# Research and Education Activities in Electric Power Systems at the University of Liège

Louis Wehenkel, Damien Ernst*, Patricia Rousseaux, Thierry Van Cutsem*, Research unit in Systems and Modeling, Department of Electrical Engineering and Computer Science (Institut Montefiore), Sart-Tilman B28, B4000 Liège, Belgium
** Fonds de la Recherche Scientifique (FNRS)*


## Summary

*This paper presents research and education activities of the power systems group of the Department of Electrical Engineering and Computer Science of the University of Liège. These activities cover power systems stability, security, reliability, and markets, within the contexts of expansion planning, operation planning and real-time operation and automatic control. The paper also reviews the international collaborations of the team.*

## Résumé

*Cet article présente les activités de recherche et d'enseignement en systèmes d'énergie électrique au département d'Electricité, Electronique et Informatique de l'Université de Liège. Ces activités couvrent stabilité, sécurité, fiabilité, et les marchés de l'énergie, dans le cadre du développement des réseaux, de la gestion prévisionnelle, de la conduite en temps-réel, et du contrôle automatique. L'article décrit également les collaborations internationales de l'équipe.*

## Samenvatting

*Dit artikel presenteert de onderzoek- en onderwijsactiviteiten van het onderzoeksteam in elektrische energiesystemen van de Elektriciteit-, Elektroniek- en Informaticaafdeling van de Universiteit Luik. Deze activiteiten hebben betrekking op de stabiliteit, veiligheid, betrouwbaarheid en de energiemarkten. Ze vinden plaats in het kader van de ontwikkeling, het voorbeheer, het besturen in real time en de automatische controle van de energiesystemen. Dit artikel beschrijft eveneens de internationale medewerkingen van het team.*


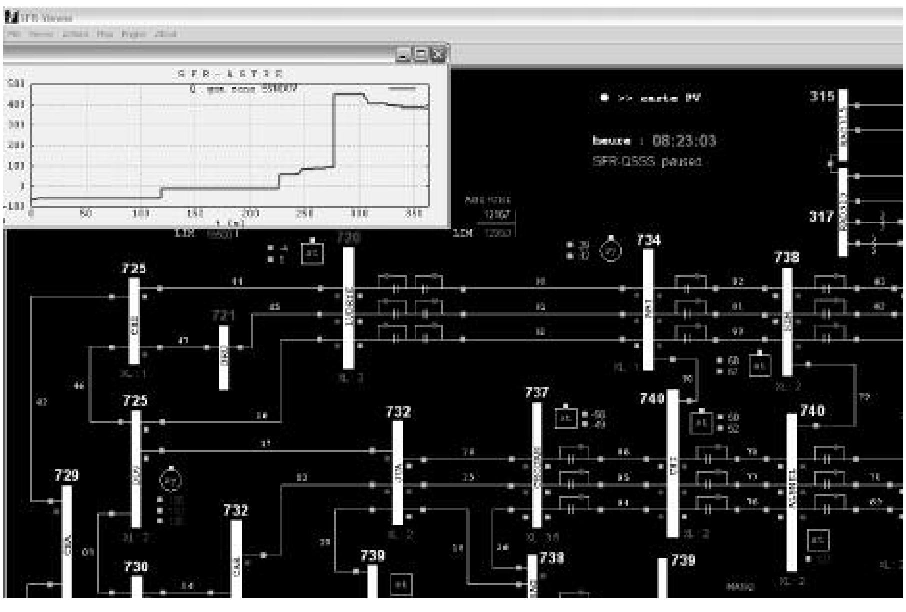


Fig. 1: Quasi steady-state simulation has been used as computational engine of a simulator for training system operators to control transmission voltages

## Introduction

Research in Power Systems at the University of Liège (ULg) is carried out by the research unit in Systems and Modeling of the Dept. of Electrical Engineering and Computer Science (Montefiore Institute). The whole unit is run by five full-time professors, three permanent FNRS researchers, and one adjunct professor. The research unit ensures a good balance between a strong track of fundamental research, in the fields of optimization, control, machine learning and statistics, with an equally strong track of applied research in the fields of electric power and energy systems as well as in other complex systems such as bioinformatics, systems biology, and industrial process monitoring and control in general.

This paper outlines the past, present and future research topics within the specific context of electric power systems. It also stresses the international involvement of the power system group in various collaborations and organizations.

Research into power systems at the University of Liège has been initiated in the late sixties, at the time where systems theory and computational approaches emerged as the main elements of progress in the field. The early subjects of investigation of the group were devoted to transient stability analysis and real-time state estimation.

During the late eighties and nineties, the group progressively increased in size and hence broadened the scope of its research activities to various aspects of:

– power system dynamics, control and stability;
– security assessment and enhancement;
– probabilistic and statistical approaches;
– automatic learning based approaches;
– optimization in the context of planning and operation;
– real-time operation of power systems.

Simply stated the research efforts are directed towards the development of methods and algorithms to deal with the above aspects, from a large-scale system perspective. In parallel, through long-term industrial collaborations, the group has had opportunities to test his approaches on real-life, large-scale applications.

## Research topics in electric power systems at ULg

Power systems are complex owing to the large size of their models, the multiple time scales involved and the presence of various interacting phenomena and components. A natural engineering approach consists of reducing the model complexity according to phenomena and/or time scales, and devising specific analysis methods dealing with these more tractable problems.

### Transient stability analysis and control

The purpose of dedicated stability analysis methods is at least threefold:

– obtain efficient analysis tools, much faster and complementary to full time-domain simulation. These tools are typically used to assess the impact of incidents (faults, equipment outages, etc.), referred to as contingencies;
– use them in Dynamic Security Assessment (DSA) in order to evaluate security with respect to incidents and identify the best preventive control measures to reinforce security of operation; computational efficiency is a key-point in real-time DSA performed in control centres;
– possibly embed them into controllers performing automatic emergency actions.
This applies to both transient stability and voltage stability.

Transient (angle) instability relates to the loss of synchronism of generators following short-circuits and the action of fault-clearing protections. These phenomena are characterized by their high speed (a few hundred milliseconds), their strongly non-linear nature, and their possible system-wide impact.

#### *Development of the SIME method*

Already in the late sixties, the group of Liège has been pioneering in the development of so-called direct methods for transient stability assessment based on the second Lyapunov method. In the eighties this research track led to development of the so-called Extended Equal Area Criterion, for multi-machine power systems, and in the nineties to the development of the Single Machine Equivalent (SIME) method. This hybrid method combines time-domain simulation of the full-scale, multi-machine power system model with the identification of the critical subsystem of unstable generators, the construction of a single-machine infinite-bus equivalent description of the mode of instability, and the derivation of stability margins and preventive control information from this equivalent.

The SIME method imposes no constraints on the dynamic model used for studying transient instability mechanisms. It has been coupled with various time-domain simulation software packages and extensively tested on numerous large-scale power system models (EDF, Hydro-Québec, WECC and other EPRI test systems, Brazilian, Italian and Greek systems, etc.). Besides accelerating the computations of stability margins with respect to pure time domain simulation, its main feature is its ability to identify the physical mechanism of loss of synchronism and hence to provide guidelines for preventive and emergency control.

#### *Application to Transient Security Analysis (TSA)*

The SIME method has led to the development of a software package for fast TSA and for the computation of preventive controls in the form of generation rescheduling. TSA is carried out by exploiting sensitivities of energy margins with respect to the fault clearing time or with respect to power flows in some interfaces, in order to accelerate the iterative search of critical clearing times or of power flow limits. Generation rescheduling is computed by exploiting the sensitivities of energy margins with respect to the generations of the so-called critical machines.

#### *Emergency control of transient instability*

The SIME method was adapted so as to exploit real-time measurements of rotor angles, in order to detect in closed-loop mode the risk of loss of synchronism and determine stabilizing control actions (such as generation tripping, dynamic braking or fast valving). In order to estimate in real-time rotor angles from synchronized phasor measurements, a neural network based approach was also developed.

**Voltage stability analysis and control**

In many power systems throughout the world, voltage instability has been identified as a potential source of blackouts. It results from the inability of the combined transmission and generation system to deliver the power requested by loads. It may manifest itself in the short term (typically a few seconds, caused by induction motors stalling after a short-circuit) or in the long term (typically ten or so minutes, caused by load power restoration through distribution load tap changers, combined with reactive power limitations of generators).

***Development of simulation tools and models***

Long-term simulation of voltage dynamics and control is computationally demanding. Fortunately, the problem lends itself to simplification using time-scale decomposition, replacing the short-term dynamics by their equilibrium conditions and focusing on the long-term phenomena. This idea is at the heart of the Quasi Steady-State (QSS) time-domain simulation, implemented in the ASTRE software, and used by several partner Transmission System Operators (TSOs). As a simplified simulation engine, it has been used in a training simulator (see Fig. 1) as well as for building large data bases of Monte-Carlo simulations. The tool has been also progressively extended:

– to incorporate instability diagnosis, provided by sensitivity analysis;
– to couple it with detailed time simulation to deal with large disturbances impacting the system response in the short-term;
– to reproduce frequency dynamics (relevant to isolated systems or systems undergoing a split);
– to identify plausible cascading event scenarios (involving hidden failures of protections).

The aggregate loads seen from a transmission system may significantly impact voltage stability but their model is often oversimplified. In this respect, efforts have been made to developing improved, while practical equivalents of sub-transmission/distribution systems.

***Application to Voltage Security Analysis (VSA)***

VSA – one aspect of DSA – is the area where the QSS approach has found its most significant applications. For VSA purposes, it is relevant to compute secure operation margins such as the maximum load power increase that the system can accept before one of the specified contingencies becomes harmful for the system. This involves repeating QSS time simulation of the disturbances for various levels of pre-disturbance load power. To reduce the computational burden in large-scale applications, contingency filtering schemes have been successfully devised.

When the system is found insecure with respect to credible disturbances, its operating conditions have to be modified accordingly. The usual tool to optimally change an operating point is the Optimal Power Flow (OPF). Procedures have been set up to derive from the VSA analysis inequality constraints readily incorporated in an OPF.

***Emergency control of voltage instability***

The usual practice is to deal preventively with credible disturbances (e.g. the loss of single equipment) and face more severe disturbances (e.g. the outage of several equipments) through System Protection Schemes (SPS). In the context of voltage instability, extensive investigations have been performed in the design of undervoltage load shedding by combinatorial optimization as well as its implementation through distributed controllers. Emergency control schemes to preserve transmission voltages against load tap changer effects also received our attention.

SPS against voltage instability rely to a large extent on the observation of sagged voltages, i.e. actions are taken when the instability effects are already pronounced. As an alternative, investigations have been carried out on the early detection of an impending instability from the observation of the (properly filtered) distribution voltages. Presently, a system-wide approach is being investigated using information gathered from network voltages provided by Phasor Measurement Units (PMUs), a fast evolving technology that opens exciting perspectives for the real-time control of future power systems.

Let us also mention recent or on-going works using techniques inspired of Model Predictive Control to alleviate line thermal overloads as well as control transmission voltages.

**Operation planning**

Operation planning studies in the context of security control are based on screening a set of scenarios (combining possible operating conditions, disturbances, and modeling hypotheses about the behavior of the power system and its neighboring areas) by time-domain simulation, and then extracting from these simulations decision rules that may be used by operators or automatic devices in real-time. Examples of applications where such studies have to be carried out on a regular basis concern the determination of preventive security limits, the definition of congestion management rules, the preparation of emergency control policies, and the design of system protection schemes. Depending on the particular context, these studies are carried out from a few days to a few months ahead in time.

Since the mid-eighties, and during the nineties, the group has been active in developing a general methodology for operation planning studies based on the combination of three sets of techniques:

– experiment design methods, to choose probability distributions defining a range of scenarios that should be sampled by Monte-Carlo simulations in the context of a particular study;
– parallelization of numerical simulation engines and data-base approaches, to efficiently generate and manage very large datasets of time-domain simulation results;
– Data-mining techniques, including filtering, visualization, and supervised and unsupervised automatic learning, to extract useful knowledge from the simulation results.

This approach aims at freeing engineers from tedious ‘manual’ trial and error cycles typical of operation planning studies, while allowing them to use more efficiently their computational resources and to take into account in a better way the uncertainties present in their problem.

Examples of specific problems to which this methodology has been applied successfully by several TSOs in the last twenty years are the following:

– identification of key parameters influencing transient and voltage stability;
– construction of decision rules to assess the security in preventive mode and to manage congestions:
– design and tuning of automatic emergency control devices for load and generation shedding;
– analysis of blackout modes of a large power system and identification of crisis management policies.

In the last ten years, further research has been carried out in the group in order to extend this approach to multi-stage decision and closed-loop control problems. This new direction of research is based on the reinforcement learning paradigm which allows one to combine in a principled way experimentation and automatic learning based exploitation of systems dynamics. Generation shedding, control of variable series compensation, and dynamic braking for the prevention of transient instability and damping of transient power oscillations are examples of applications studied in this context.

These works have led to the development of a strong research track in automatic learning within the group, especially in the context of supervised and reinforcement learning. Moreover, a spin-off company (PEPITe SA) has been launched in 2002, which delivers data-mining based solutions to the industry.

**Transmission system expansion planning and reliability analysis**

System planning studies aim at determining, a few years ahead of time, whether and which new lines, substations, or other auxiliary devices, should be constructed. Given the long-term horizon of such studies, they are subject to a large number of uncertainties, especially since the unbundling of generation and transmission systems. These studies can be decomposed into three major steps:

– reliability analysis of the existing system projected into various possible future conditions;
– identification of risk scenarios and of relevant strategies of system expansion;
– economic analysis of the system expansion alternatives and choice of a strategy to implement.

Within the context of system planning and reliability analysis our group has been or is active in the following areas:

– variance reduction in Monte-Carlo simulations, aiming at the efficient assessment of the expected cost of security constrained power system operation over a sample of typical years defined by water supply scenarios, temperature scenarios and scenarios of planned or unplanned equipment outages;
– data-mining approach for transmission system expansion planning, aiming at the identification of the main risk scenarios and structural weaknesses of the transmission system over a seven years period;
– rare event simulation by cross-entropy based importance sampling, aiming at the identification of a priori rare combinations of possible events which could lead to highly severe blackout scenarios.

**Generation planning**

Generation planning is of primary importance for power producers, since it directly impacts their earnings. There is a multitude of issues that need to be considered for computing good generation plans. Among them, one can mention the difficulties related to the stochastic nature of this optimization problem (for instance, water resources and load cannot be predicted with 100% accuracy, generation units may become unavailable, etc.), the sheering size of the optimization problem (commercial optimization software's do not necessarily scale well to problems with millions of variables!), not to mention many technical aspects (for instance, the need to take into account maintenance periods of units).

The work at ULg focuses on exploiting stochastic models for the temperature and water inflow scenarios through the use of quasi-Monte-Carlo methods, as well as on taking benefit from experiences in Machine Learning, so as to design computationally efficient multi-stage stochastic programming approaches to compute optimal decision strategies, from day ahead to yearly generation planning of mixed thermal and hydro systems.

**Operation of large interconnections in the multi-TSO environment**

Large interconnected power systems are usually decomposed into areas based on various geographical, organizational or technical criteria. In Europe, for instance, each country has one or several TSOs responsible for the operation of the transmission system. The opening of the electricity market pushes towards greater power exchanges between the various areas. As a counterpart, operation becomes more complex in particular because the decisions taken by one TSO impact on the sub-systems controlled by other TSOs. TSOs are therefore under increasing pressure for adopting new practices for ensuring a safe operation of the interconnection. In this respect, there is a consensus that improved coordination is required between TSOs, while preserving the autonomy of each of them.

Early research work had been devoted to multi-area (hierarchical) state estimation, a topic which is regaining importance, in Europe and North America for instance, after major blackouts pointed out the need for each TSO to have a real-time model of the system that extends well beyond the borders of the network he is in charge of.

More recently, the group has been carrying out several investigations in this framework:

– in the context of security analysis, a collaborative framework has been proposed in order to carry out multi-area security assessment through proper information exchange of contingency analysis results between control centers; this involves in particular the notification of the impact that contingencies occurring in one TSO sub-system have on other TSO sub-systems;
– for the situations where the control of the system by each TSO can be for-

mulated as an optimization problem, efficiency and fairness (with respect to the various partners) of distributed control schemes have been investigated for voltage optimization as well as for relieving congestions on the interconnection tie-lines;
– presently, work is being performed on multi-objective (possibly conflicting) optimization; in this context, it is assumed that each TSO optimizes its objective under a common set of constraints describing the interconnected grid operation; coordination schemes are investigated in the cases where the independent optimizations result in operating constraints violations; after some investigations devoted to the control of phase shifting transformers, the approach is presently applied to market clearing and congestion management.

**Modeling the behaviour of market participants**

Power system engineers have spent considerable efforts in developing simulation models for better understanding and controlling their system. Nowadays, the behaviour of market participants (generation companies, customers, traders, etc.) plays an increasingly important role in the dynamics of the system. This has fostered the need for modeling not only the physical components but also the behaviour of the various actors. Our research has approached this problem from a Machine Learning perspective, an approach inherited from more fundamental research carried out in this area within the research unit. In particular, reinforcement learning techniques have been used to develop software able to mimic the way market participants learn from their interaction with the system to optimize their behaviour. These simulation tools have revealed very useful to study the influence of congestions on electricity spot prices or to optimize investments at the transmission level.

## Projects and collaborations

**Institutional research projects**

Over the recent years, the ULg group has been involved in several projects sponsored by the European Union:

– OMASES (Open Market Access and SEcurity aSsessment), in which the group was in charge of TSA and VSA functions of the platform;
– EXAMINE which focused on the use of GPS-based synchronized measurements for emergency control of power systems and on the development of a distributed state-estimator and static simulation software for monitoring and preventive security assessment of interconnected power systems;
– NAVELEC (funded by the Galileo Joint Undertaking) which focused on the use of synchronized measurements in electric power transmission grids;
– PEGASE: recently launched and described in another paper of this issue.

The group has also worked on several Belgian projects funded at regional or federal level, among which we quote:

– study of the transposition of the EC directive on electric energy systems liberalization (for the Ministry of Energy of the Belgian federal government);
– development of a combinatorial optimization tool to generate distribution system restoration plans ("First-Université" project, funded by Walloon region, in partnership with Gillam-FEI);
– development of a mixed discrete/continuous optimization software platform and its application to optimal power flow problems in electric power systems and pump-scheduling in water supply systems (PIGAL project, funded by the Walloon Region).

**Collaborations with other universities**

The group maintains active collaborations with:

– National Technical University of Athens, Greece (C. Vournas): on various aspects of power system dynamics and stability, in particular within the context of the OMASES project;
– Carnegie Mellon University, USA (M. Ilic): on the arbitration between short-term and long-term market regulation policies to ensure security of supply;
– Supelec, France: on multi-TSO control, experimental economics as well as FACTS devices;
– University of Genoa, Italy (S. Massucco): on transient stability assessment and control;
– University of Calgary, Canada (W. Rosehart): on model predictive control of transmission voltages.

**Collaborations with industry**

The group has been involved in fruitful collaborations, some of them on a long-term basis with:

– (formerly EDF, now) RTE, Hydro-Québec (TransEnergie division and IREQ);
– ELECTRABEL and (formerly CPTE, now) ELIA;
– HTSO (Hellenic TSO) first within the context of the OMASES project (for on-site test of the platform), then together with NTUA for the follow-up of the VSA function at the national control center;
– AREVA: on Energy Management Systems;
– EDF: in the nineties on security assessment, blackout prevention, system planning; since 2005, on generation planning under uncertainty.

The expertise of the group has been also used in studies or software development with:

– CREG (the Belgian regulator): for the determination of secure operation limits of the Belgian system;
– Gillam-FEI in the area of power system analysis software for Distribution Management Systems;
– Hydro-Québec for the development of a QSS-based simulator to train operators to control transmission voltages (see Fig. 1);
– BC Hydro/PowerTech Labs, Canada: as a consultant for a Canadian research project.

## Other scientific and education activities

In their fields of expertise, the members of the group are actively involved in the scientific and technical animation within national and international, scientific and technical organizations, as reflected by the following statistics and examples:

– the group as authored or co-authored four books (edited by Springer – formerly Kluwer – and J. Wiley) and contributed with chapters in four other books;
– over the last 5 academic years, the

group has published around 90 articles in (mostly international) journals and conference proceedings. For a complete list, please refer to the regularly updated Web page: http://www.montefiore.ulg.ac.be/services/stochastic/elec/doku.php?id=publications. In addition, 5 PhD theses have been defended in the power system area over the same period of time;
– members of the group have taken an active part in several international working groups and task forces, for instance:
  – CIGRE Task Force 38.02.23 on Coordinated Voltage Control of Transmission Networks
  – joint IEEE/CIGRE task force on stability terms and definitions
  – CIGRE working group C4.601 on Power System Security Assessment
– two members of the team are acting as editors of the IEEE Transactions on Power Systems and the International Journal of Electrical Power and Energy systems;
– ULg organized the 15th Power System Computation Conference (PSCC) held in Liège in August 2005 (about 400 participants);
– the group is active in the scientific and steering committees of several international conferences: Power System Computation Conference, IEEE Power Tech, Intelligent Systems Applications in Power Systems, Modern Electric Power Systems, Intern. Conf. on Electrical Engineering, International workshop on Electric Power Control Centres, etc.
– the team is involved in review activities for the above listed journals and conferences, as well as for IET Proceedings on Generation, Transmission and Distribution, IEEE Power & Energy Society letters, IEEE Power and Energy Society General Meetings, Electric Power System Research, European Transactions on Electric Power, etc.
– numerous evaluations of grant applications, research projects, academic applications, PhD theses, and scientific awards (in Belgium, Australia, Canada, France, Italy, Singapore, Spain, Sweeden, Switzerland, UK, European Union, USA, etc.).

In connection to its research in the field of electrical power and energy systems, the group is involved in several forms of teaching in this field.

Following the Bologna reform and a recent internal restructuring, the electric power system track of courses at the University of Liège includes:

– fundamental (undergraduate level) courses: Analysis and operation of electric energy systems, Transmission and distribution of electrical energy, Energy markets;
– more advanced (also attended by PhD students) courses: Electric power systems dynamics, Control and optimization of electric energy networks, Electromechanical behaviour of networks.

The first group includes mandatory courses taught in the 1st and 2nd year of the Master in Electromechanical Engineering (oriented towards various engineering aspects of Energy) while the second group includes elective courses offered to the students of 2nd master. All courses are also offered as elective to the students of the Master in Electrical Engineering.

Final projects are carried out in the 2nd master year, often in collaboration with industry, and possibly complemented by a stay with the industrial partner. In this context, students have the opportunity to contribute to the various research themes and industrial collaborations outlined in this paper.

Finally, the group is involved in dissemination activities such as:
– the intensive short courses organized by the EES-UETP association (see description at www.eesuetp.unibo.it);
– lectures given at other universities: University of Manchester, National Technical University of Athens (within the Erasmus exchange framework), Supelec, Unversity of Genoa;
– invited seminars offered when visiting other universities or research centres;
– lectures given in study days (e.g. organized by SRBE and SEE);
– tutorials or invited lectures in the context of conferences (e.g. PSCC, IEEE PES meetings).