Energy Transmission and High Voltage Laboratory

Annual Report

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Annual Report 2001

Issued by

Energy Transmission and High Voltage Laboratory
(Institut für Elektrische Energieübertragung und Hochspannungstechnologie)

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Front cover: Numerical simulation of electrical tree development in a needle-plane arrangement in a polymer dielectric together with equipotentials represented by uniform colours. (see contribution on project ACIM, pp. 44-45)
Preface

Dear Friends of the Laboratory,

During the year the research activities of the laboratory were further consolidated. In total more than twenty active researchers are associated with the laboratory, and the international profile of the research is further enhanced. Members of the laboratory have made numerous visits to other research institutes and participated in a large number of conferences presenting their latest research results, and we have had several external visitors during the year.

At a seminar at ETH in November on Decentralized Power Generation organized by the Swiss Electrotechnical Society (SEV/ETG) contributions were made by both Prof. Andersson and Prof. Fröhlich. This field of research is believed to be more important for the laboratory in the future. A research grant in this area has been granted from Alliance for Global Sustainability (AGS), and discussions are going on with other partners for further projects. The total competence of the laboratory, including both system and technological aspects, together with the resources of the power electronics group are a key factors for success.

Concerning details of the different research projects, the reader is referred to the descriptions of the projects in the report.

Concerning teaching we could last winter semester experience a large increase in the number of students to the lectures in Electric Power Systems, an elective course in the fifth semester. A co-ordination of the courses in the higher semesters is going on, which together with a continuous update and revision of the lectures and course material, should guarantee a high quality of the undergraduate teaching, which is the long-term basis of the activities of the laboratory.

During the year, Mrs D. Metzler retired as secretary of the power systems laboratory after many year in this capacity. We want to thank Mrs Metzler for her excellent services, and we also want to welcome Mrs A. Wieland as new secretary in the group.

We also want to thank all young hard working, enthusiastic and talented PhD students of the laboratory, who have done most of the work reported in this annual report.

G. Andersson

K. Fröhlich
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1. Organisation

1.1 Power Systems Laboratory

Head: Prof. Dr. G. Andersson

Secretariat: D. Metzler until 30.7.01
A. Wieland from 19.4.01

Scientific Staff: Dipl.-Ing. J. Allmeling from 1.7.01
Dipl.-Ing. W. Hammer
Dipl.-Ing. A. Karpatchev
Dipl. El.-Ing. W. Rohr until 31.8.01
Dipl. El.-Ing. C. Schaffner
Dipl.-Ing. U. Stumkat until 30.4.01

Scientific Associate: Prof. em. Dr. H. Glavitsch

1.2 High Voltage Laboratory

Head: Prof. Dr.-techn. K. Fröhlich

Secretariat: B. Rutz

Scientific Staff: Dipl. El.-Ing. H.-P. Burgener
Dipl. Phys. Th. Farr
Dipl.-Ing. M. Grader from 19.3.01
Dipl.-Ing. W. Holaus until 31.12.01
Dipl.-Ing. W. Hribernik
Dipl. El.-Ing. R. Hug
Dipl.-Ing. P. Jankowitz
Dipl. El.-Ing. H. Krauss from 1.11.01
Dipl. El.-Ing. U. Krüsi
Dipl. El.-Ing. St. Neuhold from 1.6.01
Dipl. El.-Ing. D. Politano
Dipl. Math./Nat. U. Straumann from 8.10.01
Dipl.-Ing. R. Vogelsang
1. ORGANISATION

Permanent Staff: El.-Ing. HTL H.J. Weber High Voltage Laboratory
Ch. Sigrist Electronics Group
H. Vögele Electronics Group
H. Kienast Workshop

Scientific Associates: Tit.-Prof. em. Dr. sc. techn. H. Brechna
Dipl. El.-Ing. St. Neuhold until 31.5.01 FKH
Dr. rer. nat. T.H. Teich
Prof. em. Dr. Ing. W. Zaengl

1.3 External Lecturers

Dr. R. Bacher Bacher Consulting, Baden
Dr. D. Reichelt Arthur Andersen AG, Zürich
Dr. W. Hofbauer ABB High Voltage Ltd., Zürich
Dr. W. Paul ABB Corporate Research Ltd., Baden-Dättwil (WS 00/01)
Dr. M. Lakner ABB Corporate Research Ltd., Baden-Dättwil (WS 00/02)

1Fachkommission für Hochspannungsfragen
2. Education

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

We use standardised terms to characterise the listed lectures and laboratories:

<table>
<thead>
<tr>
<th>Semester</th>
<th>Title</th>
<th>German title</th>
<th>hours per week</th>
<th>Lecturer</th>
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What is the "EMG"? What does liberalization mean? What is the subject of the referendum in December 2001? What are the current developments in the energy sector? Which effects can these have on your career after graduation?

To be able to give answers to these and other questions on power economics is the task of this seminar.

During an introductory discussion, a broad overview of the current issues will be gained. You will also be given a subject to work on independently, using literature, internet and newspapers. At the end of the semester, the results of this work will be presented in a report, which will be discussed with the seminar leader and the other participants.

5th semester | Electric Power Systems | Elektrische Energiesysteme | 4G | G. Andersson | K. Fröhlich |

Structure of electric power systems; symmetric three phase systems; modelling of power transformers and generators; analysis of plain and unsymmetrical three phase systems; transient switching phenomena; basics of current interruption; principles and applications of distribution- and transmission switchgear; basics of insulation coordination.

1V = lecture; U = tutorial; G = lecture with assoc. tutorial; P = laboratory class; S = seminars
6th semester

**Modelling and Analysis of Power Systems**

G. Andersson

(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 und 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.

7th semester

**Portfolio and Risk Management in a Liberalized Electricity Market**

D. Reichelt

(Portfolio und Risk Management im liberalisierten Strommarkt)

Open electricity market; Swiss electricity market law; power trading (OTC); transmission system operator (TSO); ancillary services; congestion management; Swiss electricity price index (SWEP); European power exchanges (EEX, LPX); financial products: futures, options, swaps; risk management: value at risk, profit at risk, simulations; hedging strategies; marketing of electricity (product development); further developments in the European electricity market

7th semester

**Optimization of Liberalized Electric Power Systems**

R. Bacher

(Optimierung liberalisierter elektrischer Energiesysteme)

Mathematical optimization methods; Karush-Kuhn-Tucker optimality conditions; equality constrained non-linear optimization; Linear Programming (LP) (Simplex, Interior Point), Quadratic Programming (QP) and applications; non-linear optimization; Goals of a power exchange (PX), of the “independent system operator” (ISO), of the regulatory institutions, of the new electric power utilities; principles of optimization of a power exchange: offer-Bids; optimal regulated network operation: payments for network use; long-term and medium-term network optimization as goals; handling of network security limitations by optimization methods; optimization methods to determine the efficiency of networks; optimization of ancillary services as part of the liberalized electric power system.

8th semester

**Power System Dynamics and Protection**

G. Andersson

(Dynamik von Netzen und Leitungsschutz)

Dynamic properties of electrical machines, networks, loads and connected systems; models of power stations and turbines; regulation of turbines; power and frequency control; power exchange among networks; model of the synchronous machine connected with the network; biaxial theory; transient model; block diagram; behaviour of the machine in case of disturbances; transient stability; area criterion; model for small disturbances; voltage control and static stability; condition
of protection systems (selectivity, reliability, reserve, economic efficiency); principle of protection; protection of transmission lines; distance protective system; earth return circuit; influence of fault impedances; location of power supply; trigger characteristics and staggering; balanced protective system; phase comparing protection; direction monitoring protection; (digital) protective gear; algorithms; fault location; intelligent alarm signal processing; use of expert systems.

2.2 Lectures, labs, and seminar provided by the High Voltage Laboratory

Laboratory classes, project work and seminars (PPS)

1st and 2nd semester
Laboratory class "Introduction to high voltage engineering" ("Einführung in die Hochspannungstechnik") K. Fröhlich and teaching assistants

The weekly laboratory classes are taken in two different locations on two afternoons, usually in groups of two to three students each.

It is the aim of the laboratories to familiarise the students with the handling of high voltages and the most important phenomena occurring in high voltage applications.

Specialised studies (General section)

5th and 6th semester
Specialised laboratory classes I and II K. Fröhlich and teaching assistants

The students have a choice from a list of experiments offered by the sections of the Electrical Engineering Department. Each student of electrical engineering should carry out a total of 25 experiments in the 5th and 6th semester (one afternoon each).

The High Voltage Laboratory currently offers four experiments which can be carried out without preceding attendance at the specialised lectures. A detailed description including theory and intensive supervision are provided. The experiments offered have proved popular:

- Breakdown behaviour of an electrode arrangement including computer modelling and measurements
- Investigation of critical current interruption in the kiloampere range
- High temperature superconductors
- Lightning impulse voltage test to 500 kV.
Specialised studies (fundamentals)

1st Semester  
**Networks and Circuits I**  
(Netzwerke und Schaltungen I)  
K. Fröhlich

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 thorough exercises.

Specialised studies (Core subject)

5th Semester  
**Electric Power systems**  
(Elektrische Energiesysteme)  
G. Andersson  
K. Fröhlich

Structure of electric power systems; symmetric three phase systems; modelling of power transformers and generators; analysis of plain and unsymmetrical three phase systems; transient switching phenomena; basics of current interruption; principles and applications of distribution- and transmission switchgear; basics of insulation coordination.

Specialised studies (Principal subjects)

6th or 8th Semester  
**High voltage technology**  
(Hochspannungstechnik)  
K. Fröhlich

Basic phenomena connected 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 co-ordination.

7th Semester  
**Integrated subsystems in electrical transmission and distribution**  
(Integrierte Subsysteme der elektrischen Energieübertragung und -verteilung)  
K. Fröhlich  
P. Jankowetz

Associated physics and methods for interruption of DC currents and AC currents in transmission and distribution systems; intelligent circuit breakers; superconductor as an interrupting element; gas-insulated systems; high voltage DC current systems (principle, field of application, benefit); essential system components; testing
techniques; measuring techniques (e.g. electro-optical measuring transformers); development methods, electronic and informatics based development tools; exercises in application of these tools (two small projects).

Specialised studies (Options)

7th Semester 2V
**Applied high-temperature superconductivity**
(Angewandte Hochtemperatur-Supraleitung)

W. Paul
M. Lakner

Introduction: history, basic experiments and phenomena; physics basics: thermodynamical description, microscopic model, flux quantization, pinning, Bean model; low temperatures: cryostats, open and closed circulation cooling systems; high temperature superconductors: structure, anisotropy, weak links, topical state of materials development; energy technology: AC loss, rotating machines, transformers, current limiters, cables, energy storage, magnetohydrodynamical generators, magnet levitation vehicles; research: magnets, radiation detectors, Josephson junctions, SQUIDs; electronics: filters, transistors, digital circuits.

7th Semester 2V
**The activities of the engineer in engineering and commerce**
(Ingenieurarbeit - Technik und Wirtschaft)

W. Hofbauer

After a general introduction, the concrete example surge diverter is used to outline the purpose of the commercial enterprise, its controlling organisation and the role of the engineer within the enterprise. Accounting schemes will be treated at considerable breadth, introducing the purposes of financial accounting, profit accounting as well as the financial report, giving practical examples. Furthermore, the importance of investment accounting will be treated, considering product-related cost factors such as the principle of operation, the cost structure and the multiplicity of possible variants as well as process-related cost factors such as investment in manpower, infrastructure as well as make-or-buy decisions. The importance of the research and development processes in relation to the success of the enterprise is presented in detail, taking the activities of the engineer particularly into account.

7th Semester 2V
**Computer processing oriented project work**
(EDV-orientierte Projektarbeit)

K. Fröhlich

and assistants

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. As we have close collaboration with the FKH some of the student projects as well as diploma work (see the following section) are supervised by staff of the FKH.

**Summer 2001**

D. Grand  
Statistische Analyse von Preiskurven in der Elektrizitätswirtschaft

S. Mutter  
Modellierung des CCC (Capacitor Commutated Converter) mit Hilfe der Phasor Dynamics Methode

**Winter 2001/2**

P. Favre-Perrod  
Dependence of critical current in a Bi$_2$Sr$_2$Ca$_2$Cu$_3$O sample on magnetic field and tensile stress (Magnetfeld- und Zugspannungsabhängigkeit des kritischen Stromes in einer Bi$_2$Sr$_2$Ca$_2$Cu$_3$O Probe)

R. Hofer  
RF radiation from a switching arc (Lichtbogenstrahlung im Radiofrequenz-Bereich)

R. Frik, J. Meyer  
Compilation of a system for characterizing dielectric samples (Aufbau eines dielektrischen Messsystems)

### 2.4 Diploma Projects

Allocated time is four 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).

**Winter 2001/2**

J.-S. Hentz  
Market Models for Studying Congestion Management in Liberalized Electricity Markets Using FACTS

D. Grand  
Influence of grading capacitors on residual flux after transformer de-energization

L. Graber  
TRV determination procedures - a proposal for the international standards

S. Berchil  
Caractéristiques du développement des arbres électriques dans la résine époxy dû aux décharges partielles avec et sans l’introduction de barrières (Tree growth in electrical engineering epoxies with and without internal barriers)

O. Duchy  
(HTL Fribourg)
2.5 Projects utilizing electronic data processing

In the high voltage laboratory two such projects were carried out in the summer semester 2001; one was allocated for the winter semester 2001/2002.

2.6 Excursions

17 January 2001  NOK, Thalwil
220 kV gas-insulated substation (220 kV-GIS-Schaltanlage)

17 January 2001  KKG, Gösgen
Nuclear power plant

5 June 2001  NOK, Beznau
Hydro power plant and 380/220/50 kV substation

11 June 2001  ABB High Voltage Technologies Ltd., Oerlikon
Gas-insulated substations (Gasisolierte Schaltanlagen), Generator circuit breakers (Generatorschalter)

20 June 2001  NOK, Baden
Load dispatch center

25 June 2001  ABB High Voltage Technologies Ltd., Wettingen
Surge arrestor production
3. Seminars and Lectures

3.1 Colloquia "Aktuelle Probleme der Energietechnik"

"Die Liberalisierung des Strommarktes in Deutschland"
E. Hagenmeyer, Universität Stuttgart, Germany
23 January 2001

"Informationstechnologie in Energienetzen - Der Königsweg zu höchster Effizienz und definierter Zuverlässigkeit?"
J. Bertsch, ABB Power Automation AG
8 May 2001

"Verbundisolatoren: Eigenschaften, weltweite Betriebserfahrungen und innovative Lösungen im Schweizer Netz"
K. Papailiou, SEFAG AG
5 June 2001

"Controlled Switching of Transformers"
J. H. Brunke, Bonneville Power Administration (BPA), Portland OR, USA
11 June 2001

"Ist die Energieverteilung der Zukunft bereits erfunden?"
K. Kaltenegger, ABB Schweiz, Zürich
26 June 2001

"Die Rolle der ETRANS im schweizerischen Hochspannungsnetz"
K. Imhof, CEO, ETRANS AG, Laufenburg
3 July 2001

"Das vollelektrifizierte Schiff – Ein Energiemassstab der Zukunft in kleinem Massstab"
M. Steurer, Center of Advanced Power Systems, Florida State University, USA
17 December 2001

3.2 Other Lectures

"Course*: Deregulation of the Electricity Market"
W. Vouets, ALSTOM (Schweiz AG)
13 June 2001

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*This course was given as part of the lecture “Modeling and Analysis of Power Systems”
3. SEMINARS AND LECTURES
4. Activities of the Power Systems Laboratory

4.1 Completed PhD Theses

Fast Control of an Active Filter with Low Switching Frequency for the Medium Voltage Grid

Candidate: Dipl. Ing. Jost Allmeling
Thesis: ETH No. 14428
Date of oral examination: 14 November 2001
Examiner: Prof. Dr. G. Andersson, ETH Zürich
Co-examiner: Prof. em. Dr. H. Stemmler, ETH Zürich (Supervisor)

Author’s summary

Disturbing loads like arc furnaces and thyristor rectifiers draw fluctuating and harmonic currents from the utility grid. These non sinusoidal currents cause a voltage drop across the finite internal grid impedance, and the voltage waveform in the vicinity becomes distorted. Hence, the normal operation of sensitive consumers is jeopardized.

Active filters are a means to improve the power quality in distribution networks. In order to reduce the injection of non sinusoidal load currents shunt active filters are connected in parallel to disturbing loads (Fig. 1). The active filter investigated in this project consists of a PWM controlled three-level VSI with a DC link capacitor. The VSI is connected to the point of common coupling via a transformer. The configuration is identical with an advanced static var compensator.

![Figure 1: Shunt active filter](image)

The purpose of the active filter is to compensate transient and harmonic components of the load current so that only fundamental frequency components remain in the grid current. Additionally, the active filter may provide the reactive power
consumed by the load. The control principle for the active filter is rather straightforward: The load current is measured, the fundamental active component is removed from the measurement, and the result is used as the reference for the VSI output current.

In the low voltage grid, active filters may use inverters based on IGBTs with switching frequencies of 10 kHz or more. The harmonics produced by those inverters are easily suppressed with small passive filters. The VSI can be regarded nearly as an ideally controllable voltage source. In medium voltage applications with power ratings of several MVA, however, the switching frequency of today's VSIs is limited to some hundred Hertz. Modern high power IGCTs can operate at around 1 kHz. Therefore, large passive filters are needed in order to remove the current ripple generated by the VSI. Furthermore, in fast control schemes the VSI no longer represents an ideal voltage source because the PWM modulator produces a considerable dead-time.

In this project a fast dead-beat algorithm for PWM operated VSIs is developed [1]. This algorithm improves the load current tracking performance and the stability of the active filter. Normally, for a harmonics free current measurement the VSI current would be sampled synchronously with the tips of the triangular carriers. Here, the current acquisition is shifted in order to minimize the delays in the control loop. The harmonics now included in the measurement can be calculated and subtracted from the VSI current. Thus, an instantaneous current estimation free of harmonics is obtained.

The VSI not only has to track stochastic transients as fast as possible but also to compensate stationary harmonics in the load current. With the dead-beat control alone a complete compensation cannot be achieved because the inherent dead time causes a persistant phase error between load current and VSI current. At higher frequencies the VSI would even amplify certain load current harmonics. Therefore, an outer control loop is required that compensates for the the phase error.

This work presents and compares different strategies for filtering stationary harmonics such as rotating reference frames, integrating oscillators and harmonic analysis in a prefilter. Based on integrating oscillators a control structure is derived that allows selective harmonics compensation. The fast tracking performance of the inner control loop is maintained for load current transients.

To demonstrate the feasibility of the new control algorithms a 10 kVA laboratory model of the active filter has been set up. The VSI operates at a semiconductor switching frequency of 900 Hz according to the capability of high power IGCTs. The measurements made in the laboratory show good corresponance with the simulation results on a microcomputer.

References

4.2. Current Projects

Modelling techniques for power electronic devices

Wolfgang Hammer

There is a general trend that power electronics based devices are increasingly being used and considered in power systems applications. These devices can be classified into FACTS devices (Flexible AC Transmission Systems) such as the thyristor controlled series capacitor (TCSC) and the unified power flow controller (UPFC) on one hand, and the more traditional HVDC applications on the other hand.

In order to understand and control the interactions between power electronics devices and the power system they are connected to, there is an increasing need for appropriate models. However, the question which model is appropriate is not a trivial one, as these interactions have many causes (e.g. electromechanical, harmonic, and control interactions) and their characteristic frequencies may range from a fraction of a Hz to several kHz.

Obviously the detailed time domain three-phase simulation will yield the most accurate results for any type of interaction. The drawback of detailed modelling, however, is the computational effort. The long simulation times render it virtually useless for the study of slow phenomena that require the simulation of long time periods. The standard approach for such problems is the quasi-static method which relies on the assumption that the system operates in a steady state (i.e. the ac quantities being sinusoidal, and the dc quantities constant). By this approach one arrives at models that are very simple but capture the behaviour of a system quite accurately up to a few Hz. There remains a frequency range from several Hz up to around fundamental frequency for which the detailed simulation is too slow, and the quasi-static model, too coarse.

Recently, new modelling techniques, based on so-called phasor dynamics, have been proposed that may close this gap [1]. However, the applications reported so far have mostly been concerning FACTS devices. This project focuses on HVDC applications. The systems studied are the conventional converter and the capacitor commutated converter (CCC). For the conventional converter, a reduced model has been developed which shows good accordance with a detailed three-phase simulation in a frequency range up to fundamental frequency [2]. The new model can be seen as an extension of the standard quasi-static model and is identical in the steady state. This new model can easily be incorporated in any phasor-based simulation. The techniques are now applied to the CCC. Preliminary studies have been carried out in a student project by Sandro Mutter.

References


Increased Transmission Capacity by Forced Symmetrization

Andrei Karpatchev

The research project deals with an investigation of possibilities for enforced symmetrization on a damaged transmission line to ensure power transmission through the line even in a faulty state. The utilisation of two remaining healthy phases of a three-phase transmission line with a damaged phase can be an economical way to ensure the system reliability. The electrical power sector experiences nowadays a considerable need in modern techniques for increasing the capability of transmission systems. Firstly, the reason for this lies in increasing power flows due to increasing power consumption and, secondly, due to the deregulation of the electrical market demanding power flows to be more flexible. The conservative expansion of the high voltage grid is often not desirable, because the approval of new overhead transmission lines meets strong opposition in society. Furthermore it takes long time and is generally a risky long-term financial investment. In the present planning of high voltage networks the (n-1) criterion is mostly respected. This means, that the network should not be subject to any overload or voltage drop below a strict given limit when any network element is disconnected. Based on the statistics, the single phase-to-ground faults are the most frequent faults in transmission systems. The percentage of faults due to the phase-to-phase and three-phase faults is considerably smaller. Present planning procedures are often based on single outages of three-phase circuits, which do not take the actual fault pattern into account. For the single-phase faults it is necessary to avoid unsymmetrical conditions or unsymmetrical currents in the network. The reason for this is that the currents in the zero-sequence system mean earth currents, and those can be dangerous for people and cause adverse interaction with other systems. The currents and voltages in the negative-sequence system are a concern to rotating synchronous machines like generators and motors, but if no such machines are connected to a network part, the negative-sequence voltages can be tolerated on that part.

Symmetrization means the suppression of both zero- and negative-sequence currents on the network side of both breakers so that the network do not experience any unsymmetrical conditions. This can be performed by the installation of two
FACTS-devices as shunt or serial elements at the line terminals (see fig. 1).

Different arrangements and strategies are considered in the work. To try all the different arrangements a special system simulator was developed. It is based on power flow calculation with multiple symmetrical system representation and allows simulating the effect of symmetrization in a complex meshed network. The fault currents in the negative- and zero-sequence systems can be studied directly. Results of simulation of some fault cases of IEEE sample networks are represented. Implementation of the symmetrization technique can be a competitive solution to the common extensive methods for providing system availability. Shorter installation terms, easy administrative permission way and possibility to use the installed equipment for auxiliary system services are supportive arguments for the new technology.

Value of Controllable Devices in a Liberalized Electricity Market

Christian Schaffner

Abstract In a liberalized electricity market, the transmission capability of a transmission system is of an economical value to the network company. This company has a natural monopoly combined with the commission to maximize the benefit for its customer while giving a reasonable profit to its owners. Due to physical constraints in the surrounding network, the lines are often only utilized at a fraction of their individual limits. To improve customer benefit one possibility would be to add to the value of the transmission lines by increasing the amount of transported energy over these lines. Additionally, there will be a gain in overall market efficiency since more energy trading can take place between competing regions with different price structures. Flexible AC Transmission Systems (FACTS) devices allow the increase of the overall utilization of an electrical power network by controlling the power flow.

Since installations of FACTS devices require huge investments with costs similar to new transmission lines (see [1]) the effect of higher transfer capability only, can not necessarily justify these new installations. Therefore, it is evident that one has to consider all possible aspects, that add to the value of FACTS devices in a transmission system: static and dynamic stability, increased transfer capability, increased system reliability, regained controllability over the power flow for Independent System Operators (ISO) or Transmission System Operators (TSO) in a liberalized electricity market, and the possibility of relocation. (See fig. 1)

Objective In this PhD thesis it will be examined what additional economic value the increased transmission capability provided by controllable devices (such as FACTS) gives in a liberalized electrical power transmission system.

Outline To achieve the objectives described in the preceding paragraph several research areas in the field of electric power transmission and controllable devices in such systems are examined. The Synthesis of these areas and new research based on them will be used to describe methods to determine the value of controllable devices in a MAEM.
In addition to quantitative results, qualitative aspects will describe the most important factors when evaluating this value.

Industry partners will help in defining example systems, providing information on real congestion situations, stability issues etc. In addition, there will be collaboration with other academical institutions in the area of general economical methods for liberalized markets.

PLECS - Piece-wise electrical circuit simulation with Simulink
Jost Allmeling, Wolfgang Hammer

The development of power electronic systems usually involves the design of both the electrical circuit and the control algorithms. To study the behavior of these systems thoroughly simulation is essential.

For the simulation of purely electrical circuits powerful programs like Spice and Saber exists. They allow the user to enter the circuits as netlists or schematics. However, incorporating complex control structures requires a thorough knowledge of the specific program.

Simulink, an extension to Matlab, is a program for simulating dynamic systems. It is widely used for the simulation of control systems, since even complex structures can be built easily and Matlab provides powerful evaluation of the simulation results. Therefore, Simulink is also convenient for the design of closed loop controlled power electronic systems. However, systems containing electrical circuits cause difficulties, in that they cannot be modeled in a straightforward way. Simulink accepts neither schematics nor netlists for electrical circuits. Instead they must be represented by mathematical formulae be it state-space equations or nodal formulation which must be set up individually for every topology. This process is time-consuming and error-prone. Since summer 1998 the Power System Blockset is available. This toolbox allows the user to combine the electrical system and the controller in one system model by entering the circuit diagram at Simulink block level. Although the Power System Blockset also contains components such as diodes and GTOs the extensive use of these elements leads to very long simulation times. Furthermore, ideal elements like switches require snubber circuits to make the simulation converge. Thus, this toolbox is not well suited for simulating large power electronic systems.
The Power System Blockset models semiconductors and switches as inductances in parallel with current sources to make the simulation continuous even during switching actions. When simulating complex power electronic systems, however, the processes during switching are of little interest. Here, the use of ideal instantaneous switches is more appropriate. Firstly this yields systems that are linear between two switching instances. Secondly, to handle the discontinuities at the switching instances only two integration steps are required. Both speed up the simulation considerably. To achieve the goal of improving simulations under Simulink by the use of ideal switches, the program PLECS has been developed.

PLECS is a toolbox for piece-wise linear simulation of electrical circuits within the Simulink environment. Circuits to be simulated with PLECS may consist of ideal resistors, inductors, capacitors, transformers, voltage and current sources, meters, and switches. These latter elements sources, meters, and switches form the interface between the electrical circuit and the control system. This points towards modeling the electrical circuit as one single Simulink subsystem. Its inputs are the commands for controlled sources and switches. Measurements taken by the voltmeters and ammeters are provided as the subsystem’s outputs.

PLECS provides linear elements and switches. At any time the switches in PLECS are either short or open circuits. This means that before and after the instant of switching the circuit is purely linear and hence its overall behavior is piece-wise linear. Switches are the basis for power electronic components. They can be controlled externally or internally or a combination of both. External in this context means that the control signal does not directly depend on voltages or currents in the circuit but is instead supplied by the overlaying control system. Examples for externally controlled switches are breakers and half-bridges of VSIs. Internal control variables are voltages or currents that can be measured in the circuit. The simplest example of a purely internally controlled switch is a diode, which is switched on by a positive voltage and off by a negative current. Power electronic components such as thyristors, GTOs and IGBTs operate according to a logical combination of external and internal switching conditions.

Currently, a schematic editor is under development that facilitates the graphical entry of circuits. In previous versions of PLECS netlist are required for the circuit definitions. The new editor is adapted to the look and feel of Simulink. Therefore, users familiar with Simulink can easily create their own simulation models with PLECS. The editor is already used by students in a simulation colloquium.

References


FlowDemo.NET: Interactive, Internet-Based Tool to Visualize Power Flow in an Electric Transmission System

Christian Schaffner

Abstract  FlowDemo.NET is an interactive load flow visualization software for education in electrical engineering. Its strength lies in the utilization of the Internet: The software can be run on any Internet browser and thus there is no special installation needed for the user. Lecturers use it to visually demonstrate load flow in electric transmission systems in a convenient way: They access predefined examples on a server. After class students can access the same examples via an Internet browser to strengthen the new knowledge: The time on task will be increased, which has a high effect on learning efficiency. This principle of learning software can easily be applied to other fields in the future.

Figure 1: Graphical user interface of Flowdemo.NET showing a six-bus example network
Description  FlowDemo.NET gives a visual representation of a calculated load flow including the network topology, graphical representation of the load flowing through a line, numerical and graphical representation of bus voltages and angles, state of switches etc. The user can interact with the calculation by switching on or off lines and components, changing parameters such as the voltage of a regulating generator or the active and reactive power of a load. The graphical user interface (GUI) is programmed in Java. The calculation is carried out on a server running Matlab that communicates with the java applet on the client computer. This applet can be loaded by any Internet browser thus eliminating completely the need to install software on the client computer and making the software platform independent.

Whenever the user changes the network by switching on or off a line or a component or by changing component parameters the server receives the changes and requests new results from Matlab. These are sent back to the client applet that displays them immediately.

Applications in Education  A typical application of FlowDemo.NET is as following: The lecturer prepares demonstration networks and puts the according net lists on the server. During class he can explain theoretical principles using one of the prepared networks. All he needs is a computer with Internet access and a computer display projector. To strengthen the knowledge students will use the same simulations after class to work through written questions.

New concepts or devices can be implemented directly by the lecturer, since the source code is available. Also, as Matlab is well known by most engineering people, no special programming knowledge is needed.

Outlook  Apart from including new devices such as FACTS region control is planned to allow the control of the amount of power flowing from one region to another. This gives the opportunity to study congestion management or transaction scheduling.

For use in education a tutorial system will be developed allowing the lecturer to include problem descriptions and their solutions directly into the graphical user interface. This will give the students the possibility to verify their results immediately.

Also the change of network topology online on the client systems is planned for a future version of FlowDemo.NET.
4.3 Publications and Reports


4.4 Conferences and Visits

IEEE Power Engineering Society Winter Meeting 2001
28 January - 1 February 2001, Columbus, Ohio, USA
G. Andersson, C. Schaffner

Internationale Fachtagung der ETG des VDE und des SEV sowie der ÖVE/ÖGE
9-10 May 2001, Friedrichshafen, Germany
C. Schaffner, W. Rohr

Doktorprüfung, Norwegian University of Science and Technology
18-19 May 2001, Trondheim, Norway
G. Andersson
IEEE Power Engineering Society Summer Meeting 2001
14-18 August 2001, Vancouver, Canada
G. Andersson, A. Karpatchev

9th European Conference on Power Electronics and Applications (EPE 2001)
27-29 August 2001, Graz, Austria
W. Hammer

Doktorprüfung, University of Zagreb
12 October 2001, Zagreb, Croatia
G. Andersson

7th International Conference on AC-DC Power Transmission
28-30 November 2001, London, UK
C. Schaffner

27th Annual Conference of the IEEE Industrial Electronics Society (IECON 2001)
29 November - 2 December 2001, Denver, Colorado, USA
J. Allmeling

4.5 Presentations and Seminars

G. Andersson, “The Liberalization of the Scandinavian Electricity Market”
Faculty of Electrical Engineering, University of Zagreb
23 March 2001, Zagreb, Croatia

G. Andersson, “The Liberalization of the Scandinavian Electricity Market”
Faculty of Electrical Engineering, University of Bologna
25 May 2001, Bologna, Italy

G. Andersson, “Die Sicherheit der Stromübertragung im geöffneten Markt”
Energiewirtschaftliches Kolloquium, ETH Zürich
15 November 2001, Zürich

G. Andersson, “Zukunftsperspektiven und technische Herausforderungen”
ETG-Informationstagung “Neue dezentrale Energieerzeugung und deren Einbindung in bestehende Netze”, ETH Zürich
22 November 2001, Zürich
4. ACTIVITIES OF THE POWER SYSTEMS LABORATORY
5. Activities of the High Voltage Laboratory

5.1 Completed PhD Theses

A hybrid, medium-voltage switching system for fault-current limitation and interruption

Candidate: Dipl. Ing. M. Steurer
Thesis: ETH No. 14059
Date of oral examination: 5 February 2001
Examiner: Prof. Dr. K. Fröhlich, ETH Zürich
Co-examiner: Prof. Dr. J. Hugel, ETH Zürich

Author's summary

Short circuits in electric power systems do not only interrupt the power flow to the consumer, they also cause high mechanical stress on those components carrying the short circuit current. As the prospective value of the fault current often reaches ten to twenty times that of the rated current, it has long been a wish of electrical engineers to limit the amplitude of the fault current. Nowadays, with rising energy consumption and deregulation of the energy market, measures like connecting subgrids and cost reduction by new grid operation strategies are necessary. Such measures strongly demand short circuit current limitation.

The only way to limit the short circuit current in medium and high voltage systems is still to choose a high permanent network impedance, which not only bears operative drawbacks but is also economically unsatisfactory. In contrast, the voltage drop of the arc developing in mechanical switches has been used for current-limiting in low voltage technology for a long time. Extrapolating this principle towards higher voltages with economically acceptable expenditure is not possible due to physical reasons. Although there are different approaches for current-limiting apparatus for medium and high voltage applications, no economically and technically feasible solution has so far been in sight. Approaches employing superconductors as well as those using resistors based on conducting polymers with a high positive temperature coefficient of resistivity (PTC-resistors) still have considerable material technology problems. However, current limiting hybrid switches have now increasingly been proposed, in which the continuous current is carried by a mechanical switching system. The latter opens very rapidly and commutates the rising short circuit current into high power semiconductors that finally transfer the current into a voltage dependent resistor, thus limiting the current. For both DC and AC, such principles are available up to a rated voltage of approximately two kV. With higher
voltages, it is necessary to commutate into a series connection of semiconductors which is economically not reasonable. Furthermore, it is uneconomical to cascade such systems, since the cost of turn-off semiconductors amounts to a significant part of the total.

Based on those known hybrid approaches it is the task for the present work to search for a suitable topology for higher voltages, provide the design tools for the components of such a system by means of computer models and their physical basis as well as to investigate the functionality of the entire system to assess both, the economic and technical feasibility.

The hybrid switching system proposed in this work consists of three parallel paths where the continuous current is carried by a novel mechanical contact system designed by the author. With this transfer switch it is economically feasible for the first time to commutate high currents of several kA within approximately two hundred s into the second path. The latter consists essentially of a series connection of a GTO thyristor serving as a commutating aid and a mechanical disconnecting switch. Approximately 0.2 ms after the current in the transfer switch becomes zero, the GTO thyristor commutates the current into the third path which consists of a PTC-resistor connected in series to a load switch. On the basis of this switching principle the PTC-resistor is designed to provide an initial voltage drop across the transfer switch of several kV only. Subsequently, the mechanical switch in the second path opens without arcing, thus disconnecting the GTO thyristor from the rest of the circuit. Because of the rise in resistivity, due to self-heating of the PTC-resistor, and the further rise of the current the voltage rises only slightly above the system voltage within approximately one ms, thus finally limiting the fault current. By utilizing these synergy effects it is therefore possible to create a switching system for rated voltages of several ten kV, exceeding by several times that of the only GTO used.

Investigating the principle of the novel mechanical transfer switch as one of the key elements is a major part of this work. In contrast to other designs which also utilize an electrodynamic drive for fast contact opening, the presented concept minimizes the mass of the moving contact. As the only moving part of the switch, the latter is a conducting ring placed between annular fixed contacts. It carries the continuous load current, which is uniformly distributed along the circumference, in a radial direction. For opening, an insulated driving coil placed close to the ring induces an eddy current perpendicular to the load current in the ring. The latter is used to carry both currents, so the mass of the ring can be minimized. After contact separation, arcs develop on the inner and outer edges of the ring. Their voltage drops add up, thus shortening the time of commutation into the second path.

For medium voltage applications the optimum width of the ring is found to be (7...20) mm when utilizing compressed air for insulation. The diameter of the ring normalized to the rated current is approximately 60 mm/kA. Since the height of the ring is nearly independent from all other parameters, only about 200 J have to be stored in the capacitor of the electrodynamic drive to reach an opening velocity of (15...20) m/s necessary for a switch with a rated current and voltage of 2 kA and 12 kV, respectively.
No knowledge was available about the physical basis for modeling the voltage recovery of such very fast opening contact systems used with current commutation. Therefore, an experimental switch was designed to measure its load characteristics. For the opening velocity mentioned before, the rate of rise of recovery voltage without arcing was measured with approximately 80 V/µs. Although this contact system does not employ forced cooling of the arc, the same rate of rise of recovery voltage was measured for currents up to 6 kA with an arcing time of 100 s when keeping a zero voltage pause of several ten µs after current zero. Based on those findings the hypothesis is plausible, that the primary mechanism of voltage recovery of such contact systems after current commutation is due to the continuing travel of the moving contact with constant velocity into zones of cold insulating gas. Although modeling of the recovery is so far not yet possible based on that hypothesis, a comparison between the measured voltage recovery and computer simulations of the transient recovery voltage caused by the hybrid current-limiting system show clearly that the novel switch meets the requirements.

With the design guidelines elaborated for the PTC resistor it is shown that, for example, a hybrid system within a typical network configuration with a rated voltage of 18 kV does limit an asymmetric fault current below 50% of the prospective symmetric value, although the current throughput generally rises with the rated voltage. Current limitation is obtained with a robust and cost effective PTC resistor constructed with nickel wire. To verify those theoretical results, a single phase experimental setup of the hybrid system was designed and tested in an industrial high current laboratory. A prospective fault current of 13 kA at the generator terminals was limited to less than 50% of this value at a no-load voltage of 12 kV.

A rough cost estimate suggests that the overall costs of the hybrid system are still too high compared with conventional, non current-limiting systems. However, costs can be saved somewhere else when the higher performance potential of the hybrid switching system is taken into account.

It is concluded that the principles, physical basics and relationships, as well as the fundamental design guidelines elaborated within this work provide a powerful tool for future development of such a hybrid current-limiting switching system. The latter offers a wide range of applications within present AC power systems, for example as coupling switch between sub-networks or as current-limiting generator circuit breaker for distributed energy generation. Furthermore, the presented system leads towards economically attractive solutions for current-limiting switching at DC voltages of several ten kV, which eventually might be very interesting for future power systems.

Whether changes in presently used protective relying systems or in the standards for the type test of current-limiting switchgear will eventually be necessary, is still an open question. Besides that, a reliability analysis is also pending. It is proposed to investigate more closely the mechanism of voltage recovery of very short commutation arcs to optimize the opening switches for such hybrid current-limiting systems.
Ultra fast switches – Basic elements for future medium voltage switchgear

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Thesis: ETH No. 14375
Date of oral examination: 25 September 2001
Examiner: Prof. Dr. K. Fröhlich, ETH Zürich
Co-examiner: Prof. Dr. J. Hugel, ETH Zürich

Author's summary

The steadily increasing demand on electric energy and the continuing liberalization process of the electricity market raise the utilities’ need for further reduction of operation costs, increased functionality and power quality. One possibility to do so is the use of fault current limiters. Although many solutions for fault current limiting devices at medium and high-voltage levels have been presented in the literature, utilization of these limiters is restricted to particular installations due to shortcomings in economical feasibility. One specific hybrid system for current limiting using an assembly of three electro dynamically driven opening switches, power semiconductors and a pure wire resistor, had already been proposed and successfully tested in the course of this research project. This solution has a much better potential of being economical than previous ones but some features are still not satisfying.

Therefore, in the present work, it has been decided to start investigations for medium-voltage fault current limiting devices from a fundamental discussion on ultra fast-acting switches. As the basic element of these ultra-fast switches, so-called “elementary switches” are defined which are only capable of carrying the nominal current when closed and withstanding the rated voltage when open. The basic idea of the project was, to realize high power switchgear with a combination of such elementary switches using precise control of the operation instants. Elementary switches are not designed to withstand high-current arcing and they do not have facilities for forced arc cooling. Given this definition and using a repulsion drive, the vital characteristics of elementary switches using linear or rotational operation are derived as follows:

The moving mass in an elementary switch turns out to be around 1 g/MW dimensioning power, resulting in a drive energy requirement of several 100 J depending on design parameters. Linear operation requires up to 3 times the drive energy at rotational operation, especially if using air as switching medium. A generally applicable equation for calculating the resulting opening velocity as a function of design parameters is given. The results were compared to measured velocities and show good coincidence for linear and rotational operation up to 50 m/s. With the use of several implementations of elementary switches, theoretical and experimental investigations of their switching performance were conducted. Elementary switches can also be closed using a repulsion drive, resulting in an overall closing time down to 0.5 ms. The contact force required to carry the nominal current is provided by the inertia of the moving part and results in a 20% decrease of opening velocity. Repetitive switching at a repetition frequency above 10 Hz is not feasible due to poor drive efficiency.
Elementary switches are well suited for synchronous interruption of high ac currents at medium voltage levels up to 24 kV. As the energy dissipated by the arc at synchronous interruption is only around 1 J and the fast switch noticeably increases its contact gap during rise of TRV, elementary switches show a dielectric breakdown mechanism. The reignition voltage linearly increases with time from current zero but shows at least minimum breakdown strength according to the instantaneous recovery. The arc voltage of fast opened elementary switches is higher than the arc voltage of free burning arcs but lower than the one of strongly cooled arcs. This can be utilized to commutate high currents on a parallel resistor or capacitance. Both cases are treated theoretically and experimentally with an eye on applications in a hybrid system.

Applications of elementary switches arise either from combinations of several switches in series or in parallel with one common drive or by using the switches in a hybrid system. Combinations of elementary switches in parallel leads to a further reduction of dissipated arc energy in any single switch. A combination of many elementary switches in series leads to a linearly increasing gain of breakdown strength after synchronous interruption. Theoretically, even the ability for transient recovery performance of a standard vacuum switch is equalled by a combination of elementary switches using air at 5 bar, 12 breaks in series and an opening velocity of 50 m/s. A hybrid fault current limiting circuit breaker using three elementary switches or combinations with many breaks in series and one pure-wire resistor is proposed together with a trigger strategy to get low contact wear at load switching. Successful tests in a medium voltage circuit were performed. This system seems feasible up to a rated voltage of 24 kV and a rated current of 2...3 kA.

It is concluded from this work, that the given characteristics of ultra fast acting switches give them the potential to be the basic elements for future applications in medium voltage systems, such as fault current limiting circuit breakers and dc breakers.
5. ACTIVITIES OF THE HIGH VOLTAGE LABORATORY

5.2 Current Projects

Diagnosis of high voltage circuit breakers

P. Jankowetz

Goal One essential part of a future ‘intelligent’ circuit breaker is its capability of self-assessment of its condition. Therefore attention is turned on the detection of faulty components and denotation of the fault for repair as well as the identification of prospective faults.

Introduction Today’s condition monitoring systems can supply a tremendous amount of data from the equipment under observation which gives the information if something is wrong or not without being able to interpret the received data and to draw conclusions from them.

As has been adequately discussed to date (e.g. in CIGRE committee no. 13), in addition to monitoring, sophisticated diagnosis is also necessary. First of all, this would reduce maintenance costs and could also increase life expectancy and availability of the equipment.

With a diagnostic system it should be possible to interpret this tremendous amount of data gathered by the monitoring system and to draw conclusions. The information received turns thus from ‘there is something wrong with the device’ to define the problem and to state more precisely ‘what is wrong’ and ‘why’. Additionally this information can be condensed into short instructions given to the operating personnel, or slightly more comprehensive information could be supplied to the maintenance personnel about the nature of a fault, which has occurred or may be expected.

One powerful approach, which has been investigated for several years at the High Voltage Laboratory at the ETH Zürich, is the model-based diagnosis. It predicts, simulates, and explains the resultant behaviour of the system from its structure, causality, and functionality by using a model of the device. Comparison of the simulated behaviour and the observed behaviour of the device is used to evaluate the condition of the equipment and to generate a diagnosis.

Another important feature of a diagnostic system should be to give advance warning. This enables one to establish a better estimate of the required maintenance intervals and permits an assessment of the life expectancy.

Completed work and recent activities In figure 1 there can be seen the overall concept of a condition monitoring, analysis and diagnostic system, which was implemented to prove the results of the investigations previously described.

For verification, the modules depicted in figure 1 were programmed using the programming language Matlab. A hydraulically-operated drive of an SF6 circuit breaker,

1In cooperation with ABB High Voltage Technologies Ltd Zürich, Switzerland and ABB Power T&D Greensburg, USA
which was used to derive diagnoses, was modelled qualitatively. I. e., neither numerical values nor mathematical transfer functions were used to describe the behaviour of the circuit breaker, but qualitative statements and arguments similar to those in the human language.

This implementation was then tested off-line in a high voltage laboratory, and also on-line at the ETH itself. The test results show promise for finding the right diagnosis including faults of the diagnostic system itself (e.g. operational error of sensors). One considerable advantage of use of a qualitative model can be proven by applying the same computer model to another subtype of hydraulically-operated drive without changes. It could be demonstrated, that, although a different monitoring system was used, the same results could be achieved.

At this time a more comprehensive model, which was developed to identify a larger range of faults and to have the possibility of using more sensors, was implemented into the diagnostic system. The first test results are available, but further tests and interpretation of these tests are in progress.

In parallel, a sensor assessment tool has been programmed. The test results have shown that the capability to differentiate between different diagnoses depends primarily on the number, the type, and the location of the sensors. With this sensor assessment tool the manufacturer or the utility should be able to find the optimal sensor set fulfilling their requirements.

**Future work** As mentioned above, there are additional tests pending. A greater variety and number of faults have to be applied into the test object in the laboratory to enhance the confidence in the functionality of the diagnostic system and there is also some work to be done for the final assessment of test results.

The last step to complete the diagnostic system is to construct the trend analysis module. Some investigations on detecting trends in measured parameters have already been carried out, especially for gas leakage. As described above, with advance warning it should be possible to change from interval-based preventive maintenance to predictive (or condition-driven) maintenance.
Architecture of artificial intelligence for circuit breakers

Urs Krüsi

Industrial Partnership
ABB High Voltage Technologies Ltd, Zürich
ABB Greensburg USA
BPA Bonneville Power Administration, Portland OR, USA

Goal of the project
The overall goal of this project is to develop a circuit breaker with a certain amount of artificial intelligence. To determine what kind and how much artificial intelligence is required, and which tasks it will perform are the questions to be answered.

Last year’s efforts focused on two subjects:

- Influence of grading capacitors on residual flux after de-energization of a power transformer
- Laboratory setup to verify the proposed identification method for circuit breakers already installed

Influence of grading capacitors on residual flux after de-energization of a power transformer
HVAC circuit breakers are usually equipped with grading capacitors. After opening such a breaker a small voltage is still applied to the load side via these capacitors. In the case of an unloaded transformer this implies that the flux in the core is not constant but still dynamic. The question was, how does this dynamic flux behave and how is it affected by the value of the grading capacitors. In his diploma thesis [1], Damian Grand addressed this problem and arrived at the following conclusions:

- The residual flux is not reduced to zero as long as the ratio of flux associated with the voltage applied through the grading capacitors and the residual flux without grading capacitors is small enough.
- The decrement—always towards zero—was proportional to the actual voltage that is left on the transformer terminals (Details in [1]).

Once more the point-on-wave controller that considers residual flux—developed at our laboratory—was used to energize a 0.4/16kV transformer. These efforts resulted in a paper [2] in which the implementation of the closing strategies proposed by J.H. Brunke and the performance of the controller were presented. Figure 1 summarizes the results. Taking residual fluxes into account allows the use of circuit breakers with significantly more scatter than usually specified for controlled switching applications.

Laboratory setup to verify the proposed identification method for circuit breakers already installed
A controller was programmed to synchronize and to add the appropriate delay to the close command. It is based on the hardware that was used for the controlled energization of transformers. The whole process of setting up the laboratory test proved to be more tedious work than expected. However, the
Figure 1: The measurements of four different closing strategies are compared to the uncontrolled case. The different symbols denote the three phases—which is which is not relevant. Simultaneous closing strategy is the only strategy that does not imply independent pole control. The performance of this strategy depends largely on the residual flux pattern. Assuming zero residual flux—most controllers nowadays make use of this assumption—leads to significantly better results. The consideration of residual flux allows still further reduction of inrush currents or the use of less accurate circuit breakers—see rapid or delayed closing strategy.

setup—incorporating a 145kV SF$_6$ circuit breaker—is now ready to verify the identification procedure proposed in paper [3].

**Outlook 2002**

- Execution and evaluation of identification tests
- Define a concept of an intelligent circuit breaker controller

**References**


5. ACTIVITIES OF THE HIGH VOLTAGE LABORATORY

New switchgear technology ¹
W. Holaus, M. Grader, U. Straumann

Goal of the project  Electromechanical switching devices are economically superior to other switching devices at most current and voltage levels for load switching and short circuit interruption. However, the task of fault current limiting remains unsolved at high voltage levels due to two reasons, compare to Fig. 1:

- The conventional operation mechanism of high-voltage circuit breakers does not provide the required opening time of around 1 ms.
- The voltage drop of a high-current switching arc is too low for efficient fault current limitation.

Figure 1: Principle waveforms presented for comparison between conventional short circuit interruption and switching with fault current limitation

The goal of the project is to find novel designs for fault current limiting devices (FCLD) at medium voltage levels. According to the above-mentioned reasons, we search for designs based on hybrid systems that are composed of mechanical high-speed switches and nonlinear elements.

Several solutions for ultra-fast acting switches [1], [2], and hybrid systems for fault current limitation at medium voltage levels [3], [4] have already been proposed and investigated in this ongoing research project. Now, the search for future medium voltage current limiting switching devices is pursued as hitherto by W. Holaus but also additional approaches are to be tried (M. Grader, U. Straumann, see below).

Fast switches and hybrid combinations (W. Holaus)

A novel hybrid system for current limitation based on fast switches and a metal-wire resistor according to Fig. 2 was implemented. The working principle is similar to other proposed hybrid systems [3], [4], but no power semiconductor switches are required.

A fault current limitation and interruption sequence using this system will now be briefly described, referring to the principle in Fig. 2 and to measured waveforms in Fig. 3:

¹In cooperation with ABB High Voltage Technologies Ltd. / Zürich
During normal operation, switch A has to carry the load current. When triggered by an external fault detection system, the instantaneous current has to be commutated onto parallel path B at $t_1$ (see Fig. 3). Switch A is designed to have very low moving contact mass and is operated by a repulsion drive. It is thus capable to achieve contact separation within 0.1 ms after triggering. The switching arc provides a commutation voltage of several ten to hundred Volt, forcing the instantaneous current onto path B.

Switch B is a fast switch that has several tens of breaks in series, all of them driven by one common repulsion drive (see Fig. 2). When opened (at $t_2$), its overall arc voltage is the total sum of the individual arc voltages of the series breaks. The arc voltage of switch B reaches $U_{arc,B} \approx 1$ kV at $t_3$ which is sufficiently high to commutate the (still rising) fault current $i_{s}(t)$ onto path C. In this example, 76 breaks were connected in series in switch B. The cold resistance of $R_{PTC}$ was 0.7 Ohms.

Switch C has 24 breaks in series, which are all opened at $t_4$ shortly prior to the cur-
rent zero of $i_r(t)$ at $t_5$. The arc voltage of switch C reaches $U_{arc,C} = 0.8$ kV. The current is successfully interrupted and the gap withstands the transient recovery voltage (TRV) of 3.8 kV with a frequency of 5.9 kHz. For this test, the switches were operated in air at ambient pressure and no closing drive had been attached. More detailed discussion and results for the fast switches and this hybrid system can be found in [1].

**Outlook for future work**  The investigation on fast-acting switches and hybrid systems will be continued with both theoretical and experimental approaches.

**Simultaneous switching of multiple relays in a matrix (M. Grader)**

Relays are low-voltage and low-current mechanical switching devices which are economically and technologically well optimized. One approach for medium-voltage fault current limiting devices is to investigate the switching capability of a matrix of many series- and parallel-connected relays, which are all simultaneously operated, see Fig. 4.

![Figure 4: Principle of a matrix of many series and parallel connected FX-relays](image)

The questions to be answered for such a switching matrix are:

- What are the opening time of a single relay and the jitter of the instant of contact separation?
- How can the overall voltage $U_R$ be uniformly distributed across the individual relays during arcing and after current interruption?
- How can the overall current $I_R$ be uniformly divided among the parallel current paths during arcing and after current interruption?

Some fundamental investigations using FX2 relays [5] have been carried out to answer these questions. The measured operation times for different relays are shown in Fig. 5:

The results from these measurements are, that the operation time of the relays used is sufficiently low, but the jitter the instant of contact separation is rather high.

Example current and voltage waveforms during a DC interruption process using 3 relays in series are shown in Fig. 6. The sum of the arc voltages of the 3 relays reaches 90 V in some steps, which indicate the different instants of contact separation. Interruption occurs sharply, when the current falls below 1.6 A, resulting in
5.2. CURRENT PROJECTS

The interruption process is successful while showing a maximum arcing time of 80 ms. It can be concluded from these preliminary experiments, that a successful current interruption using these relays is only possible at instantaneous currents below 1.6 A. The reignition voltage is $\sim 400\text{V}$ per series break.

The interruption process looks different for initial relay currents below $\sim 1.5\text{A}$, compare to Fig. 7. Here, no stable arc is burning and the relays show multiple reignitions during the interruption process. The reignition voltage rises to $\sim 800\text{V}$ during the first 20 ms. The initially increasing values of the voltage peaks characterize the successive opening of the series-connected contacts. Due to the instantaneous recovery of the opening contacts, they can individually hold about 400 V.

**Outlook for future work**  Further experiments are to be conducted using higher numbers $n, m$ of series and parallel-connected relays. As the interruption current is a transient overvoltage of $U_R = 1.5\text{kV}$. The interruption process is successful while showing a maximum arcing time of 80 ms. It can be concluded from these preliminary experiments, that a successful current interruption using these relays is only possible at instantaneous currents below 1.6 A. The reignition voltage is $\sim 400\text{V}$ per series break. 

**Outlook for future work**  Further experiments are to be conducted using higher numbers $n, m$ of series and parallel-connected relays. As the interruption current is
limited to 1.6 A when using the present type of relay, other types of relays are also to be tested in a matrix layout.

**Theoretical investigation of the switching arc (U. Straumann)**

In this part of the project, a theoretical approach – together with simulations of the switching arc – is pursued to accompany the switching matrix experiments of M. Grader (see above). To start with, a modified Mayr equation was used to represent a simple arc model. Modified means here that the hyperbolic stationary arc relation which is applied in the Mayr equation [6] was not considered appropriate for our problem: As the experiments showed, a critical current exists (∼ 1.6A), below which interruption occurs promptly for voltages up to 400 V. This behaviour can not be simulated with a simple hyperbolic relationship, but with a starting assumption

\[ u_{\text{stationary}} = a_4 i_{\text{stationary}}^{-4} + a_o \]

with \(a_4\) and \(a_o\) as fitting parameters.

The circuit to which this model of the arc was applied is sketched in the inset in Fig. 8. Simulating a matrix of two relays each with two contacts in series (see Fig. 4) leads to 5 equations.

![Figure 8: Simulation of current and voltage waveforms during interruption of \(i_R = 2.2\) A and \(U_s = 240\) V using 2 dual contact relays in series (4 sequential interruptions).](image)

Fig. 8 shows the results of such a simulation – performed using Matlab – in comparison with experimental results for the same configuration. One may notice, that the damping of the oscillation of the transient recovery voltage from the simulation does not coincide with the experiment. The rise of the voltage at the beginning of the interruption occurs more smoothly due to the the model.

First general insights gained from the simulations of a switching matrix incorporating \(m\) parallel paths and covering a low current range are:
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- Because relays show a scatter in switching time of several 100 ms (see Fig. 5), one has to enforce a relatively uniform current division between the parallel paths by insertion of inductors, otherwise the current may be commutated into a single path. However, even inductance values up to 100 mH prove not to be sufficient to maintain switching capabilities of the same order as one has for single serial paths.

- The current is interrupted with a very steep rate of decrease, which leads to high overvoltages, especially if path inductances are inserted. Therefore reignition of the gap is to be expected which in turn requires surge protection.

**Outlook for future work** A more representative model for the arc and dielectric recovery are to be incorporated with further analysis of the switching matrix. Investigations for a better-suited arc model and of the dielectric recovery are pursued, as well as the analysis of such models in a switching matrix.

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MATiC—Measurement of Arcing Time in Circuit Breakers
Michael Chapman

Industrial partnership: ABB High Voltage Technologies Ltd / Zurich; ABB Power T&D Greensburg, USA

Project goal Power-system maintenance strategies rely on information about the existing infrastructure. In this context, the interruption capability of circuit-breaker chambers is of central importance; for this the aging and wear processes of contact and nozzle materials are key. The exposure times of the contacts and nozzle(s) to the arc for each switching event—which are directly related to the total arcing time—are very important parameters in any algorithm that can meaningfully estimate the contact and nozzle wear. Until now no non-invasive method exists in practice to measure the arcing time, although it can be calculated, given a knowledge of the arcing zone and a measurement of the moving contact’s travel curve. [1] It is therefore desirable to find a non-invasive, alternative, direct method for measuring the arcing time.

Arc detection Promising methods involve the detection of one or more of the arc’s various forms of emitted energy: radio-frequency (RF) electromagnetic emissions are being investigated for this purpose. Although historically treated from the perspective of interference, these emissions offer a seemingly elegant solution to the problem. The arc has been observed in experiments to demonstrate some distinguishable characteristics for at least one given arc type: an SF₆ medium-voltage breaker at around 300–600 A. The next challenge consists of showing how to couple the arc’s electromagnetic RF-energy in such a way as to consistently distinguish it from spurious sources in a noisy environment.

In order to observe the level and patterns of the arc’s radiated energy—the arc is regarded as radiating together with the surrounding breaking circuit—a setup was constructed to measure over a broad spectrum. Measurements with this setup have yielded signals that demonstrate the distinguishable characteristics mentioned above, which can be qualitatively seen in Figure 1. A strong burst at contact ignition is recognizable, as well as the continued presence of the signal throughout the arc, until the signal abruptly ceases at current zero.

The actual energy content of the signal is better illustrated by its short-time Fourier transform (STFT), seen in Figure 2, which is a time-frequency map of the signal strength. The characteristics which may be qualitatively observed are: low energy content outside the arcing time (due to measuring in a low-noise chamber), the strongly broadband nature of the arcing signal at contact separation, the presence of certain frequencies throughout the arcing time, and the abruptness of the onset and termination of the radiation in time. Comparison with the antenna’s environmental radiation characteristic shows that the presence of these frequencies corresponds roughly to resonances of the measuring technique. The measured frequency components are thus observed to be existent throughout the arc’s duration and point toward a broadband behavior, but are determined largely by the environment and method of coupling.
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Figure 1: Example of an arcing signal in the time domain, scaled for comparison with the arcing voltage; the interrupted current was approximately 530 A peak.

Figure 2: Short-time Fourier transform of the arcing signal seen in Figure 1.

Actual measurement of the arcing time actually only requires information about the presence of the radiated energy. Work toward development of an envelope detector using amplitude demodulation has been performed by Rémy Hofer in a semester project.

Outlook for 2002

- investigation of longer duration arcs with current-zero crossings
- investigation of the effects of varying the current magnitude, environment, and circuit
- development of an algorithm for measuring the arcing time
- distinction between co-existing arcs of a three-phase system

References

5. ACTIVITIES OF THE HIGH VOLTAGE LABORATORY

Technology of fibre-reinforced materials for gas-insulated switchgear components

Hans-Peter Burgener

Industrial Partnership
ABB High Voltage Technologies Ltd, Zürich

Aim  The influence of the different stress parameters on fibre-reinforced synthetics are to be recognised (cp. annual report of 2000). The results achieved in these investigations should help the manufacturers and users of fibre-reinforced insulation to design their materials to be more economical, more robust and free from defects.

Dielectric sensitivity of fibre-reinforced epoxy tubes to mechanical stress  Fibre-reinforced epoxy tubes are used as switchgear rods in GIS circuit-breakers. Therefore the investigations concentrate on the mechanical and dielectric behaviour of such materials.

Measurements have shown (cp. annual report 2000), that even very high mechanical stresses do not lead to measurable partial discharges (PD). To enlarge the knowledge on the appearance of PD and their development in microcracks [1] a concept has been elaborated which was published in the annual report 2000.

Besides PD measurements with fibre-reinforced tubes, a model of the probability of PD inception in small voids, a model of the avalanche development in a thin crack and experiments with defined void geometries shall give further insight into the deterioration process of fibre-reinforced insulation materials.

In [2] the influence of the voltage waveform, the pressure and the geometry on the PD inception probability of one small cylindrical void representing a thin crack is given. The following conclusions have been arrived at:

- With the voids considered and sufficiently high field values \( E > 2 \cdot E_{\text{inc}} \) the pressure and the kind of voltage have a minor influence on the time lag compared to the inherent scatter. The calculated spread of the probability due to the scatter of the time lag is similar to that found with measurements.
- Parameters such as radius of the void and field strength have a major influence on the time lag.

Considering a distribution of cracks in a mechanically stressed fibre-reinforced material, the probability of PD inception of a multitude of cylindrical cracks arranged in parallel has been calculated, too. The lengths of the cylindrical voids were assumed to be exponentially distributed and the radius was set constant. In fig. 1 the probability of a PD inception in any one of these cracks is depicted as a function of the time \( t \) to inception and of the peak value of a sinusoidal 50 Hz field. The pressure in each crack is assumed to be 0.6 bar (air) and the temperature 293 K.

\[ E_{\text{inc}} \] Inception field strength
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Fig. 1 demonstrates that short time lags $t$ with high probabilities can only be obtained at high field values. However, very few 'big' voids lead to inception also at moderate fields but have very large time lags $t$.

Besides this model which allows to assume the PD inception the effects of the geometry of the void on the avalanche are of interest. This influence of the geometry could be measured with an experimental setup, but the results are still to be fully evaluated.

**Outlook**  An additional model which is already under construction shall help to explain the avalanche development and the results obtained by the experiments in small voids mentioned above.

**References**


Project ACIM: Ageing of Micaceous Insulation Materials

Failure mechanisms of the electrical insulation of rotating machines

R. Vogelsang, T. Farr
Partners: Schweizerische Isola Werke AG, PDtech Power Engineering AG

Projekt Goal The goal of the project is to investigate the physical failure mechanisms of micaceous insulation materials in order to improve the material properties, to optimise the manufacturing process and to detect the failure state of such insulation systems.

Strategy of approach With many insulating materials, the process of electrical treeing is regarded as the most significant physical mechanism for dielectric breakdown in solid insulation. In the composite structure of epoxy-based micaceous insulation the process of electrical treeing takes place over a wide area. Thereby the electrical treeing creates a path mainly through the epoxy around the mica-tape barriers. As a wide range of micaceous insulations is in use, the process of electrical treeing has been investigated widely for different barrier materials. For this purpose, a special test setup has been developed to survey treeing. In parallel, simulations of electrical treeing in composite insulation have been developed to serve as a tool for qualitative analysis and to provide parameter values on which further treeing experiments can be based.

Results The experiments show that the process of electrical treeing within the polymer takes much longer when a barrier is introduced between the electrodes, it is thus very dependent on the type of barrier used. This is so because the electrical tree breaks either through the barrier, such as with PET foils, or the electrical tree propagates on a path around the barrier, such as with mica. When the tree propagates around the barrier, the path which bridges the electrodes will be spread out and extended (Figure 1). For propagation along the barrier, the speed is very much dependent on the material of the barrier. The experiments showed that the tree growth along a barrier of mica is much slower than the tree growth along a barrier of PTFE. The propagation of the electrical treeing along the barrier is furthermore dependent on the production process of the samples. The experiments with a barrier of mica showed that the tree propagation is significantly slower along the barrier with samples produced in vacuum than that of with a sample produced under ambient pressure. The propagation of electrical treeing around a barrier and the effect of the extension of lifetime of the samples by introducing a barrier could also be shown by the numerical simulations (Figure 2), together with the deleterious effect of a weak barrier interface. The simulations showed that a significant extension of the lifetime of the insulation could only be achieved when the barrier can not be destroyed by the tree and the barrier does not have a weak interface. The propagation of the electrical treeing has simultaneously been recorded by a camera and by partial discharge (PD) measurements. The recorded data show a clear correlation between the propagation state of the electrical treeing, the size of the created treeing channels and the measured PD data.
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Figure 1: Propagation path of an electrical tree around a barrier of mica in the experiment

Figure 2: Propagation path of an electrical tree around a barrier of mica in the numerical simulation

**Outlook** Further investigations shall be focussed on the question how the electrical treeing propagates through a generator bar and how this process can be slowed down. The study will cover the parameters electrical -, thermal - and mechanical load. For the experiments concerning mechanical load a suitable bending machine has been designed. In parallel, the numerical simulations will be extended to describe the breakdown process in micaceous insulation materials caused by multi-stress aging. They will be focussed on mechanical fatigue of material interfaces and the role of mechanical cracks with respect to tree initiation. Furthermore, investigations regarding the propagation of electrical treeing along different barriers shall be carried out in order to test new barrier materials regarding their behaviour with respect to tree growth. In all investigations the focus will be set on the application of the results to practical high voltage machine insulation systems and to establish a relation between the microscopic structure of the insulation, partial discharges and the reduction of lifetime under the influence of multiple stress.
PDT-Coil - Power and data transmitting composite coiled tubing
Roland Hug, Stefan Neuhold

Industrial partnership: Shell SIEP-RTS (NL), Airborne Development (NL), BJ Services (UK), Corrocean (N), Smartec (CH), K.U. Leuven (B)

Aim Assessment of the properties and capabilities of flexible tubing with integral electric power and signal transmission for subsea oil and gas exploration.

Introduction Basics and literature references have been given in the Annual Report 2000. The ETH High Voltage Laboratory studies and develops three phase electrical power supply to the drilling face by way of conductors buried in the tube walls. The study uses simulations with subsequent verification in laboratory tests. This will show the limits of the design and the materials. Suitable diagnostics for assessing the integrity of the entire system during service are also to be developed.

Simulations The simulations are divided into two main parts, dielectric and thermal as shown in Figure 1.

The dielectrics investigations were performed by FEM-modelling\(^1\). FEM is also used to obtain the thermal stress and to calculate the electrical parameters of the system. These parameters, which are highly frequency dependent, are used to simulate the whole system. Up to now these simulations have only been performed in the frequency domain which merely gives a rough overview of losses and travelling waves. This simulations will show what stress one has to expect and if the concepts would be feasible. As a next step, the models have to be simulated in the time-domain to obtain more accurate information about transients and their impact.

\(^{1}\text{FEM = finite element method}\)
Testing and Monitoring  Due to the very rough condition down hole (high temperature, very aggressive liquids and high pressure combined with further mechanical stress) chemical and mechanical tests have to be linked with electrical tests. A first evaluation of possible dielectric materials has been completed and specific tests have been successfully started. The evaluation of the necessary and possible monitoring and sensing configuration for the electrical power transmission line is still in progress.

Outlook for 2002

- Simulation of the whole system in the time domain
- Final design of the insulation system
- Development of an overall testing and monitoring strategy

References

Model-based transformer diagnosis
Wolfgang Hribernik

Partnerships
PSEL\textsuperscript{1}
EPF Lausanne
Bonneville Power Administration (BPA), Portland OR, USA

Goal of the project  In order to identify the actual condition of a power transformer or to locate faults in the transformer, diagnosis systems are needed. For this purpose off-line measurement techniques such as partial discharge (PD) measurement, polarisation – depolarisation current (PDC), frequency response analysis (FRA), etc. are available. In addition to that, “intelligent” sensors (e.g. for oil humidity, gas in oil, temperature, etc.) provide the possibility for on-line monitoring. However, the interpretation of the results has so far mostly been based on human experience. Therefore the goal of the project is to find process models for the measurements that objectively predict the measured values. Comparing measurements and predicted values provides a chance to identify fault conditions (Fig. 1).

Figure 1: Model-based transformer diagnoses. The measured values which are subjected to noise are fed into a process model. Comparison between measurements and model outputs should permit fault detection.

Sensitivity study on off-line diagnosis measurement techniques  FRA is a common method for detection of mechanical displacements (e.g. due to fault currents) that have occurred in the transformer winding. FRA involves the measurement of the

\textsuperscript{1}Projekt- und Studienfonds der Elektrizitätswirtschaft
complex frequency response of properties such as impedances, admittances, voltage ratios, etc. A mechanical failure in the winding changes the measurement result. However, the measurement instruments (vector network analyzer, frequency response analyzer, lightning impulse test-set) influence the result too. Up to now FRA is a purely comparative technique. A comparison of results obtained with different equipment may therefore be unsuitable for fault detection.

Using proper signal processing software tools, modelling of the measurement process becomes possible [1]. In a joint project with Bonneville Power Administration (BPA) the influence of cables, amplifiers and quantization effects on the FRA result is studied. The goal is to define a standardized procedure for transient recovery voltage (TRV) determination from FRA data (see also [2]).

Sensitivity studies including comparison between time-domain and frequency-domain techniques are also carried out in the field of dielectric spectrum measurements. Related to this topic is a student project in cooperation with the Institute of Mechanical Systems, Structure Technologies Group, ETHZ, which involves the measurements of polarization effects of ferroelectric polymers.

**Identification of process models for on-line monitoring** In order to implement a model-based monitoring system, mathematical models which describe the dynamic processes of the transformer are needed. The models are used to generate residuals between measured and calculated values. Evaluating these residuals leads to fault detection and isolation [3].

In a first step the process models for temperature, gas in oil, oil humidity and load are arrived at by means of experimental parameter identification. This should show that such models exist rather than generate models universally applicable to any transformer.

In order to implement different operating conditions, an experimental setup for system identification and verification has been developed. It consists of a 630 kVA distribution transformer operated with short circuited secondary winding. The transformer is equipped with an external sensor box containing sensors for oil humidity, gas in oil and oil temperature which are connected with a TMAP 2230 data acquisition unit (Fig. 2).

**Outlook 2002**

- The measurements for transformer process system identification are to be continued. Based on that, algorithms for fault detection and isolation are to be developed.

- Comparing results from the on-line oil humidity sensor with results from dielectric spectrum measurements should permit the modelling of an online paper humidity estimator.

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2 Schenk [4] presented an intelligent power transformer monitoring system using self-organizing maps (SOM) based on these variables.

3 produced by GE/Harley
Figure 2: Experimental setup for process-model identification and verification. The short
circuited transformer is loaded using a switchable resonant circuit at 380 V or 500 V. Sensor
signals (temperatures, oil humidity, gas in oil and load) are passed to a T-MAP2230 data
acquisition unit where they are stored for later processing. The sequential control is imple-
mented with a PLC.

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Dielectric response methods for diagnostics of power transformers
W.S. Zaengl

**Goal of the TF activities** The dryness and ageing state of the oil-paper insulation is a key factor in both the short and long term reliability of power transformers since moisture has deleterious effects on dielectric quality and ageing rates. Up to now, there is no universally accepted method of determining the dryness of the pressboard as used and embedded within such insulation systems. Because moisture partitions unequally and highly temperature dependent between the oil and the pressboard, the humidity predominantly residing within the solid insulation, the measurement of moisture in oil is not a reliable indicator of dryness, particularly for lightly loaded transformers. Although in principle moisture can also be extracted from pressboard samples and measured, this approach is hampered by the impossibility of obtaining samples on-site from a transformer still in use. Most recent attention has been directed to methods of determining moisture content and ageing of the pressboard indirectly by measuring the effects of moisture on dielectric properties. Rather than the traditional measurement of only power frequency loss factors, which are in general not very sensitive to moisture and ageing, recent attention has focussed on measuring other dielectric response parameters, which characterise some known polarisation phenomena. The three foremost techniques are:

- recovery or return voltage measurements (RVM),
- dielectric spectroscopy in the time domain, i.e. measurements of polarisation and depolarisation currents (PDC), and
- dielectric spectroscopy in the frequency domain, i.e. measurements of electric capacitance $C$ and loss factor $\tan \delta$ in dependence upon frequency (FDS).

**Project status** Task Force 15.01.09 was set up in 1999 to compare the three main techniques. Initial work has concentrated on measurements using all three techniques on an insulation model designed specifically to verify the influence of insulation geometry on dielectric responses, and has included comparisons with a mathematical model of polarisation behaviour. Furthermore, the influence of the thermodynamic equilibrium between paper and oil as well as the oil conductivity were tested in this model. In parallel, activities were undertaken in the UK, Switzerland and Sweden, which included performing measurements with the above named techniques on selected power transformers under field conditions. Until recently, the RVM technique has by far been the most popular method. The investigations as already performed by the Task Force showed, however, that for the RVM technique the usual interpretation based only on simple relationships between a “dominant time constant” of the RVM “polarisation spectrum” and the water content in cellulose is not correct. Improved interpretations are possible by applying dielectric spectroscopy in the time (PDC) or the frequency (FDS) domain, for which the geometrical layout of the insulation system can be taken into account. For both methods, commercial measurement systems are now available. Note that the dielectric spectroscopy in the time domain (“PDC Analyser”) takes advantage of earlier inves-
tigations which have been performed in our High Voltage Laboratory by Vahe Der Houhanessian (see his Thesis, Diss. ETH No. 12’832, 1998).

**Outlook for 2002**  In September 2001 the work of TF 15.01.09 was summarised and conclusions regarding the state of the knowledge on the applicability of the techniques were prepared. A summary of the investigations will be published in 2002 in ELECTRA, and a full version of the work will be published by a special CIGRE Brochure lateron.

**Members of the Task Force:**
Stanislaw M. Gubanski (chair), Uno Gäfvert, Peter Werelius, **Sweden**; Gustav Csépes, **Hungary**; J. Filippini, P. Guuinic, **France**; John Lapworth, **UK**; Pierre Boss, Volker Karius, Giuseppe Urbani, Vahe Der Houhanessian, Walter S. Zaengl, **CH**.
EASY – Economical advantages of innovations in power subsystems
Diego Politano

Industrial partnership: ABB (CH), ALSTOM (F), RWE (D), NGC (GB).

Abstract This project presents an innovative methodology for the economic analysis of capital investments that are expected to reduce long-term overall costs of power systems/components. It should be useful for evaluating the costs and benefits of innovative technologies. In the presented methodology a correlation between the stress conditions acting on the various power devices and the life cycle costs of the devices is created. Therefore the economical impact of a modification in the stresses due to a change or an introduction of new equipment in a power system can be evaluated.

Aim of the project In today’s cost calculation tools, costs are evaluated considering investment, operation and maintenance elements. In some models the reliability costs are also computed, normally a constant failure rate is assumed for every device and the costs due to unavailability are calculated. In none of these models the influence of the stress condition is considered. The goal of the project is to develop a mathematical model that takes the dependence of the costs on the stress conditions into account. Considering that the probability of a failure in a component depends on the condition of the component itself, and considering the direct relationship between stresses acting on the system and its condition it follows that the stress acting on the system has a direct influence on the costs of the system, which are resulting from malfunction or preventive maintenance. During operation, a component is constantly subjected to stress depending on several factors, environmental and operative. Each of the various condition states of the particular component implies a probability of failure, and therefore of costs due to the failure. It is thus possible to establish a relationship between stress acting on every single component and yearly costs.

Methodology The analysis of the failure modes [1] of a component shows that the condition of some vital subcomponents is responsible for the condition state of the component overall. Through the combination of the various condition states of these subcomponents all possible condition states of the entire component can be modelled. The project methodology models all the condition states of power equipment during its life in a Markov process. The solution of this Markov chain [2] provides the yearly probability for all condition states. Considering that all condition states are correlated to costs, the sum of all of these costs multiplied with the probability of occurrence gives the yearly costs for the assessed power component. The cost parameters are collected in a costs database and assigned to every condition state of the component. This database includes the monetisation of soft issues like environmental impact, customer relationship and legal aspects. The state transition probabilities are stress dependent and are assigned at the beginning of the assessment and are then collected in a database. The influence of the stress acting on the component on the life cycle costs [3] is modelled by way of the stress dependence of the state transition probabilities.
Case study: Controlled switching of a transformer  The application to a case study has shown that the methodology is useful for such an investigation. Even if the calculation of the absolute life cycle costs with sufficient precision is today still an unsolved problem, the methodology permits interesting comparative analyses that show the economical impact of an innovation. However, further research is needed to increase the accuracy of the results. The case study deals with the economical impact of the introduction of a controller for a substation circuit breaker. The controller is used to reduce the magnitude of the inrush current in a 220/110 kV substation transformer, resulting in a reduction of the mechanical stress acting on the windings of the 160 MVA transformer. The introduction of the controller results in a reduction of the probability of failure and of the need of maintenance of the winding and therefore of the transformer. Thanks to the presented methodology it was possible to assess the impact of this reduction on the life cycle costs of the transformer. The picture shows that the introduction of controlled switching could lead to life cycle cost present value savings of up to 6% over a lifetime of 50 years. It indicates that the introduction of controlled switching can be a very profitable investment.

![Discounted LCC savings](image)

Figure 1: Life cycle cost savings due to the introduction of controlled switching to energise a substation transformer

Outlook  The work done in this year has shown the feasibility of the EASY methodology. The application to a case study shows promising results. However to reach the goal of a useful tool for the investigation of the economical impact of an innovation in a power system more research is needed. The next steps have been defined:

Application to a second case study: The application of the methodology to a second case study dealing with a different device (e.g. a circuit breaker) should
confirm the general applicability of the algorithm proposed for the evaluation of all relevant devices.

Development of a tool for the evaluation of the stress pattern: A tool for the evaluation of the stresses acting on the component should be developed. The goal is to summarise in a table the history of the stress condition acting during service life.

Upgrading to system evaluation: Today the EASY methodology focuses the evaluation on a device level. The feasibility of the application at a system level (e.g. substation) should be investigated.

Software optimization: A user friendly interface should be developed. The software should be improved in order to include user friendly features.

References


High temperature superconductors (HTSC) operating under realistic conditions in energy technology

H. Brechna und P. Favre-Perrod

To obtain a better understanding of the properties of high temperature superconductors operating under realistic conditions in electrical energy delivery systems we developed a test setup which simultaneously measures electrical, magnetic and mechanical properties of superconducting tapes in liquid nitrogen (77.3 K). The superconductors Bi(2223) and Bi(2212) when received are already imbedded in pure silver. The tapes are either reinforced with steel to obtain the necessary high strength, or are just as received as a nonreinforced tape. We have been able to measure currents up to 200 Amp dc, strain of 0.3% and stresses on the conductor of over 130 MPa. With the present test setup we obtained realistic stress data common in electrical machines, cables for tapes being delivered to us by other research institutes and by the industry.

The tests revealed several sources of conductor degradation, when the superconductor is thermally and electrically cycled.

Figure 1: Test apparatus to measure electrical, magnetic and mechanical properties of HTSL superconductors

Figure 2: Thermal cycling may cause “ballooning” due to the intrusion of liquid nitrogen into the tape. When the trapped liquid evaporates, the resulting pressure is sufficient to inflate the silver matrix.

Figure 3: Detail view of the superconductor clamping of the stress apparatus.
Tonal emission from high voltage lines
T.H. Teich and H.J. Weber

**Aim**  To establish the real causes of tonal emissions centred on twice mains frequency as the widely touted explanation in terms of momentum transfer from ion swarms appeared untenable.

**Sponsors:** EnBW Regional AG (D), Vorarlberger Illwerke AG (A), Verbund-Austrian Power Grid GmbH (A)

Under "wet" conditions high voltage transmission lines, particularly those operating in the 400 kV regime, tend to emit a clear tone noise in addition to the hissing/crackling noise with a spectrum centred on 1 kHz or above. This tonal emission is perceived as particularly annoying especially at night and when it is the dominant noise in the locality. Noise regulations take this into account by setting a lower permitted level when the noise is of tonal nature.

The laboratory investigations were based on tubular or rod model conductors operated with geometrical surface field strengths of 16 and 20 kV\text{rms}/cm and exposed to short periods of heavy artificial rain. Extensive diagnostics were employed:

- waveform and value of applied voltage
- acoustical noise with A weighting
- 2f acoustical noise (100 Hz third octave)
- partial discharge pattern vs. AC waveform
- mean partial discharge current (20 s averaging)
- visual observation (and digital camera recording) of discharges on the conductor by means of UV image converter
- time-resolved recording of UV emission by photomultiplier coupled to partial discharge detecting system 4)
- photography of conductor surface and water drops by digital still camera
- 1000 fps framing camera to record deformation of water droplets on the conductor with respect to instant on the AC waveform

**Observations**  During heavy rain (200 mm/h for 3 minutes), acoustical emissions are about the same with all conductor surface conditions. However, there are significant differences during the subsequent drying phase (observed for 20 minutes):

With *hydrophobic* or untreated conductor surfaces, water droplets and fairly high acoustical emissions as well as partial discharge currents persist over the entire observation period (Figure 1). With a *highly hydrophilic* surface, acoustic emissions and discharge currents drop by 10...13 dB within a minute after cessation of rain, and background levels (as found with completely dry and clean conductors) are once more attained within 10 minutes; the hydrophilic coating promotes the drying process significantly.
Significant partial discharges occur predominantly during the positive half-cycle and show up as brush/tree-like UV emissions. However, the photomultiplier studies of hydrophilic conductors reveal significant UV emissions during the negative half-cycle which originate from the water droplets which are confined during the drying phase to the underside of the conductor. If these emissions are connected to droplet instabilities should be subject to a future investigation. So far it has been shown that tonal emissions can persist when there are no longer any large partial discharges. The general behaviour and shape of droplets in dependence upon voltage waveform phase have been recorded by means of a fast framing camera. The instabilities theoretically treated by Lord Rayleigh in 1882 [1] and quantitatively demonstrated by Abbas and Latham [2] are clearly observed. The electric field $E$ periodically elongates the apex of the droplets and may lead to ejection of a fine water jet which quickly contracts to a small sphere carrying electrical charge. Due to inertia the deformation reaches its maximum values well after the extrema of the applied voltage; as the deformation is related to $E^2$, there are two maxima in each cycle - independent of voltage polarity - resulting in the $2f = 100\text{Hz}$ tonal emission.
Future work has to concentrate on influence of numerous parameters on tonal noise emission, including geometries, meteorological and surface conditions as well as methods for weather resistant surface treatment for existing and for new lines.

References


5.3 Presentations

Invited presentations

K. Fröhlich (invited contribution)  
"Controlled switching: Economic aspects"  
Equipamentos de Manobra em Sistemas de Potência : Novas Tendências e Tópicos Especiais, Colóquio Técnico, FURNAS, Rio de Janeiro, Brasil  
24 April 2001

W.S. Zaengl (keynote speech)  
"Dielectric spectroscopy in time and frequency domain for hv power equipment (transformers, cables etc.)"  
12th International Symposium on High Voltage Engineering (ISH 2001), Bangalore, India  
23 August 2001

Other presentations

H. Brechna  
"HTSL und HISL Supraleiter - Stand der Forschung"  
("High temperature and high current superconductors - state of the art")  
in "Supraleitung - Eine Komponente zukünftiger Energieversorgung?"  
in "Superconductivity - an element of future energy provision?"
Fachtagung der Gesellschaft für Schwerionenforschung (GSI), Darmstadt  
13 February 2001

W. Hribernik  
"Mathematical power transformer model for determination of the prospective transient recovery voltage"  
IASTED International Conference: Modelling, identification, and control, Innsbruck, Austria  
19 February 2001

U. Krüsi  
"Model based determination of circuit breaker characteristic for controlled switching"  
IASTED International Conference: Modelling, identification, and control, Innsbruck, Austria  
21 February 2001

M. Chapman  
"Robust state estimation as a reliable starting point for power system analysis"  
SEE Conference RAMS, reliability - availability - maintainability - safety, Paris, France  
7 June 2001
R. Vogelsang (poster)
"Temperature effect on dc breakdown of polyethylene cables"
12th International Symposium on High Voltage Engineering (ISH 2001), Bangalore, India
21 August 2001

T. Farr (poster)
"A new electrode configuration for pd measurement on the insulation of stator bars avoiding unwanted outer partial discharges"
12th International Symposium on High Voltage Engineering (ISH 2001), Bangalore, India
23 August 2001

H.-P. Burgener (poster)
"Probability of partial discharge inception in small voids"
Conference on Electrical Insulation and Dielectric Phenomena (CEIDP 2001), Kitchener, Canada
16 October 2001

R. Vogelsang (poster)
"A new deterministic model for tree growth in polymers with barriers"
Conference on Electrical Insulation and Dielectric Phenomena (CEIDP 2001), Kitchener, Canada
17 October 2001

W. S. Zaengl
"On-site applications of advanced diagnosis methods for quality assessment of insulation of power transformers"
Conference on Electrical Insulation and Dielectric Phenomena (CEIDP 2001), Kitchener, Canada
17 October 2001

T. Farr
"Electrical treeing als Schadensmechanismus in Maschinenisolationen"
(“Electrical treeing as a damage mechanism in machine insulation”)
FKH-/VSE-Fachtagung 2001 "Life-Time-Management von elektrischen Maschinen”,
(“Lifetime management of electrical machines”)
ETH Zürich
17. October 2001

U. Krüsi
"Controlled transformer energization considering residual flux - implementation and experimental results"
19 November 2001
5. ACTIVITIES OF THE HIGH VOLTAGE LABORATORY

W. Hribernik
"A C++ signal processing class library for power system transients"
IASTED International Conference on Power and Energy Systems 2001, Tampa, Florida, USA
21 November 2001

W. Holaus
"Design of elementary switches for high power with minimal moving mass"
IASTED International Conference on Power and Energy Systems 2001, Tampa, Florida, USA
22 November 2001

5.4 Participation in conferences and a selection of int. relations

K. Fröhlich
CIGRE Meeting WG 13.07 (Controlled Switching), Berlin, Germany (Convenor)
3/4 April 2001

Equipamentos de Manobra em Sistemas de Potência: Novas Tendências e Tópicos Especiais, Colóquio Técnico, FURNAS, Rio de Janeiro, Brasil (invited contribution)
24 and 25 April 2001
CIGRE Meeting SC 13, Arnhem, Netherlands (as chairman of WG 13.07)
20 - 23 June 2001

CIGRE Meeting WG 13.07 (Controlled Switching), Portland, USA
6/7 September 2001

K. Fröhlich, H. Brechna, Th. Farr, R. Hug, St. Neuhold, D. Politano
(“Lifetime management of electrical machines”)
ETH Zürich
17 October 2001

K. Fröhlich (chairman), W. Hribernik, R. Hug, P. Jankowetz, U. Krüsi, D. Politano
CIGRE National Committee in collaboration with the ETG: “Perspectives for the future - new trends and benefits for the grid utilities”
Universität Zürich-Irchel
8 November 2001
5.4. PARTICIPATION IN CONFERENCES AND A SELECTION OF INT. RELATIONS

ETG Informationstagung "Neue dezentrale Energieerzeugung und deren Einbindung in bestehende Netze" (see 2.5), ETH Zürich,
("Novel decentralized energy generation and its tie-up with existing grids")
ETH Zürich
22 November 2001

H. Brechna
Supraleitung - Eine Komponente zukünftiger Energieversorgung?
("Superconductivity - an element of future energy provision?")
Fachtagung der Gesellschaft für Schwerionenforschung (GSI), Darmstadt
13 and 14 February 2001

T.H. Teich
Workshop on “Utilization of photocatalytic coatings for clean surfaces”
Institut für Neue Materialien, Saarbrücken
15 - 17 February 2001

W. Hribernik, U. Krüsi
IASTED (The International Association of Science and Technology for Development)
Conference: "Modelling, identification, and control"
Innsbruck, Austria
19 - 22 February 2001

H. Brechna, D. Politano
ETG-Informationstagung, "Kabelverbindungen im Übergang zwischen zwei Jahrhunderten", ("Power cable links at the turn of the century")
Ecole d’Ingénieurs, Fribourg
21 March 2001

D. Politano, U. Krüsi (guests)
CIGRE Meeting WG 13.07 (Controlled Switching), Berlin, Germany
3/4 April 2001

U. Krüsi
Project meeting (Architecture of artificial intelligence for circuit breakers) with Technical University, Athen
9 April 2001

M. Chapman
SEE Conference RAMS, Reliability - availability - maintainability - safety, Paris, France
7 June 2001
5.5 Publications

Refereed publications

John H. Brunke, Klaus J. Fröhlich
”Elimination of transformer inrush currents by controlled switching - Part I: Theoretical considerations”

John H. Brunke, Klaus J. Fröhlich
”Elimination of transformer inrush currents by controlled switching - Part II: Application and performance considerations”

D. Politano, M. Sjöström, G. Schnyder and J. Rhyner
”Technical and economical assessment of HTS cables”

M. Sjöström and D. Politano
”Technical and economical impacts on a power system by introducing an HTS FCL”
M. Stanek, M. Morari, K. Fröhlich
"Model-aided diagnosis: An inexpensive combination of model-based and case-based condition assessment"

Conference contributions and varia

J.J. Alff, V. Der Houhanessian, W.S. Zaengl and A.J. Kachler
"A novel, compact instrument for the evaluation of relaxation currents conceived for on-site diagnosis of electric power apparatus"
Conference Record of the 2000 IEEE International Symposium on Electrical Insulation (ISEI), Anaheim, CA, USA, April 2-5, 2000, Publication 00CH37075, IEEE, Piscataway NJ, pp. 161-167

"Reduktionsmassnahmen für Koronaschallemisionen an Hochspannungsleitungen"
("Measures to reduce corona noise emissions from overhead high voltage lines")

H. Brechna
"HTSL und HISL Supraleiter - Stand der Forschung"
("High temperature and high current superconductors - state of the art")
Tagungsband der Fachtagung "Supraleitung - Eine Komponente zukünftiger Energieversorgung?", (Proceedings of the conference "Superconductivity - an element of future energy provision?")
Gesellschaft für Schwerionenforschung (GSI), Darmstadt, February 2001, No. 4, pp. 1-16

H.-P. Burgener and K. Fröhlich
"Probability of partial discharge inception in small voids"

M. Chapman, L. Mili, R. Cherkaoui, C. Tinguely
"Robust state estimation as a reliable starting point for power system analysis"

T. Farr and K. Fröhlich
"A new electrode configuration for PD measurement on the insulation of stator bars avoiding unwanted outer partial discharges"
Transactions on 12th International Symposium on High Voltage Engineering (ISH - 2001), Bangalore, India, Volume 4, Topic 6, pp. 999-1006
T. Farr, R. Vogelsang and K. Fröhlich
“A new deterministic model for tree growth in polymers with barriers”

Th. Farr, R. Vogelsang
“Electrical treeing als Schadensmechanismus in Maschinenisolationen” (“Electrical treeing as a damage mechanism in machine insulation”)
Zürich, VSE-Druckschrift 5.50 d, pp. 30-39

M. Hässig, R. Bräunlich, R. Gysi, J.-J. Alff, V. Der Houhanessian, W.S. Zaengl
“On-site applications of advanced diagnosis methods for quality assessment of insulation of power transformers”

W. Holaus
“Design of elementary switches for high power with minimal moving mass”
Proceedings of the IASTED (The International Association of Science and Technology for Development) Conference on Power and Energy Systems 2001, Tampa, Florida, USA, pp. 18-23

W. Hribernik, S. Klampfl
“A C++ signal processing class library for power system transients”

W. Hribernik, M. Steurer
“Mathematical power transformer model for determination of the prospective transient recovery voltage”
Proceedings of the IASTED (The International Association of Science and Technology for Development) Conference: Modelling, identification, and control, Innsbruck, Austria, February 2001, paper no. 324-132, pp.148-153

U. Krüsi, K. Fröhlich
“Model based determination of circuit breaker characteristic for controlled switching”
Proceedings of the IASTED (The International Association of Science and Technology for Development) Conference: Modelling, identification, and control, Innsbruck, Austria, February 2001, paper no. 324-131, pp. 931-936
5.5. PUBLICATIONS

U. Krüsi, K. Fröhlich and J.H. Brunke
"Controlled transformer energization considering residual flux - implementation and experimental results"

U. Riechert, R. Vogelsang, J. Kindersberger
"Temperature effect on dc breakdown of polyethylene cables"

W.S. Zaengl
"Dielectric spectroscopy in time and frequency domain for HV power equipment (transformers, cables etc.)"
Transactions on 12th International Symposium on High Voltage Engineering (ISH - 2001), August 2001, Bangalore, India, Keynote Speeches, Session 9, pp. 76-85

Accepted Contributions

K. Fröhlich
"Intelligenz von Hochspannungs-Leistungsschaltern - Mode oder Erfordernis? Intelligence of high voltage circuit breakers - fashion or necessity?"
accepted for publication by e&i Elektrotechnik und Informationstechnik, ÖVE-Verbandszeitschrift, Vol. 119, No. 1, (Jan/Feb 2002), pp. 7

W. Holaus, K. Fröhlich
"Ultra-fast switches - A new element for medium voltage current limiting switchgear"
accepted for publication by IEEE PES 2002, Winter Meeting, January 2002, New York, USA

M. Steurer, K. Fröhlich
"The impact of inrush currents on the mechanical stress of high voltage power transformer coils"
accepted for publication by IEEE Transactions on Power Delivery, PE-033PRD(07-2001)

M. Steurer, K. Fröhlich, W. Holaus, K. Kaltenegger
"A novel hybrid current limiting circuit breaker for medium voltage: Principle and test results"
accepted for publication by 2000 to IEEE-TPWRS
5. ACTIVITIES OF THE HIGH VOLTAGE LABORATORY

T.H. Teich, H.J. Weber
"Origin and abatement of tonal emission from high voltage transmission lines"
accepted for publication by e&i Elektrotechnik und Informationstechnik,
ÖVE-Verbandszeitschrift, Vol. 119, No. 1, (Jan/Feb 2002), pp. 6

B. Breitenbauch, A. Küchler, W.S. Zaengl
"Zustandsbewertung von Transformator-Isolationen durch dielektrische Diagnose"
("Assessment of transformer insulation by means of dielectric diagnosis")
accepted for publication in proceedings of ETG Fachtagung: Diagnostik elektrischer
Betriebsmittel, Berlin, February 2002

Book

Patents granted
K. Fröhlich, W. Holaus, K. Kaltenegger, M. Steurer
Schnelle mechanische Schaltstelle (Fast-acting mechanical switch)

K. Fröhlich, W. Holaus, K. Kaltenegger, M. Steurer
Schneller strombegrenzender Schalter (Fast current-limiting switch)
European Patent - EP 1 098 332 A2, 9.5.2001

Award
Mrs. Elida Muminovic was awarded the best diploma report in the field of electrical engineering by the IM-Maggia Company SA, Ascona, Switzerland, 15.6.2001
6. Services

Throughout the year 2002 the High Voltage Laboratory provided once more various services for different Swiss companies and institutions.

**Accredited calibration laboratory (SCS 081)**
The primary tasks this year were the calibration of complete high voltage measuring systems under operating conditions, according to the recommendations of IEC 60060-2 (1994), and performance tests on calibrators for the calibration of partial discharge measuring systems, according to the recommendations of IEC 60270 (2000).
All calibrations were performed in the laboratories of the ETH Zürich.

**Accredited testing laboratory (STS 181)**
Our testing laboratory for tests of electrical properties of components of electrical energy supply performed a wide variety of tests according to international standards and also following laboratory-developed test procedures.
The extensive investigations on high voltage vacuum insulation systems, as reported last year, were terminated on schedule.