoren“

K. Brunner  „Modellierung von internen Störlichtbögen in GIS-Anlageteilen“

E. Stojkaj-Mahmutaj  „Evaluierung von Formeln für die Berechnung der akustischen Emissionen von Hochspannungsfreileitungen“

R. Waespe  „Distributed Generation Pricing for Network Companies“

A. Beffa / N. Genazzi  „Réglage du courant de charge pour un banc d’essai“ EIA Fribourg

J. Horner / S. Ropraz  „Vérification expérimentale d’un modèle de disjoncteur haute tension“ EIA Fribourg
2. TEACHING

2.4 Internships

Our laboratory has continued its tradition of participating in the program of the International Association for the Exchange of Students for Technical Experience (IAESTE) in summer 2007.

The following students took advantage of two- to four-month internships at the High Voltage Laboratory:

Nitin Tirthdas Aswani  
Student at Purdue University, West Lafayette, USA

Davor Karolji  
Student at University of J.J. Strossmayer, Osijek, Croatia

2.5 Excursions

EWZ Kleinwasserkraftwerk, Zurich-Hoengg, 12 January 2007  
„Besichtigung des EZW, Vortrag zur Bedeutung & Integration erneuerbarer Energieträger für die Energieversorgung der Stadt Zürich“

ABB, Oerlikon, 21 May 2007  
„Besichtigung der Gasisolierten Schaltanlagen/Generatorschalter“

ABB Wettingen, 11 June 2007  
„Vorstellung der ABB Schweiz, Vortrag über Hochspannungsableiter“

ABB, Baden, 7 November 2007  
„Besichtigung eines Hochleistungslabors mit Lichtbogenlaufversuch“

NOK/EKZ Unterwerk, Thalwil, 19 December 2007  
„Besichtigung einer 220kV GiS Schaltanlage“
3. Research Activities

3.1 Completed PhD Theses

A HYPER ELASTIC CONDUCTOR FOR BULK ENERGY TRANSFER IN THE WALL OF SPOOLABLE TUBES FOR ELECTRIC DEEP DRILLING

A Candidate: Dipl. El.-Ing. ETH S. M. Neuhold
Thesis: ETH No. 17358
Date of oral examination: 26 July 2007
Examiner: Prof. Dr. K. Fröhlich, ETH Zurich
Co-examiner: Prof. Dr. M. Farshad, ETH Zurich

Author’s Summary

Deep drilling technologies are used to exploit oil, gas, water and geothermal energy resources. Sixty percent of the world’s energy demand is guaranteed by means of these technologies. Even small improvements in the efficiency of the exploitation therefore lead to a high economical impact.

The conventional rotary drilling technology was invented in the beginning of the 20th century. Although many improvements were made during the last 100 years, the drilling process is still slow, expensive and shows low precision. Each change of the drill bit requires the dismantling and re-assembling of the entire drill string. For the driving of the drill bit, the entire drill string with a length of up to several kilometres is rotated, resulting in a power consumption of several MW. Furthermore, hardly any information can be retrieved from the wellhead during drilling.

The so-called „steel coiled tubing technology” features a significantly reduced trip-time including a reduced work load and energy demand. The technology based on spoolable steel tubes with a length of up to 6 km is applied for cleaning, stimulation and „fishing” of broken drill strings in existing wells. Drilling with hydraulic drilling motors is, however, limited to a length of approx. 900 m.

In order to make a significant step in the development of deep drilling technologies, a new technology was researched and developed on the basis of the coiling principle of the steel coiled tubing technology within the 5th framework of the European research program.

The Power and Data Transmitting-COILed drilling technology (PDT-COIL) aims for drilling of workholes of up to 5 km depth with significant improvements in speed, cost and precision through the use of an electric downhole drilling motor, high strength composite material and high speed data transfer. The electric conductors for the supply of the downhole motor as well as the optical fibres for the data transfer and the measurement of temperatures and strain with longitudinal resolution are embedded in the tube wall of the spoolable drilling tube. The drilling tube shows a diameter of 6 to 9 cm, is transported in segments of 1 km and is assembled to the required length at the drilling station.

The work of the high voltage laboratory group at the ETH Zurich focused on solutions and system aspects of the electric energy transmission from the surface to the drill head.
Within this work, two aspects were investigated:

- The evaluation and optimisation of solutions for the electric energy transfer in the tube walls of spoolable tubes
- The estimation of the electric power transfer capability of the PDT-COIL drilling technology under service conditions

First spooling experiments with tube wall embedded copper conductors showed a complete mechanical destruction of the conductors already after 40 bending cycles. The reason was the low elasticity of approx. 0.08% of the applied conductor material and the problem of buckling under compression load. No conductor material was available that fulfilled the requirement of 1000 load cycles at a resulting strain and compression amplitude of ± 1.5%. Therefore, it was necessary to find a new conductor system fulfilling the fatigue life requirements and providing a power transfer capability of at least 20 kW to a well depth of 5 km.

The optimal solution evaluated consists in an elastic core with helically wound electric conductors; hereafter called: “elastic conductor”. The elasticity of the elastic conductor can be optimised by the pitch angle of the helical conductor.

The scientific challenge was in the optimisation of the electric conductivity of the elastic conductor at a given fatigue life.

Based on the calculation of the maximal axial and total strain in the helical conductor and the fatigue life data of the applied material, a method was developed for the estimation of the elastic range, the fatigue life and the optimisation of the electric conductivity depending on the design parameters of the elastic conductor. The experimental investigations showed an elastic range of 43%, which is in good correlation with the elastic range of 40% obtained through theoretical calculations based on the method described above.

The simulation and the experiment showed a highly non-linear dependence of the elastic range and the pitch angle of the helical conductor. An industrially produced shielded cable based on the elastic principle was tested for fatigue life with 1100 bending cycles at 1.5% strain and 5500 bending cycles at 1.0% strain. A permanent resistance change or visible damage could not be detected.

A theoretical reduction of the applied ± 1.5% axial strain to the cable to 0.052% axial strain in the conductor was obtained. The experimental investigation showed a reduction to 0.016% since tolerances further reduce axial strain. Fatigue life estimations showed a fatigue life of more than 130,000 cycles, until cracks in the surface of the conductor wire would occur.

At an axial strain amplitude of ± 1.5% and a fatigue life requirement of > 2000 cycles, a conductivity of 21.5% compared to a straight solid copper conductor of equal dimensions was obtained for the electrically optimised design.

For the second subject, the scientific challenge consisted in the complexity of the thermal situation. The maximal electrical current in the embedded conductor is dependent on the thermal rating of the electrical insulation, the ambient temperature and the heat dissipation of the electric losses. One part of the drilling tube is spooled on a reel on the surface; the other part is in the well. In the annulus of the drilling tube, cool drilling fluid is flowing towards the drilling head.
This drilling fluid is heated up by the electric losses in the conductor, by the heat emission of the ground and the drilling fluid returning from the well head on the outside of the drilling tube. The conductor losses respectively the electric resistance are temperature-dependent, as well as different parameters of the drilling fluid like density, specific heat conductivity, Prandt number and dynamic viscosity. Due to the high number of parameters, a closed model is not realistic. Based on empirical values, two model geometries were calculated, one for the realised drilling tube and one for a drilling tube with a larger diameter made of PEEK, a high-temperature thermoplastic material. For the model, the drilling tube including the drilling fluid and the ground were discretized in radial and axial direction. With the help of material and energy balance equations, the power transfer capability of the particular model geometry as well as the temperature of the conductor, the drilling fluid and the surrounding ground were calculated depending on the well depth.

For the first model geometry a maximal drilling depth of 3700 m with a transferable electric power of 25 kW was calculated. At reduced depths 80 kW at 1000 m and 50 kW at 2000 m can be transferred at a service voltage of 2 kV DC. The maximal drilling depth for the second model geometry is practically unlimited due to the high temperature rating of the material. It is possible to transfer 500 kW to 500 m, 300 kW to 1500 m and 100 kW to 5500 m drilling depth at a service voltage of 3 kV DC. The second model geometry was designed for a fatigue life of 2000 bending cycles at a bending radius of 2 m and a service temperature of 250 °C including a safety factor of 2.5. All calculations are based on conservative assumptions, for example the application of direct current (DC) power transmission, which requires a conductor for the return current. Compared to alternating current, direct current shows no reactive power losses and features advantages in explosive environments (no induced currents). By applying a symmetrical three phase alternating current transmission the available conductor would double since no separate conductors for the return current are needed. This would lead to a significantly increased power transfer capability. Further measures for increasing the power transfer capability can be the increase of the service voltage or the increase of the drilling fluid mass flow.

It was shown that the electrical energy transfer of the drilling tube with the presented elastic conductor is a solution that works. The elastic conductor features a wide range of applications; much wider than originally required. Due to its high elasticity range, the elastic conductor would also be suitable for embedding inside drilling tubes with a smaller bending radius or drilling tubes with a significantly larger diameter. The possibility of embedding in solid structures opens a wide field of applications like for instance the energy supply of actuators in highly loaded composite structures of the aircraft industry. A miniaturised version of the elastic conductor could also be used as an elastic and fatigue resistant solution for biomedical applications like intramuscular electrodes, cardiac performance monitoring or artificial nerves which stretch along with muscles. A power transfer capability of 100 kW to a drilling depth of 5500 m was calculated for a temperature-optimised drilling tube. This high electric power available at the well head allows the supply of novel electric rock destruction processes based on plasma and discharges.
Foul weather (rain, fog, snow and hoar frost) can lead to discharges on high voltage overhead transmission lines. These corona discharges result in a broadband crackling noise. In addition in these situations there often occurs a further noise component with a low tone at twice the mains frequency (2f, 100 Hz in Europe). When the introduction of UHV (Ultra High Voltage) overhead transmission with up to 1500 kV was under consideration in the 1960s to 1980s, an intensive research into the broadband crackling component of the noise was initiated. However, as it only contributed a minor share to the A-weighted level, the low-frequency tonal noise went largely unnoticed or uncommented until recently. Nevertheless, the tonal 2f-emission can present a significant problem because such low frequency noise is less subject to attenuation by building structures and tonal noise is generally perceived as more annoying than a stochastic signal of the same strength. This latter fact is also taken into account by national noise regulations.

As a result there are situations, especially in rest periods, in which noise emissions can have a particularly disturbing and annoying effect. It is therefore not surprising that transmission line operators are receiving complaints by residents living in the proximity of the transmission lines. The only measures known to date to reduce the levels of noise immission have been relocation of the line or to use a larger number of subconductors or thicker subconductors in the bundle. All these measures are mostly connected with unacceptably high costs for the operators of such lines.

In the CONOR (Corona Noise Reduction) project, the noise emissions of high voltage overhead transmission lines were therefore investigated with a special focus on tonal components in rainy weather. The project with which the work presented here is directly associated concentrates on the search for procedures and methods enabling high voltage power line operators to quantify the tonal components and to protect residents near the lines from annoying noise disturbance caused by the lines but in a manner that is economically viable.

The goals are to understand the mechanisms of the 2f-emission as well as to gain the ability to calculate its levels on the one hand, and on the other, proceeding from this basis, to provide and improve protection and reduction measures. These goals have largely been achieved in the framework of the present thesis.

For the first time the mechanisms leading to 2f-emissions can be quantitatively described in a satisfactory manner, underpinned by systematic measurements. While the overall level of corona noise emissions – dominated by high-frequency crackling and hissing – has its immediately origin in discharges themselves, the 2f-emissions arise from the movement of ions left behind by the discharges.
These ions move in a drift zone, in which, due to collisions with gas molecules, they transmit heat and in the sum a force to the neutral gas. Both quantities – heat as well as force – are sources of 2f-emissions, depending on the situation, both can give rise to contributions of similar magnitude. If one knows the heat and force affecting the gas at 2f-frequency, the emissions can be computed.

Other mechanisms producing 2f-emissions are conceivable as well. By theoretical estimates it can be shown, however, that a purely mechanical sound emission through the movement of the water drop surface as a membrane will not contribute significantly to the emissions. Also the mechanism of the 2f-emissions proposed in the literature by the modulation of individual pulses of the discharge does not stand the test of closer examination and therefore is not relevant for the 2f-emissions.

The computation of the emitted 2f-levels presupposes the knowledge of the corona current and the force evoked by the ions around the conductors. In this work a simulation determining these magnitudes is presented. The emission levels thus computed coincide fairly well with measured results, though they do not yet consider the intensity of the rainfall.

The 2f-emission mechanism as understood attributes the emissions to the discharges. Thus measures like larger bundle geometries, which already have an effect on the overall level of emissions, also reduce the 2f-emissions. As an alternative, further measures partly not yet discussed in the literature have been explored. What is common to them all is the attempt to either reduce the field strength in the relevant places or to remove the protrusions such as constituted by water drops from the conductor as rapidly as possible. This is presented in more detail:

- Bundle geometries do not only reduce the 2f-emissions when the number of subconductors or their diameters are increased. For conventional bundle geometries there is also a potential for improvement by changing the subconductor-arrangement. A reduction of the electrical field strength, especially on the underside of the conductor cables, i.e. the location of the essentially discharge-active large drops, is made possible by asymmetric bundle geometries. In a four-conductor bundle this can e.g. be effected by a trapeze-shaped bundle. Such an improvement is currently being tested by a project partner within a section of a transmission line. In addition to conventional cables, Z-cables and hollow-core conductor cables have also been experimentally tested. According to their large cross section, hollow-core conductors produced smaller audible noise levels at equal applied voltages. Z-cables do not effect a noise reduction in comparison with conventional cables of the same size. This result must, however, be qualified by the following circumstance: The effect of Z-cables was measured under unnaturally strong, artificial precipitation; in the circumstances of such strong rainfalls emission-reducing measures generally have a smaller effect.

- Hydrophilic coatings showed a noise-reducing effect both during and after rainfalls, while the cables were drying. The testing of such a coating in a real transmission line section is being planned. Hydrophilic coatings can be combined with so-called drip-off sites separating the water as discharge-free as possible from the cable; this can lead to a further reduction of 2f-emissions.
3. RESEARCH ACTIVITIES

Computation of the 2f-emission levels is now possible in principle. What is lacking to date is their correlation with rainfall intensity. For this modelling the discharge process in dependence on the water drop size might be interesting. Furthermore, what is required is simulation in the area of lower electrical field strengths, as these can occur in unusually large bundles. A follow-up project is planned aiming at the creation of a computation tool for the levels of 2f-emissions combined with overall noise levels. In the framework of the follow-up project, testing of hydrophilic coatings in field experiments is also planned.

So far the work presented here as well as the CONOR project have focussed on rain. On the basis of physical principles, computations for snow and fog are also conceivable. As parameters they simply require the field strength at which corona sets in. The suggested measures directed at reduction of conductor surface field strengths could also have a beneficial effect under climatic conditions of snow and hoar frost. For the climatic condition of fog it is expected that all suggested measures should apply in a similar manner as to rain.
A CONCEPT FOR THE COMPREHENSIVE ASSESSMENT OF STATOR WINDING INSULATIONS

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Author’s Summary

A concept for the comprehensive assessment of stator winding insulations to avoid unplanned outages of large power generators is presented. Once power generators have become operational, only a limited number of replacement bars or generator bars that have been dismantled during revisions will be available for such an assessment. Thus the number of specimens available for assessment would normally be less than the five full generator bars required by IEEE Std. 1043. Still the assessment should be as comprehensive as possible, i.e. as many in-service failure mechanisms as possible should be considered.

Apparent charges not significant as indicators of winding insulation ageing

Partial discharge diagnosis is one of the main methods commonly employed to monitor the condition of power generators. Accordingly, the significance of this method in the assessment of insulation ageing of dismantled generator bars is examined in this work. For this purpose, a commercially available instrument and a novel arrangement for discharge location were employed to record partial discharges during the ageing of ten full generator bars. Neither the temporal evolution of partial discharge amplitudes nor the distribution of discharge activity along the generator bars were found to be significant indicators of the progress of insulation ageing. The investigation of phase resolved partial discharge patterns did however result in systematic and reproducible changes during insulation ageing. Yet it is worth emphasizing that the interpretation of partial discharge patterns by human experts is not reproducible enough to qualify as a reliable method to assess ageing of dismantled winding insulations.

Significant differences between various insulating materials with respect to the impact of mechanical 100 Hz vibrations

Apart from partial discharge activity, mechanical vibrations in the endwinding are frequently recorded to monitor the condition of large power generators. In particular, this method allows for the observation of mechanical oscillations at 100 Hz vibrational frequency. Such vibrations occur as a consequence of mechanical forces that are proportional to the square of the 50 Hz current through the winding. Depending on their amplitudes these vibrations often result in cracks that propagate through the insulation. Mechanical oscillations at a frequency of 100 Hz were induced in an arrangement examining the combined electrical and mechanical ageing of winding insulations. An acceleration of insulation ageing by a factor 40 was found to be caused by mechanical vibrations for film-backed insulations. In contrast to the film-backed material, no reduction of insulation life was found on generator bars made of glass-backed insulations.
A successfully tested concept for the assessment of individual generator bars in the laboratory

In addition to mechanical influences, further factors that impact on insulation ageing should be considered to effectively assess individual dismantled generator bars. The comprehensive nature of such assessments requires a detailed planning of each test involved. Such a concept is outlined in the last chapter of this thesis.

To facilitate a comprehensive assessment of generator bars, corona protection and stress grading sections are taken into account in addition to groundwall insulations. The stress grading section was examined by means of a black-out test, in which a voltage 1.2 times the rated voltage was applied. According to this test, no visible corona must occur at the junction between the corona protection and the stress grading section. In addition, a voltage endurance test at 110 °C was employed to test the groundwall insulation as well as the outer corona protection: Upon completion of that test more than 50% of the outer corona protection must still be attached to the insulation. Otherwise the corona protection would be considered defective. Further, the groundwall insulation was tested for electrical treeing (which is known as the main mechanism of electrical ageing). To investigate this failure mechanism, the groundwall insulation was tested by applying three times the rated voltage between square copper electrodes mounted on the surface of the generator bar and the earthed copper conductor. Subsequently, time to breakdown values were determined for each electrode. This concept was applied to both new and in-service aged winding insulations. In two cases, new generator bars failed because of corona protection and groundwall insulation problems. A significant reduction in insulation life was observed for a winding that had been employing surface mounted electrodes.

To account for the various mechanisms that may result in failure the concept described here is recommended when a winding has to be assessed by testing a limited number of generator bars. It should therefore be the preferred method when individual dismantled insulations or replacement bars are tested.
A MODEL-BASED DIAGNOSIS SYSTEM FOR THE MOISTURE CONTENT OF POWER TRANSFORMER INSULATIONS UNDER VARYING LOADING CONDITIONS

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Author’s Summary

Motivated by economic pressure resulting from the liberalized electricity market, power utilities are increasingly working on a reduction of costs, especially in the field of maintenance. Moreover, power transformers are one of the most expensive investments in an electric power system. The tasks fault detection and diagnosis reduce both maintenance costs and the risk of a power transformer failure. Existing diagnosis concepts for power transformers are traditionally categorized by the underlying measurement technique (online vs. offline). The division into physical subsystems (e.g. mechanic subsystem, dielectric subsystem, thermal subsystem) is a first step for a model-based approach. Interpretation methods for measurement results and the integration of the subsystems into a common diagnosis scheme are missing links on the way to a model-based diagnosis concept.

Model-based diagnosis methods utilize an explicit mathematical model of the monitored system. Physical and analytical redundancy methods provide the possibility to distinguish between between systems faults, sensor faults, and modelling errors. A process model for the thermal behaviour of the power transformer is developed. It consists of a set of discrete heat reservoirs with non-linear heat exchange coefficients between them. Temperatures for windings, oil, tank and sensor box can be predicted from measured load current with a very satisfying quality compared to measured values. The diffusion of water in paper – the cellulosic part of the transformer insulation system – and the exchange of water between paper and oil is simulated with a moisture diffusion model. It covers temperature dependent diffusion coefficients and acts as a non-linear control loop for the water concentration in transformer oil. With the proposed model the estimation of water distribution in the transformer insulation system can be calculated from operation parameters without transformer shutdown.

An experimental setup consisting of a medium voltage distribution transformer equipped with a controllable loading setup provides the functionality for heat runs. Sensors for temperatures and relative water concentration in oil are installed at the transformer and connected with a data acquisition unit which stores measured data on a PC.

In order to evaluate fault scenarios, a structured residual approach is chosen. Fault patterns which are characteristic for a certain fault type are generated in order to identify faults. Both process models and diagnosis structure are verified by comparing measured and simulated system variables.
The diagnosis system is proposed to be implemented either as a strictly online fault detection system for large power transformers or as an inexpensive offline evaluation method for medium voltage distribution transformers. Both methods have major economic advantages over conventional offline measurements thanks to the fact that no transformer shutdown is necessary. This avoids costs related to the loss of production or distribution capacity and saves availability of equipment which is even more important within liberalized electricity market schemes.
IMPACTS OF ENERGY STORAGE ON POWER SYSTEMS WITH STOCHASTIC GENERATION

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Author’s Summary

Planning and operation of electric power systems are increasingly influenced by the presence of stochastic infeeds from converters of renewable energy such as wind and photovoltaic systems. The implications reach from complex voltage band management methods on the distribution system level to more and more demanding power flow management methods on the transmission system level. The volatile character of the stochastic generation is the main reason for such complications, especially since the unrestricted, maximum infeed of as much renewable energy as possible is becoming a declared goal in the energy strategies of many countries worldwide. One possibility to reduce this volatility is the use of energy storage devices, distributed in the system. They may be used to shift energy from periods of high infeed power to periods of low power and hence approach the characteristics of stochastic generation to conventional generation schemes.

This work is aimed to be a theoretical contribution to answer the question of the usefulness of distributed energy storage devices in complex systems. It is directly connected to the question of the necessity of new energy storage technologies, both questions being probably one of the best-known chicken-and-egg problems of energy technology.

The assessment of systems with a high repartition of stochastic generation, supported by energy storage, has so far been elaborated with the same deterministic methods that are typically used for conventional power systems. Furthermore it should be noted that there have been no concise standard procedures for the integration of storage into stochastically fed, meshed power systems. Especially for unmeshed stand-alone solutions, that is, island systems with no connection to national electricity networks, many deterministic dimensioning methods are in use. The concession to the stochastic nature of the infeeds is made only through the utilisation of measured time series of the power generation process and the subsequent calculation of the most inconvenient operation point during the sequence. It can, however, be easily shown that the obtained results may be paradox or at least misleading: the more data material is at hand, the more capital-intensive would be the chosen energy storage asset. The present report shows the theoretical background of this fact and proposes to invert the energy storage assessment method: Instead of planning the necessary characteristics of the storage assets based on the available data, the storage technologies and their characteristics are taken as fixed boundary conditions and the system performance is analysed subsequently, based on synthetic system infeed data.
The use of computer simulation is a necessary tool for carrying out these investigations. Especially for short measured time series, it may be verified that the extension of the infeed to synthetic stochastic time series of arbitrary length has to be carried out for the observation of result convergence in complex system configurations. This is due to the special setting of the problem. The statistical properties which have to be contained in the synthetic time series are determined and implemented in a suited vector-valued autoregressive model. The method is appropriate to generate multivariate dependent time series with defined chronological persistence and dependence structures. The implications of stochastic generation on important technical parameters such as probabilistic power flows on transmission lines can subsequently be investigated with and without energy storage devices. In order to compare different energy storage technologies, a general storage equation, together with a general simulation algorithm is developed, which facilitates the direct comparison of energy storage technologies with different characteristic loss behaviours. The equation is the same for all storage technologies and is developed in the structure $\dot{E} + P_l = P$, where $\dot{E}$ is the instantaneous energy charge state change, $P_l$ is the loss power, and $P$ is the storage terminal power.

Two examples are given, one of which concentrates on the possibilities the proposed data synthetisation method offers, while the other one is dedicated to the analysis of a complex power system with stochastic generation and energy storage. The latter example could not show any clear energetic advantage of systems with energy storage over systems without energy storage, as the use of energy storage devices with realistic characteristics is expected to increase system-wide losses in most configurations. However, the operational and planning benefits of energy storage technologies in power systems can be considerable, since already relatively moderate maximum energy contents serve for a considerable reduction of the maximum loads on transmission lines.

Energy storage devices may thus be utilised to influence the topological configuration of power systems with stochastic generation. It could be shown that the quantification of such benefits needs to be made based on probabilistic and statistical information, generated in methods such as the one presented here.
4. Current Projects

**DIELECTRIC COORDINATION OF HIGH VOLTAGE GAS CIRCUIT BREAKERS**

Philipp Simka

**Introduction**

In the development of gas insulated circuit breakers great progress was achieved when aiming to improve the reliability, the compactness and the required energy for operation. Because a more compact design comes closer to physical limits and leads to increased operational stress for the circuit breaker, the insulation coordination becomes more and more challenging.

The physical processes inside the circuit breaker during switching must therefore be understood in more detail.

![Figure 1: High Voltage Circuit Breaker (ABB Pass M) in Service](image)

**Goal of the project**

The aim of the project is to identify and quantify the electrical processes inside a circuit-breaker chamber during switching and therefore during transient voltage stress. The very fast transient (VFT) voltage development is of special interest when the structure becomes large compared to the electrical wavelength. In this range the spatio-temporal distribution of potentials and currents must be explicitly understood. Following, the influence of the design of the circuit breaker chamber, the interaction with additional elements and the resulting influence on the dielectric strength of the circuit breaker are to be quantified.

**Strategy**

To achieve the aims mentioned the following approach is chosen:

- Implementation of an electrical model of a circuit breaker chamber
- Identification and description of the excitation which provoke VFT in circuit breakers
- Using the circuit breaker model for identification of the predominant parameters influencing the shape and damping of the VFT
- Analysis of the effects of VFT on the dielectric strength of the circuit breaker elements
4. Current Projects

Circuit breaker model
In order to have an explicit comparison between the real circuit breaker switching chamber and the computed electrical model, the modelling is based on a specific design. This is the puffer breaker Pass M1 from ABB. (Rating: 420 kV, 63 kA short circuit current) as shown in Fig.1.

The build up of the circuit breaker model is accompanied by the assembly of the circuit breaker itself. Doing so the model can be verified stepwise through measurements on the actual circuit breaker setup. Fig 2 shows three parts of the immobile contacts of the circuit breaker and the schematic drawing which represents the basis for the calculation of the electrical model.

![Figure 2: Immobile contact system of the circuit breaker under investigations](image)

The model verification is done by measuring the S-Parameters (frequency domain) and the step response (time domain) between different ports of the modelled item. Fig.3 shows the comparison between the modelled and measured values using the arcing pin of the contact shown in Fig.2 as input and the nominal contact as output.

![Figure 3: Measured and Simulated Transfer Function and Step Response](image)

The accordance between measured and simulated curves is satisfactory and shows that the underlying principles of the modelling are accurate.

Excitation
Within a power network exists only one kind of transient electrical event which has high enough frequency content to excite the structure of a circuit breaker in the frequency range of interest. This is the formation of an arc between two contacts of different potentials. During normal operation of the system there are two actions which result in such an arc formation:

- Disconnector switching
- Circuit breaker switching
The arc formation leads to a potential step up to nominal voltage within 4-7 ns [1]. This steplike excitation results in travelling wave phenomena which shall be described by the circuit breaker model introduced. In order to get a reliable simulation result the shape of the voltage curve and its dependences on electrode shape, applied voltage, insulating medium and pressure must be known in as much detail as possible. However, the time dependant devolution of the potential rise is not clearly known and will be subject of further investigation.

**Outlook 2008**
The project will further follow the tasks mentioned in the paragraph “Strategy”. That is to say: Completion of the circuit breaker model, development and experimental verification of the excitation and then start with the simulation of the whole circuit breaker

**Partnerships:**  
ABB Switzerland Ltd, Corporate Research  
ABB Switzerland Ltd, High Voltage Products

**Reference**

Andreas Ebner

Introduction
Transient inrush currents appear during the energisation of power transformers. Their values can exceed the nominal current and may reach the rated value of the short-circuit current of the power transformer. These transient inrush currents affect the power quality and can trip protective relays. Due to these transients, huge current forces arise in the transformer windings that possibly reduce the lifecycle of power transformers, which are one of the most expensive components in electrical power systems. Observations made at Hydro-Québec might support these statements: The failure rates of power transformers at the 735kV level are much higher than those of lower voltage levels ([1]).

To date, several methods such as pre-insertion or grounding resistors, as well as controlled switching have been developed to reduce inrush currents. Controlled switching taking into account the residual flux is currently the most promising method, because it can be used in every switching case and for any core- and winding-configuration of power transformers. With this method inrush currents can theoretically be completely eliminated ([2]). Despite these results, the methods have been hardly deployed in substations so far.

Figure 1: Layout of a typical substation
Goal of the project
To date no accurate method is available to measure or identify the residual flux of power transformers without additional sensors. Therefore, the goal of this project is to find, implement and test appropriate and feasible options to determine the residual flux with the existing sensor system (see Figure 1).

Systematic Transformer Inrush Current Study
Real factors such as closing time scatter and residual flux measurement uncertainty have to be considered when checking the suitability of controlled switching in the field. On account of this, a systematic transformer inrush current study for the first phase energisation of a 400 kVA dry-type distribution transformer depending on closing time- and residual flux measurement deviations was carried out in the laboratory and with simulations in EMTP-ATP ([3]).

The measurements were taken using the experimental setup of Figure 2. IGBTs are used as instantaneous switches to energise and de-energise the transformer. Furthermore, the source voltage, the current and the voltage across the transformer coils – to calculate the magnetic flux in the transformer core – are measured. These components are connected to a rapid prototyping environment, where the algorithms for controlled switching and the control of the systematic inrush current studies are implemented ([4], [5]).

The experimental setup of Figure 2 was modelled in EMTP-ATP (Figure 3): The transformer represented with the linear BCTRAN-model and external pseudo-nonlinear hysteresis inductors (type 96) is fed by a three-phase voltage source. The switches used to energise the transformer are independent single phase time controlled switches. To configure the linear BCTRAN-model, typical test data are used, and extended test data or construction data are required for the parameterisation of the nonlinear inductors.
For an easier analysis of the results, the deviations are examined separately. The upper graph of Figure 4 shows the results if the circuit breaker is implemented like in a real substation and the residual flux measurement is assumed to be ideal. The results of the simulations using real residual flux measurement and an ideal circuit breaker are shown in the lower graph of Figure 4. These results show that the acceptable deviations depend directly on the limitation of the tolerable inrush current peak. If no inrush currents are allowed, the circuit breaker must have a closing time scatter less than 1.15 ms respectively a measurement uncertainty of 0.29 p.u. is permitted (regions marked yellow in Figure 4). The constraints can be relaxed by permitting larger inrush current peaks. If the rated current is admitted as maximum inrush current peak, the closing time scatter which can be tolerated increases to 3.87 ms respectively 1.0 p.u. of residual flux measurement uncertainty is allowed.

Figure 4: Comparison of maximum inrush current peaks for different residual fluxes (solid line: simulation, chain dotted line: measurements); upper graph: influence of closing time scatter; lower graph: influence of residual flux measurement deviations
The transformers of the power transmission level – for which controlled switching using the new residual flux measurement method will be implemented – are designed and optimized according to the specifications of the utility. The utilisation of the magnetic core is much higher than for distribution transformers, which means that the saturation flux is typically 1.05 – 1.1 p.u. of the nominal flux (400 kVA transformer: 1.29 p.u.). This leads to more stringent conditions for the residual flux measurement device, where a deviation of only 0.05 – 0.1 p.u. can be accepted.

Outlook
The project will now focus on the de-energisation phenomenon of transformers in real substations. Therefore, different substation layouts and transformer configurations will be implemented in EMTP-ATP. The goal of these studies is to quantify the influence of different configurations on the transformer ringdown behaviour.

References

Partnerships: ABB Switzerland
**INTELLIGENT SWITCHGEAR DIAGNOSIS**

Lukas Graber

**Aim**

The leakage of SF$_6$ gas is of crucial importance among the many reasons for the failure of high-voltage circuit breakers [1]. It is therefore necessary to monitor the SF$_6$ gas to increase system reliability and to address the concerns of growing environmental awareness [2].

**Problem**

The measurement of small leakage rates is not trivial. The often performed density readings show significant daily and seasonal fluctuations. The reason is the non-uniform and time-varying temperature distribution of the gas caused by ohmic heating of the current conducting elements and by environmental conditions. Assuming ideal gas and the volume being constant, the density distribution is inversely proportional to the temperature distribution. In order to detect small leakages and leakage rates a filter technique for the sensor signals becomes an inevitable task.

**Model-based filtering**

In the author's opinion filter methods which are based on physical knowledge have intrinsic advantage over statistical methods. While the statistical approach only analyses the data, a physical approach considers environmental impacts and the inner state of the situation.

The quintessence of this filtering method is a computational model which calculates the expected density distribution in the gas domain of the switchgear (Figure 1). The difference between the model prediction and the measured value is the leakage component (plus nondeterministic fluctuations) in the measured gas density signal. The input parameters for the model are load current, intensity and direction of solar radiation and ambient temperature. In order to provide these input parameters some additional sensors are needed. The author regards this as a task with minor cost impact since the sensors are all external and one set of sensors can serve for a whole substation. The model consists of two parts. The thermal network model calculates the boundary temperature distribution i.e. the temperature of the solid parts. This boundary condition is the input parameter for either the Computational Fluid Dynamics (CFD) model for the gas density distribution or the much simpler pressure correction model in case of pressure monitoring. The difference between the measured value and the model output is directly the gas leakage.

Instead of the use of a thermal network model the temperature distribution on the solid parts could come from a measurement. They could be fed to the CFD model directly (dashed arrow in Figure 1). This approach might be suitable for laboratory purposes but in a real substation the addition of several thermocouples to dead and live parts of the switchgear is generally undesirable.
**Test setup**

In order to test the model performance a test setup for research related with gas leakage detection was developed. It consists of several GIS elements from the ABB ELK-3 series. The main part is a 2 m bus bar segment. On one side (left side in Figure 2) the inner conductor is short circuited with the encapsulation serving as the return conductor. On the other side a computer controlled low voltage transformer injects continuous AC currents of up to 4 kA. Inside the vessel are several sensors for temperature, pressure and density. These sensors were used to test the thermal network model and the CFD model. Besides the ohmic heating from load current, solar radiation has a considerable impact on gas density distribution. Therefore a radiation source, consisting of an array of IR radiators, is also part of the test setup.
4. Current Projects

Results
It has been shown [3] that a model-based filter of the type proposed and implemented here can reduce the deterministic disturbances by around a factor of 3 and therefore allows to detect leakages much earlier. A signal treated in this way also permits measurement of the yearly leakage rate with greater accuracy.

Outlook 2008

- Design of the thermal network model (co-operation with TU Dresden)
- Transient version of the CFD model
- Qualification of the model-based filter approach at a real substation

Partnership: ABB Switzerland

Reference

FEATURES AND LIMITS OF SERIES- AND PARALLEL CONNECTION OF CONTACTS

M. Grader

Aim
Out of the research activities of the last years a model of the matrix has been created, based on a modified model of the voltage-current characteristic and on a model to describe the current commutation between the parallel paths of a matrix [1]. The aim has been to simulate and investigate the switching behaviour of such a matrix switch, made up of a large number of contacts in series and parallel according to different applications (dc breakers, current limiting breakers and current zero breakers) envisaged and for different voltage levels in medium and high voltage systems.

Parameters of the matrix
The simulations for the different applications are made by varying different parameters of a model of a matrix switch as seen in fig. 1.

![Figure 1: Matrix switch consisting of n x m contacts.](image)

The following parameters of the matrix switch can be modified:

- The number $n \times m$ of contacts of the matrix switch connected in series in the parallel paths.
- The values of $R_{Pm}$ are given by the contact resistances and include additional inserted resistances. The values of $L_{Pm}$ are influenced by the geometry and additionally added coils.

The commutation behaviour can be influenced by the additional added resistances and coils. For the simulations it has to be mentioned that the values of the contact resistances of a path decreases during the opening process and so influence the switching behaviour during the interruption process.

Switching behaviour of the single matrix contacts
Describing the switching process of the single contacts the following points are considered:

- If there is a stable arc burning after contact separation the voltage over the opening contact jumps to the minimal arc voltage and is characterized by a linear increase of the voltage till current interruption.
- Falling below the minimal arc current in the single paths of the matrix means an extinguishing of all the arcs in the contacts of this path.
• Inserting the dielectric strength of the opening contacts allows the simulation of reignition during the interruption process.
• With the help of condensers parallel to the opening contacts the increase of the voltage after arc interruption over a single contact and the transient effects after a successful interruption of the path current can be controlled.

Meaning of such a simulation model
The simulations should point out how the parameters of the matrix elements influence the switching behaviour in different applications, in particular for matrix switches for higher voltage levels and of greater dimensions, where experiments would be too complex. With the help of such simulations the number of switches can be calculated for implementing synchronous circuit breakers, dc breakers and current limiting breakers for higher volt-age levels.

The simulation results confirm that a high number of timing contacts in series as necessary for dc breakers and current limiting breakers at high voltage levels result high nominal power losses. Calculations show that for a practicable implementation of matrices for applications at high voltage levels, contact resistances in the sub-μΩ range are necessary. This cannot be attained by using switching elements of conventional technology.

Implementing switches with a series and parallel connection of contacts fails when the current commutation between the parallel paths due to the timing jitter at contact separation is accelerated by switching under conditions of a negative voltage-current characteristic of the burning arcs [2]. As mentioned above in the simulations a modified model of the volt-age-current characteristic is used, based on contacts with contact gaps up to one mm and interrupting currents of several ampere. The simulations show that with the help of contacts having such a voltage-current characteristic the current overload can be limited to uncritical values. The simulation model helps to define the design of such matrices and the requirements on the parameters for implementing practicable solutions for current-limiting breakers, synchronous circuit breakers and dc breakers.

Outlook 2008
The research in the implementation of a matrix switch will be concluded with the publication of the dissertation in the first quarter of 2008.

Reference


Fault Current Limiters – Novel Principles for Fault Current Limitation Based on Hybrid Architectures

Josep Manel d’Aniceto Calero

Background
Faults in electric power systems cannot be avoided. The progressive increase in the number of severe short-circuits developed into a significant issue for the operators of power systems as the electric systems modernized, grew and became increasingly interconnected. Thus, prospective fault-current levels that are higher than those included in the original long-term forecasting may increase even beyond the capabilities of the existing protection equipment. An old system may not be adequate to handle present-day faults, and the ratings of the protection devices are often exceeded, leaving such devices overloaded. Replacement of substation breakers with higher-rated breakers is not economical [2] and also often not viable due to space constraints. The increase of the fault-current level is especially critical when additional generation capacity is added close to a substation. Hence, in order to mitigate the severity of the fault currents the installation of fault-current limiters (FCL) appears as an attractive alternative.

This requires further research into fault-current limitation (see figure 1), which many utilities have already requested, but an economic technology is not yet available [1]. This interest in devices capable of limiting fault currents is not limited to old power systems, but also represents a solution for planned power grids that allow the use of equipment with lower ratings, with the goal of achieving considerable cost savings. As a result, interest is emerging in devices that are capable of limiting fault-currents, thus avoiding equipment failures and saving large sums in maintenance and replacement costs.

![Typical current waveforms due to a fault](image_url)

**Figure 1:** Fault current limitation, typical current waveforms due to a fault (adapted from [3])

Current state of fault current limitation
Power-system operators have long desired reduced fault-current levels while preserving a robust and uninterrupted system [3]. A large number of research projects have been undertaken to produce economically viable new FCLs, and many types of FCLs with various principles and technologies have been proposed. Diverse solutions are currently available, but they are considered uneconomical and often come with noteworthy operational inconveniences, such as increased impedance or outage time for fuse replacements.

**Aim**

As current solutions for fault current limitation are uneconomical and inconvenient; FCLs appear on the other hand to be an attractive alternative to mitigate the severity of fault currents.

The aim of this new project is therefore to collect and analyse the existing principles and technologies for fault current limitation; to rethink, enhance, and combine them synergistically; and likewise to find new ones where possible on the bases of hybrid architectures (see figure 2). Furthermore, an elaboration of the technical and economical analysis of the impact of such novel fault current limitation solutions when applied to the Electric Power System will be carried out. Consequently, analysis of future fault-current scenarios is necessary to assess the growing demands on these principles and technologies.

**Strategy**

The main goal of this project is to find, combine and use novel principles and technologies for fault current limitation based on hybrid architectures. The basic idea of a so-called hybrid architecture is to subdivide the device into different modules which each have a specific task to handle during operation (see figure 2), arranged in different parallel paths which also contain series elements. These tasks include the following:

- carry the continuous current during normal operation
- rapidly increase impedance after fault occurrence
- dissipate energy during limitation
- interrupt the limited current

From the functions mentioned above, the most demanding ones are the impedance increase and the energy dissipation. The challenge of hybrid FCLs is to find elements that fulfil the required tasks and to precisely coordinate all these elements.
Outlook 2008
A novel solution for the commutation principle, energy absorption element and switching technique has been recently conceived and is currently under study. First simulations for the commutation system have already been carried out. Further simulations with higher degrees of complexity will be carried out to conclude a complete model of the system. Together with the simulation work, a verification of the results will be effected with a small scale laboratory prototype.

References
ECONOMIC ADVANTAGES OF INNOVATION IN POWER SYSTEMS

Martin Hinow

General facts
Live cycle cost (LCC) calculation is a major topic for new switch gear designs but often focusses upon the LCC of individual switchgear components rather than that of the entire switchgear. However, effective new design investigation should take account of all potential cost influences including substation layout, component technology, substation maintenance, substation failure and substation penalty cost for not supplied energy in consequence of a failure. The cost classification of a substation is pictured in figure 1, see [1]. The cost structure of the developed methodology has been published in paper [2]. Taking account of all such cost parameters creates a complex, multi-dimensional problem which is not best solved by conventional techniques based on cost comparison of various fixed solutions. A new approach based on cost optimization algorithms and sensitivity analysis is much better suited to this type of problem.

Life Cycle Cost of HV-Substation

Cost of Acquisition

Cost of Operation

Renewal cost

Scheduled Maintenance

Unscheduled Maintenance

Failure

Cost

Component Replacement

Penalty Cost

Figure 1: life cycle cost structure of a HV-substation

Goal of the work
The current work presents a method of applying an optimization algorithm to identify the lowest LCC switch gear solution considering a wide range of possible combination of all cost parameters. The optimization algorithm can also be used to explore sensitivities to particular variables. The optimization algorithm can identify the switch gear solution with the lowest LCC and can provide information regarding those cost parameters which have the highest impact on the LCC result. The innovation feature of this idea is to utilize a single optimization algorithm to assess the LCC of the substation as a whole.
Principle of the genetic algorithm

All cost parameters are written in a component specific file card. During the optimization process the algorithm changes the given substation layout and provides by this manner the substation with the lowest LCC. The changing process follows the main rules, [3]:

- acquiring taking over the best substation solution,
- combination of low LCC substation layout to find a better substation solution and
- stochastic variation of substation layouts to find a better substation solution.

The principle of the algorithm is pictured in figure 2.

Figure 2: the genetic algorithm changes the substation layout using for each component a file card with all cost parameters.
4. **CURRENT PROJECTS**

**Outlook 2008**
Summary and presentation of the developed methodology in journals and at conferences.

**References**

[1] IEC 60300-3-6: Dependability management; Part 3 Application guide - Section 3: Life cycle costing


**Partnerships:**
- AREVA Switzerland
- ABB Switzerland
- National Grid Electricity Transmission PLC, England, UK
The project involves studies of concepts for novel electric drilling systems utilizing a tubular coilable conductor arrangement for downhole power transmission and condition monitoring (PDT-COIL). In its present form, the tube itself is made of composite carbon fibre reinforced material and has electric conductors and optical fibres incorporated in its wall thickness. The severe fatigue problem encountered with conductors in such a configuration has been successfully overcome by a special elastic conductor design [1]. The concepts to be assessed are to offer potential applications for deep rock drilling, for gas, oil, water, geothermal or other resources.

Recent activities

The elements involved in the tubing are subject to a multitude of stresses some of which have been assessed by comprehensive simulation. Among other parameters, these stresses are determined by mechanical dimensions, current load, voltage stress, temperature-dependent dielectric properties of the conductor insulation, environmental conditions. Furthermore, some of these stresses will also depend on supply frequency and its transients as well as harmonics introduced by the drilling device. This complex situation obviously calls for a multi-physics simulation. First attempts have been concentrated on obtaining a broadband frequency response of the PDT-COIL transmission system. As the conventional lumped-parameter pi-model doesn’t provide an accurate solution here, the literature and software descriptions have been searched for a more adequate method to simulate multiphase conductor configurations with frequency-dependent electric parameters. It appears that the FDTD (Finite Difference Time Domain) model [2] or the ULM (Universal Line Model) [3] may be the most appropriate approaches presently available. These models require per-unit-length parameters of the transmission line as input data. An algorithm for determination of such parameters has been implemented in a Comsol Multiphysics finite element modelling program, yielding the complete RLCG matrices (including mutual coupling between conductors) for the range of frequencies of interest.

With downhole provision of electrical power, a number of advanced rock fracturing methods become feasible. Apart from special electric motors for conventional rotary and percussion drilling, application of pulsed high voltage discharges is being promoted and has here been subjected to some literature studies. The method, applied to solids (rock) under a liquid (water), either uses the shock wave produced by a rapid rise transient discharge in the liquid to fracture the rock or an electric breakdown in the bulk of the rock [4]. In the latter case particular conditions have to be provided in order to create the discharge inside the rock. Voltage rise time characteristics used to describe breakdown properties of dielectrics show that for low frequency AC or DC voltage, breakdown strength of solid dielectrics is usually higher than that of liquid or gaseous ones. If such voltage is applied to rock (solid dielectric) submerged into dielectric liquid (water, oil), breakdown occurs on the surface of the rock yielding minimum damage. For the fast-rise impulse voltage, however, breakdown strength of materials increases with the rate of rise and furthermore, dielectric strength of liquids grows faster than that of solids (see Fig. 1).
As a result, for voltage pulses with a rise time less than ca. 500 ns breakdown strength of dielectric liquids is higher than that of solids. When such pulse with a magnitude of 200-400 kV is applied to a solid rock, electric discharge will take place in the rock body leading to the rock disintegration. The method described has been in practical use for rock drilling, cutting, selective fragmentation of composite materials and jewels extraction.

**Outlook for 2008**

Further efforts will be concentrated on the simulation of the system as a whole. In addition, some special motor designs will be assessed for their suitability for downhole drilling, together with associated clamping and forward thrust provision options. An interest in the advanced electric rock fracturing methods will be retained.

**References**


Aim
The main goal of this project is to show the feasibility of a thermoelectric power plant by theoretical considerations and selective experiments. Therefore highly efficient novel thermoelectric materials exhibiting low heat conductivity, high electric conductivity and large Seebeck coefficients should be developed. A variation of the module design by elaboration of microdevices (Pout up to 100mW, \(\Delta T = 500K\)) serves further to enhance the specific power flux. The next step would be a system design for a 1 kW module.

For optimization and other purposes an adequate model for the 3-D simulation of the coupled thermal and electrical problem including irreversibilities has to be developed.

General approach:

The general idea is to have a tool for evaluation and optimisation of module designs in combination with new materials. For this purpose an appropriate model for the thermoelectric devices has been developed. As a first step this was done for a single thermoelectric leg of a very simple geometry. In the next step the model has been extended to a single couple and in a further step to a multi-couple module including all the required components for power generation. An appropriate physical model of a thermoelectric device has been developed and evaluated with COMSOL Multiphysics, a 3D-finite element tool for coupled, physical problems. The validation was done by the comparison of the performance forecasts from the simulated results and the experimental data. The experimental data were taken from micro-thermographic measurements of the temperature distribution and standard data logging of the electrical behaviour. Therefore 4-leg TOMs (Thermoelectric Oxide Modules) with different leg lengths were assembled and an associated test stand has been designed, consisting of the components for heat supply and removal, the clamping fixture in combination with a scales (to obtain well defined, reproducible results) and the measuring equipment (like IR-camera, data logging unit,...) was designed.
4. CURRENT PROJECTS

The interacting of simulation results and measured data is visualized in Figure 1 and an overview of the experimental equipment is shown in Fig.2.

Figure 2: Overview of the test stand for experimental investigations of TOM’s

Results:

The following results shown here are taken from theoretical and experimental investigations of Thermoelectric Oxide Modules with a leg length of 5 mm at different temperature differences.

Figure 3: Comparison of simulation results and measured data of a 5 mm TOM @ $\Delta T = 100K$ (left) and $\Delta T = 400K$ (right), shown magnitudes: Power output vs. load voltage
In general, a good fit between theoretical forecasts and experimental data can be found. A reason for the deviations is the internal resistance of the module, which is very small, especially at higher temperatures and complicates the load variations for maximum power output. This effect will vanish with multi-couple modules.

Outlook 2008
The main future task will be the validation of the model and the development of optimized designs for multi-couple devices based on improved materials of the Solid-State Chemistry Group at EMPA Dübendorf.

Partnerships: EMPA Dübendorf, Solid-State Chemistry and Analyses, Switzerland
Swiss Federal Office of Energy SFOE
4. CURRENT PROJECTS

CONOR (CORONA NOISE REDUCTION)

Ueli Straumann, Hans-Jürg Weber

Aim
The aim of the project is the provision of information that can be utilized to mitigate tonal and other acoustic emissions from high-voltage lines and on relationships permitting prediction of noise levels.

General introduction
Acoustic emissions from high voltage lines can reach locally unacceptable levels and are linked to energy loss from the lines. Tonal noise at twice mains frequency may cause particular annoyance while the common hissing or crackling noise is more readily tolerated and easier to suppress at the immission site.

Both kinds of noise are associated with electrical discharges from particular sites of elevated electrical field strength such as blemishes on conductors and other hardware surfaces and – most importantly – water drops. The aim has to be to eliminate or reduce the number and severity of such sites and to keep field strengths low to avoid discharge inception. In this context, conductor arrangements, bundle configurations, conductor geometry and surface properties have to be considered.

MECHANISM AND REMEDIES

Simulation
The simulation aiming to calculate the corona effects on the gas sketched in last year’s annual report has been refined. At that time, a perfect recombination of positive and negative ions had been assumed in the simulation. The recombination chosen now conforms to the general recombination equation

\[
\frac{\partial n^+}{\partial t} = r n^+ n^- ,
\]

(1)

where \( n^+ \) and \( n^- \) are the local densities of positive and negative ions, respectively, and \( r \) is the recombination coefficient. Using this correction, the calculated corona current matches the measured fairly well [1].

Quantification of the sound level of the hum
In spite of the improved accuracy of the calculated corona current mentioned in the preceding section, the comparison of the resulting sound pressure levels with measured ones showed a significant difference between these levels, as the calculated levels were too low.

As the calculated and measured corona currents differ little, the focus was laid on finding additional sources of the humming component of the audible noise. Such a component was found as the force acting on the gas by directed momentum transfer from the drifting ions, a schematic representation of which is given in Fig. 1. A time-dependent force now enters additionally as source in the inhomogeneous wave equation.
The two sources, the force on the gas $F_{2f}$ and the formerly considered power $P_{el2f}$ going into a heating of the gas, both acting with twice the mains frequency, have been compared; the ratio of the sound pressures produced by these two sources in the far field is

$$\frac{p_f}{p_h} = \frac{c}{0.4} \cos(\theta) \frac{F_{2f}}{P_{el2f}},$$

where $c$ is the speed of sound.

The cosine in (2) reveals the directional characteristic of the component of emitted hum by the force source, caused by the fact that such forces enter the wave equation as a dipole. Even though dipole emission is much less effective than monopole emission (in this case the heat source), the weight of the force source in (2) is significant.

![Figure 1: Ions of both polarities (red and blue) are located in the surroundings of the conductor where they are subject to the electrical field which results in the force $f_i$ for the $i$th ion. The sum of all these forces is $F$, which by scattering of the ions and neutrals is passed on to the neutral gas.](image)

Taking this additional force source into account, the calculated hum levels agree with the measured ones fairly well, including the asymmetry of the emission by the directional characteristic of the emission by the force source [3].

**Field Test**

A field test with a hydrophilic coating on a span of a transmission line crossing the Alps has been initiated. The coating process seemed to work out rather well; nevertheless the first results revealed a surprisingly low hum level for the coated span as well as the uncoated part of the line. With both levels so low, no benefit of the coating on such a line has as yet been detected.

A possible explanation for the low hum level in the uncoated section of the line may lie in the considerable age of the conductors. Ageing of the conductors is often connected with an increase in their hydrophilicity.

Another difficulty with the comparison measurement could be found in the very large excursions of the lateral profile of the hum level due to the interferences of the phases. An example of such a (calculated) profile is shown in Fig. 2, which reveals the sensitivity of the measurement of the hum levels on the lateral position under the line.
Figure 2: Calculated lateral profile of the hum level (the origin is located in the middle of the transmission line).

**Outlook 2008**
- Search for the reason for the low hum level in the uncoated section of the line in the field test.
- Execution of the second field test, with optional adjustments depending on the final outcome of the first field test.
- Programming of a computer application for calculation of hum and overall noise levels depending on the line parameters.

**Partnerships:**
- swisselectric research, Switzerland
- EnBW Regional AG, Germany
- Verbund Austrian Power Grid APG, Austria
- Vorarlberger Illwerke VIW, Austria
- Bundesamt für Umwelt Bafu, Switzerland
- Elektrizitätswerk der Stadt Zürich ewz, Switzerland

**Reference**
4.1 Services offered

Hans-Jürg Weber

In November the audit for the renewal of our accreditation for the calibration and testing laboratory was successfully carried out by the Swiss Accreditation Service (SAS). The accreditation has to be repeated at the latest after 5 years.

The High Voltage Laboratory provided once more various services for several Swiss and European companies and institutions throughout the year 2007.

Accredited calibration laboratory (SCS 081)
Our calibration laboratory for electrical quantities in the field of high voltage, capacitance and apparent charge fulfilled 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 customer’s laboratory. Additionally PD calibrators, impulse peak voltmeters and C-tanδ measuring systems have been calibrated.

Accredited testing laboratory (STS 181)
Our laboratory for the testing of electrical properties of components of electric energy supply performed a wide variety of tests according to international standards as well as following laboratory-developed test procedures.
5. Publications and Presentations

5.1 Reviewed Publications

C. Eisenhut, F. Krug, C. Schram, B. Klöckl
“Wind Turbine Model for System Simulations near Cut-in Wind Speed”
IEEE Transactions on Energy Conversion
Volume 22, Issue 2, pp. 414-420
June 2007

N. Karrer, P. Hofer-Noser
“Hochdynamiche Stromerfassung in der Leistungselektronik”
Book „Leistungselektronische Bauelemente“, ISBN 3-540-28728-0
Springer Verlag, pp. 849-983

N. Karrer, L. Dalessandro, W. Kolar
“High-Performance Planar Isolated Current Sensor for Power Electronics Applications”
IEEE Transactions on Power Electronics
Volume 22, No 5, pp. 1682-1692
September 2007

T. Weiers, D. Keller, W. Hutter, C.-E.
“Retardation of Electrical Tree Propagation by Resin Degradation”
ETEP
Volume 17, pp. 255-267
November 2007
5.2 Conference Presentations and Publications

Th. Smolka, K. Fröhlich, B. Klöckl, A. Schmettler, T. Hintzen
“ECO-Efficiency Assessment of Dispersed Power Generation in Distribution Energy Networks”
CIRED, 19th Conference on Electricity Distribution
Vienna, Austria
21 – 24 May 2007

W. Hribernik, K. Fröhlich
"Implementation of a model-based diagnosis system for power transformers"
CIRED, 19th Conference on Electricity Distribution
Vienna, Austria
21 – 24 May 2007

K. Fröhlich
"Key Note Speech for IEC-Cigré-UHV Symposium"
IEC Cigré UHV Symposium
Beijing, VR China
25 July 2007

L. Graber, A. Djurdjic
"Computational Model of Dynamic SF6-Gas Distribution for Early Leakage Detection in Metal-Enclosed Switchgear"
ISH 2007
Ljubljana, Slovenia
27 – 31 August 2007

P. Favre-Perrod, M. Schulze
"Synergies among several energy carrier systems in future energy networks"
ISH 2007
Ljubljana, Slovenia
27 – 31 August 2007

T. Weiers, S. Beugger, S. McClure, R. Vogelsang
"The impact of low amplitude 100 Hz vibrations on the winding insulation of rotating high voltage machines"
ISH 2007
Ljubljana, Slovenia
27 – 31 August 2007

M. Hinow, M. Mevissen
"Closed Assessment Form for Substation Asset Management"
ISH 2007
Ljubljana, Slovenia
27 – 31 August 2007

M. Grader
"Dimensions of matrix switches consisting of a series- and parallel-connection of numerous low-current contacts and requirements on their elements"
ISH 2007
Ljubljana, Slovenia
27 – 31 August 2007
5. Publications and Presentations

L. Graber, M.K. Pradhan
“Gas-Distribution Modeling for the Detection of SF6 Leakage in Metal-Enclosed Switchgear”
Cigré Meeting
Rio de Janeiro, Brazil
12 – 13 September 2007

A. Ebner
“Transient Transformer Inrush Currents due to Closing Time- and Residual Flux Measurement-Deviations if Controlled Switching is used”
EEUG Meeting 2007, European EMTP-ATP Conference
León, Spain
24 – 26 September 2007

R. Brütsch, M. Tari, K. Fröhlich, T. Weiers, R. Vogelsang
“Power Generator Insulation Failure Mechanism”
Cigré SC A1 & D1 Joint Colloquium
24 October 2007
5.3 Journal Publications and Varia

K. Fröhlich
“Overview – controlled switching system”
Mitsubishi Electric Journal
Volume 177
March 2007

K. Fröhlich
Invited lecture “Lösungsansätze zur verbesserten Einbindung stochastischer elektrischer Energiequellen in das Energieversorgungsnetz”
Veranstaltung Studiengruppe Energieperspektiven
Baden, Switzerland
14 June 2007

L. Graber
“Simulation der konvektiven SF6-Strömung zur Leckerkennung in gasisolierten Hochspannungsanlagen”
CADFEM Users Meeting
Zurich, Switzerland
14 – 15 June 2007

K. Fröhlich
Invited Lecture “Die Zukunft der elektrischen Energieversorgung an den eidgenössischen technischen Hochschulen”
Energietechnikforum
Bern, Switzerland
21 August 2007

K. Fröhlich
“Keynote speach” by the Cigré Technical Committee Chairman
ISH 2007
Ljubljana, Slovenia
27 August 2007

K. Fröhlich
Opening Speech
Cigré D2 Meeting
Lucerne, Switzerland
5 September 2007

L. Graber
“Alternative Methode zur Leckerkennung in Gasisolierten Schaltanlagen”
GIS-Anwender Forum 2007
Darmstadt, Germany
10 October 2007

P. Favre-Perrod, A. Hyde, P. Menke
“A Framework for the Study of Multi-Energy Network”
2nd SmartGrids Technology Platform General Assembly
Kloster Banz, Germany
8 – 9 November 2007
6. Conferences, Workshops and Awards

6.1 Conference and Workshop Participation

K. Fröhlich
VSE/Electrosuisse „Schweizerischer Stromkongress“
Pfäffikon, Switzerland
16 – 17 January 2007

M. Schulze
PhD Workshop BTU Cottbus
Cottbus, Germany
28 February – 2 March 2007

Cigré/CIRED ETG Fachtagung “Naturkatastrophen und Energieversorgung”
Zurich, Switzerland
1 March 2007

P. Simka, J. Aniceto Calero
COMSOL Multi-physics Workshop
Zurich, Switzerland
1 March 2007

K. Fröhlich
Cigré Steering Committee Meeting
Dubai, United Emirates
22 – 26 April 2007

K. Fröhlich
Symposium Thermopower EMPA
Duebendorf, Switzerland
8 / 15 May 2007

H.J. Weber
Highvolt Kolloquium 07
Dresden, Germany
12 – 16 May 2007

K. Fröhlich, W. Hribernik
CIRED, 19th Conference on Electricity Distribution
Vienna, Austria
21 – 24 May 2007

H.J. Weber, S. Neuhold
Workshop “Diagnostik, Mess- und Prüftechnik in der Hochspannungstechnologie”
ETH Zurich, Switzerland
24 May 2007
M. Schulze
PhD Workshop
Politecnica Torino
Turin, Italy
27 – 31 May 2007

K. Fröhlich
Veranstaltung Studiengruppe Energieperspektiven
Baden, Switzerland
14 June 2007

L. Graber
CADFEM Users Meeting
Zurich, Switzerland
14 – 15 June 2007

K. Fröhlich
IEC Cigré UHV Symposium
Beijing, VR China
25 July 2007

K. Fröhlich
Energietechnikforum
Bern, Switzerland
21 August 2007

K. Fröhlich, L. Graber, P. Favre-Perrod, M. Hinow, T. Weiers
ISH 2007
Ljubljana, Slovenia
27 – 31 August 2007

K. Fröhlich
Cigré Admin Council Meeting
Nanjing, VR China
24 – 28 September 2007

L. Graber
Cigré Meeting
Rio de Janeiro, Brazil
12 – 13 September 2007

A. Ebner
EEUG Meeting 2007, European EMTP-ATP Conference
León, Spain
24 – 26 September 2007

L. Graber
GIS-Anwender Forum 2007
Darmstadt, Germany
9 - 10 October 2007
6. Conferences, Workshops and Awards

K. Fröhlich
Cigré SC A1 & D1 Joint Colloquium
Christchurch, New Zealand
24 October 2007

P. Favre-Perrod, A. Hyde, P. Menke
2nd SmartGrids Technology Platform General Assembly
Bad Staffelstein, Germany
8 – 9 November 2007

L. Graber
Arsenal “Numerische Strömungssimulationen für verbesserte Leckanerkennung in
Gasisolierten Schaltanlagen”
Vienna, Austria
10 November 2007

H.J. Weber
FKH Fachtagung “Ölimprägnierte Hochspannungsisolationen aktuelle Probleme”
Rapperswil, Switzerland
14 November 2007

P. Favre-Perrod
Conference “Untold stories of FP7”
Budapest, Hungary
6 – 8 December 2007

6.2 Awards

Förderpreis OGE (Österreichische Gesellschaft für Energietechnik des ÖVE)
Wolfgang Hribernik
Dissertation „A model-based diagnosis system for the moisture content of power transformer
insulations under varying loading conditions“
Joint Activities

1. Joint Projects

**VISION OF FUTURE ENERGY NETWORKS**

In the project Vision of Future Energy Networks (VoFEN) various issues related to future energy systems are investigated. The major difference to similar research projects is a strong focus on multiple energy carrier systems and exploitable synergies. The motivation for this focus stems from the increased commissioning of gas-fired power stations. Many of these both small- and large-scale power stations generate electricity and heat. Thus, a certain dependency and exchangeability between the electric and the gas network is being established. Similar conversions between, e.g., the electric and the thermal network can be identified, resulting in various possibilities for interconnecting the electric, chemical and thermal supply of loads. The increasing availability of decentralized generation technology (e.g., microturbines, fuel cells and adsorption coolers), as well as third-party network access regulations, due to the ongoing liberalization processes, results in an increasing number of such interconnections. The project VoFEN applies a Greenfield approach to investigate optimal network topologies and operation strategies. Only by neglecting existing supply infrastructures and by focusing on the load demands and available and foreseeable technologies it is possible to identify potential topologies and to show in which direction networks and infrastructures should evolve.

**Risk Assessment and Investment Analysis**

Florian Kienzle

Traditional energy planning, as usually carried out today, features two main characteristics. Firstly, there is typically a focus on one single energy network, e.g. the electricity grid, whereas interdependencies with other networks such as the gas supply system are not sufficiently taken into account [1]. Secondly, investment risks are often disregarded during the planning process and decisions are taken under pure cost considerations [2]. The aim of this work package is to overcome these deficiencies and to develop tools enabling the investment planning of multi-carrier energy systems taking relevant risk factors into account.

During the last year, a multi-energy generation portfolio model has been developed. By means of this model, efficient portfolios generating multiple energy outputs can be determined. The analysis of a multi-energy portfolio with, e.g., electricity, heat and cooling power as outputs results in 3D-diagrams as shown in figure 1. For each combination of risk and return, the diagram indicates the corresponding electricity share, i.e. the part electricity production has in the total energy production within the portfolio.
1. JOINT PROJECTS

The same type of diagram can be drawn for the share of produced heating or cooling power. In this way, the energy system planner, e.g. a municipal utility, can choose an efficient mix of generation technologies for the desired amount of electricity, heat and cooling power output.

![Diagram](image-url)

*Figure 1: Electricity share vs. risk and return.*

**System Dynamics and Control**

Michèle Arnold

Today’s conventional energy infrastructures are mostly planned and operated independently of each other. This project part addresses the combined optimization of multiple energy carriers. With the novel concept of energy hubs, the couplings between the different infrastructures are taken into account enabling the analysis of a combined optimal power flow (OPF) [1, 3]. Energy systems are built up from interconnected energy hubs (Figure 2) and thus form a decentralized power generation structure. Each hub is thus controlled by its respective control authority, i.e. is considered as an autonomous agent. Different control methods are analyzed, decomposing the overall optimization problem into sub-problems according to the hubs. The coordination between the distributed hub agents is achieved by the mutual exchange of data [4].

A further step is to incorporate dynamics into the system models. Based on the dynamic models, a hierarchical control strategy is to be implemented. The faster system dynamics are handled by local controllers whereas a supervisory control layer coordinates the local controllers and intervenes in case of conflicts between them.
System Extension including Transportation Systems

Matthias Galus

Recently, economical, environmental and political issues have been expediting the development of a sustainable, green economy. Due to this progress an initiative has been launched for vehicles that utilize their battery for propulsion and then recharge it from the grid. Called Plug-In Hybrid Electric Vehicles (PHEV), these incorporate the advantages of electric and hybrid electric vehicles while alleviating the disadvantages. Hence, they are presumed to have a big market impact subsequently affecting significantly the power generation and distribution system [5]. It is intuitive to use the Energy Hub greenfield approach to deal with the yet non-existent, distributed and non-stationary (e.g. mobile) issue of PHEV charging and their possible utilization as an active storage facility within the network. As the project will incorporate recent findings of transportation theory, an agent-based approach has appeared, too [6]. Utilizing both approaches, a modelling and analysis scheme will be developed to investigate new load demand patterns and load management schemes dealing with the electricity demand at distribution network sites imposed by PHEV. Furthermore, a management scheme for using the distributed storage and a grid restoration approach will be studied. These goals will lead the way for a possible integration of individual transportation into the power system.
Multi-Energy Transmission

Patrick Favre-Perrod

An important question in the assessment of the energy interconnector principle is the derivation of a layout procedure, i.e. the determination of necessary inner radius, transmission voltage and conductor cross-sectional area as a function of the transmitted powers and line length.

The previously developed models and simplified analytical expressions lead to the determination of a set of scaling laws. A layout procedure using these laws and a set of “known” configurations has been developed, as an analytical solution to this question does not yet exist. This layout procedure can be used within the scenarios to be developed in the Vision of Future Energy networks project.

Case Study Energy Hub Baden

Matthias Schulze

Since the beginning of VoFEN activities many theoretical aspects have been examined. A basic concept for Energy Hubs has been established including the modelling of conversion, transmission as well as storage of multiple energy carriers. Different optimisation strategies were explored and proved within hypothetical examples. The mission of this work package is to implement, testify and, if necessary, to improve existing and ongoing work packages from VoFEN within a case study. The region of Baden will be the case to study, namely the district Dättwil containing the Kantonsspital and a mixture of domestic, commercial and industrial areas. Multi-period optimal dispatch and multi-carrier optimal power flow are tools to describe the scheduling performance of Energy Hubs and the boundary conditions for the energy
exchange between hubs. Therefore each particular sub-area of the grid must be described in the manner specified by the Energy Hub equations.
To enable multi-carrier and storage integration, which is not part and parcel of today’s grid, a view into the future by using scenarios and approximate consumption and generation statistics is useful. The results will show the link between theoretical and practical modelling of existing grids. The present electricity, district heating and gas grids are only marginally interconnected. The application of a multi-carrier optimal dispatch yields the specified input and output carriers of the Energy Hubs. Together with the optimal hub coupling method, constraints for the links between the Hubs are obtained.
These boundary conditions will give an idea regarding the bandwidth of transmitted energy.

References


Partnerships: ABB Switzerland Ltd.
Areva
Siemens
Bundesamt für Energie (BfE)
2. Colloquia

Topical Problems of Electric Power Engineering / Aktuelle Probleme der Energietechnik

In collaboration with the “Energietechnische Gesellschaft ETG/SEV” and IEEE Power Engineering Society Swiss Chapter

“Dynamisches Netzmodell Schweiz”
Dr.-Ing. Walter Sattinger, swissgrid
24 April 2007

“Comparative Perspective on Current and Future Energy Supply”
Dr. Stefan Hirschberg, Paul Scherrer Institute
8 May 2007

“Technological and Market Evolution of High Voltage Direct Current Transmission - HVDC”
Dr. Marcio Szechtman, Independent Consultant, Brazil
27 November 2007