Report from Dagstuhl Seminar 14441

# Modeling, Verification, and Control of Complex Systems for Energy Networks

**Edited by**

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## Abstract

Power and energy networks are systems of great societal and economic relevance and impact, particularly given the recent growing emphasis on environmental issues and on sustainable substitutes (renewables) to traditional energy sources (coal, oil, nuclear). Power networks also represent systems of considerable engineering interest.

The aim of this Dagstuhl seminar has been to survey existing and explore novel formal frameworks for modeling, analysis and control of complex, large scale cyber-physical systems, with emphasis on applications in power networks.

Stochastic hybrid systems (SHS) stand for a mathematical framework that allows capturing the complex interactions between continuous dynamics, discrete dynamics, and probabilistic uncertainty. In the context of power networks, stochastic hybrid dynamics arises naturally: (i) continuous dynamics models the evolution of voltages, frequencies, etc.; (ii) discrete dynamics models controller logic and changes in network topology (unit commitment); and (iii) probability models the uncertainty about power demand, power supply from renewables and power market price.

The seminar has covered relevant approaches to modeling and analysis of stochastic hybrid dynamics, in the context of energy networks.

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# 1 Executive Summary

*Alessandro Abate*
*Martin Střelec*

The seminar has been focused on a number of selected topics from energy networks, with an emphasis on power systems that have great societal and economical relevance and impact. These represent systems of considerable engineering interest, since:

- they can be large-scale and can involve numbers of various devices interconnected in a complex manner.
- they are heterogeneous, that is they can be naturally modelled through a combination of continuous dynamical elements (to capture the evolution of quantities such as voltages, frequencies and generation output) and discrete dynamical components (to capture changes in the network topology, controller logic, state of breakers, isolation devices, transformer taps, etc.).
- they involve substantial stochastic components. Sources of uncertainty traditionally considered in power networks include hardware faults and unforeseen events, as well as stochasticity arising from continuous processes, particularly power demand. Furthermore, the increasing availability of renewable energy sources (e. g. photovoltaic panels, wind turbines, etc.) implies that uncertainty (for example, uncertainty in weather forecasts or cloud cover) also enters at the power supply side.
- some variables are only partially observable due to absence of real-time sensing circuitry in large parts of the existing power distribution network.

Reasonable and accurate analysis of future power networks needs models that seamlessly integrate behavioural patterns like complex interaction of continuous electrical phenomena (e. g. power flows) related to connected devices, discrete events caused by switching behaviour in circuitry, commitment of supplies and loads or by decisions of market participants, and the inherently stochastic behaviour of volatile supplies, demands and market prices.

In summary, the aim of the seminar has been to survey existing and explore novel formal frameworks for modelling, analysis and control of complex, large scale systems, with emphasis on applications in power networks. The seminar has hosted researchers and practitioners working on energy network application domains, in order to import related techniques for the study of energy grids in general, their analysis and energy management, which consists in control, coordination and dispatch of multiple generation, consumption and storage devices connected to the grid. Interactions among scientists and professionals from the heterogeneous research and application fields focused on power networks has highlighted opportunities for further research concerning expressiveness of models and scalability of the methods, as well as point to related efforts in the power network community.

### General comments

The Seminar has run over the last week of October 2014 (27 to 31), has been well attended throughout the week, with about 40 participants. It has featured a fully packed program made up of presentations (at least 30), sustained discussions, and breakout sessions on three different topics. A final discussion session has concluded the proceedings of this event.

While the presence from academia has been preponderant, we have also been happy to see a number of active participants from the industry. The attendants expertise has been quite diverse. Academic participants have come with backgrounds in verification, control, and power systems. Alongside the participated and very open discussions, the seminar has additionally featured a hike and a dinner at a local restaurant.

## Program

Talks have been categorised within the following clusters: Theory and Tools from Control; Theory and Tools from Verification; Topics in Power Networks; Smart/Micro Grids and Buildings.

Beyond these clusters, we have tried to diversify the program in order to optimally engage the audience. Discussions have been fostered via an afternoon breakout session, organised on Tuesday, the social activities on Wednesday afternoon, and the final session on Friday in the late morning.

There have been three breakout sessions, focusing respectively on

- modelling issues in energy/power systems;
- simulation issues in energy/power systems;
- demand response: control and verification.

The topics elaborated during the sessions are discussed in the ensuing sections, which report the notes that have come out of the discussions.

## 2 Table of Contents

**Working Groups**

# 3 Overview of Talks

## 3.1 Aggregation and Control of Populations of Thermostatically Controlled Loads by Formal Abstractions

*Alessandro Abate (University of Oxford, GB)*

**Joint work of** Abate, Alessandro; Sadegh Esmaeil Zadeh Soudjani
**Main reference** S. E. Z. Soudjani, A. Abate, "Aggregation and Control of Populations of Thermostatically Controlled Loads by Formal Abstractions," IEEE Transactions on Control Systems Technology, to appear.

This work discusses a two-step procedure, based on the use of formal abstractions, to generate a finite-space stochastic dynamical model as an aggregation of the continuous temperature dynamics of a homogeneous population of Thermostatically Controlled Loads (TCLs). The temperature of a TCL is described by a stochastic difference equation and the TCL status (ON, OFF) by a deterministic switching mechanism. The procedure is deemed to be formal, as it allows the quantification of the error introduced by the abstraction. As such, it builds and improves on a known, earlier approximation technique used in the literature. Further, the contribution discusses the extension to the instance of heterogeneous populations of TCLs by means of two approaches. It moreover investigates the problem of global (population-level) power reference tracking and load balancing for TCLs that are explicitly dependent on a control input. The procedure is tested on a case study and benchmarked against the mentioned existing approach in the literature.

### References

1 S.E.Z. Soudjani and A. Abate, "Aggregation of Thermostatically Controlled Loads by Formal Abstractions," Proceedings of the 12th European Control Conference, pp. 4232–4237, Zürich (CH), 2013.
2 M. Kamgarpour, C. Ellen, S.E.Z. Soudjani, S. Gerwinn, J.L. Mathieu, N. Müllner, A. Abate, D.S. Callaway, M. Fränzle, and J. Lygeros, "Modeling Options for Demand Side Participation of Thermostatically Controlled Loads," IREP 2013, pp. 1–15.
3 S.E.Z. Soudjani and A. Abate, "Aggregation and Control of Populations of Thermostatically Controlled Loads by Formal Abstractions," IEEE Transactions on Control Systems Technology. 2014, In Print.

## 3.2 Spatial Temporal Logic Inference, Verification, and Synthesis

*Calin A. Belta (Boston University, US)*

**Joint work of** Kong, Zhaodan; Haghighi, Iman; Bartocci, Ezio; Aydin Gol, Ebru; Jones, Austin; Belta, Calin A.;
**Main reference** Z. Kong, A. Jones, A. Medina-Ayala, E. Aydin Gol, C. Belta, "Temporal Logic Inference for Classification and Prediction from Data," in Proc. of the 17th Int'l Conf. on Hybrid Systems: Computation and Control (HSCC'14), pp. 273–282, ACM, 2014.
**URL** http://dx.doi.org/10.1145/2562059.2562146

Networked dynamical systems are increasingly used as models for a variety of processes ranging from robotic teams to collections of genetically engineered living cells and power networks. As the complexity of these systems increases, so does the range of emergent properties that they exhibit. This presentation introduces a new logic called Spatial-Temporal Logic (SpaTeL) that is a unification of signal temporal logic (STL) and tree spatial superposition logic (TSSL). SpaTeL is capable of describing high-level spatial patterns that change over time, e. g., "Power consumption in the northwest quadrant of the city drops below 100 megawatts if the power consumption in the southwest quadrant remains above 200 megawatts for two hours." A statistical model checking procedure that evaluates the probability with which a networked system satisfies a SpaTeL formula is presented. A synthesis procedure that determines system parameters maximizing the average degree of satisfaction, a continuous measure that quantifies how strongly a system execution satisfies a given formula, is also introduced. The approach is illustrated on two systems: a biochemical reaction-diffusion system and a demand-side management system for a smart neighborhood.

## 3.3 Hybrid stochastic systems: simulation in Modelica

*Marc Bouissou (Ecole Centrale Paris, FR)*

**Joint work of** Bouissou, Marc; Elmqvist, Hilding; Otter, Martin; Benveniste, Albert
**Main reference** M. Bouissou, H. Elmqvist, M. Otter, A. Benveniste, "Efficient Monte Carlo simulation of stochastic hybrid systems", in Proc. of the 10th Int'l Modelica Conf., Linkþing Electronic Conference Proceedings, Vol. 96, pp. 715–725, Linköping University Electronic Press, 2014.
**URL** http://dx.doi.org/10.3384/ECP14096715

The purpose of this presentation is to show some of the results of the MODRIO project, relative to the practical use of hybrid, often stochastic, models of complex systems in the industry. This project is all based on Modelica models and tools. The general idea is to extend the use of the models usually built for the design of systems, to the exploitation phase of their lifecycle. This presentation is focused on the reuse of Modelica design models for performing dependability analysis. Depending on the degree of "hybridicity", several approaches can be used, going from enriching the Modelica deterministic model corresponding to nominal behavior by random features, to abstracting the model into a language dedicated to discrete systems, even Boolean abstractions like fault trees. In the presentation we explain an optimal algorithm for performing Monte Carlo simulation of a PDMP (piecewise deterministic Markov process). This algorithm was published in [1]. Then we show the needs for modeling hybrid stochastic systems in Modelica models. The main challenges (that are being addressed in the MODRIO project) are about multi-mode hybrid systems where the number of state variables changes when the system changes mode, and the introduction of stochastic transitions in continuous time state machines of Modelica. We will show the model and simulation results for a simple pedagogical example: a room heated by a heater subject to random failures and repairs.

### References

1 "Efficient Monte Carlo simulation of stochastic hybrid systems". Marc Bouissou, Hilding Elmqvist, Martin Otter, Albert Benveniste. Modelica conference 2014.

### 3.4 Dynamic coupling, nonlinear output agreement and power network control

*Claudio De Persis (University of Groningen, NL)*

**Joint work of** Buerger, Mathias; De Persis, Claudio; Trip, Sebastian
**Main reference** M. Bürger, C. De Persis, "Dynamic coupling design for nonlinear output agreement and time-varying flow control," Automatica, 51(Jan. 2015):210–222, 2015; pre-print available as arXiv:1311.7562v1 [cs.SY].
**URL** http://dx.doi.org/10.1016/j.automatica.2014.10.081
**URL** http://arxiv.org/abs/1311.7562v1
**Main reference** S. Trip, M. Bürger, C. De Persis, "An internal model approach to frequency regulation in power grids," arXiv:1403.7019v2 [cs.SY], 2014.
**URL** http://arxiv.org/abs/1403.7019v2

We discuss recent results on the problem of output agreement in networks of nonlinear dynamical systems under time-varying disturbances. The key to these results is the use of dynamic diffusive couplings and internal model controllers. For the class of incrementally passive systems, constructive sufficient conditions for output agreement are presented. The proposed approach lends itself to solve flow control problems in distribution networks. As a case study we show how recently proposed controllers for frequency regulation can be interpreted as internal model controllers and discuss how the approach can shed new light to the problem.

### 3.5 Plug-and-Play Control and Optimization in Microgrids

*Florian Dörfler (ETH Zürich, CH)*

**Main reference** F. Dörfler, J. W. Simpson-Porco, F. Bullo, "Plug-and-Play Control and Optimization in Microgrids," in Proc. of the 2014 IEEE 53rd Conf. on Decision and Control (CDC'14), to appear; pre-print available from author's webpage.
**URL** http://motion.me.ucsb.edu/pdf/2013y-dsb-conference.pdf

Microgrids are low-voltage electrical distribution networks, heterogeneously composed of distributed generation, storage, load, and managed autonomously from the larger transmission network. Modeled after the hierarchical control architecture of power transmission systems, a layering of primary, secondary, and tertiary control has become the standard operation paradigm for microgrids. Despite this superficial similarity, the control objectives in microgrids across these three layers are varied and ambitious, and they must be achieved while allowing for robust plug-and-play operation and maximal flexibility, without hierarchical decision making and time-scale separations. In this seminar, we explore control strategies for these three layers and illuminate some possibly-unexpected connections and dependencies among them. We build upon a first-principle model and different decentralized primary control strategies such as droop, quadratic droop, and virtual oscillator control. We motivate the need for additional secondary regulation and study centralized, decentralized, and distributed secondary control architectures. We find that averaging-based distributed controllers using communication among the generation units offer the best combination of flexibility and performance. We further leverage these results to study constrained AC economic dispatch in a tertiary control layer. Surprisingly, we show that the minimizers of the economic dispatch optimization problem are in one-to-one correspondence with the set of steady-states reachable by droop control. This equivalence results in simple guidelines to select the droop coefficients, which include the known criteria for power sharing. Finally, we illustrate the performance and robustness of our designs through through hardware experiments.

## 3.6 Multi-Objective Parameter Synthesis in Probabilistic Hybrid Systems

*Martin Fränzle (Universität Oldenburg, DE)*

**Joint work of** Abate, Alessandro; Fränzle, Martin; Gerwinn, Sebastian; Katoen, Joost-Pieter; Kröger, Paul

Technical systems interacting with (parts of) the real world can be modelled elegantly using probabilistic hybrid automata (PHA). Parametric probabilistic hybrid automata are dynamical systems featuring hybrid discrete-continuous state dynamics and parametric probabilistic branching, thereby extending PHA by capturing a family of PHA in a single model. Such systems have a broad range of application from controller synthesis to network protocols. In our talk, we presented a novel method to synthesize parameter instances (if such exist) of such models that satisfy a multi-objective bounded horizon specification over expected rewards. Our technique combines three distinct techniques: (1.) statistical model checking of a model instance devoid of parameters, (2.) a symbolic version of importance sampling yielding an arithmetic constraint reflecting the parameter dependence of the expected rewards, and (3.) SAT-modulo-theory (SMT) solving applied to that constraint for finding a feasible parameter instance consistent with the multi-objective design goal modulo sampling effects. Using a check-and-refine approach enhancing the constraint based on counterexamples, we are able to provide strong statistical guarantees on feasibility of the synthesized parameter instance.

## 3.7 Hybrid Systems: How Nonlinear Can We Go?

*Sicun Gao (Carnegie Mellon University – Pittsburgh, US)*

I will present the framework of delta-complete analysis for reachability problems of a very general class of nonlinear hybrid systems. We perform bounded reachability checking or invariant-based reasoning through solving delta-decision problems over the reals. The techniques take into account of robustness properties of the systems under numerical perturbations. The verification problems become much more mathematically tractable in this new framework. I will demo our open-source tool dReach, which scales well on several highly nonlinear hybrid system models that arise in biomedical and robotics applications.

## 3.8 Resilience modelling for smart neighborhoods

*Boudewijn Haverkort (University of Twente, NL)*

The use of renewable energy in houses and neighborhoods is very much governed by national legislation and has recently led to enormous changes in the energy market and poses a serious thread to the stability of the grid at peak production times. One of the approaches towards a more balanced grid is, e. g., taken by the German government by subsidizing local storage for solar power.

While the main interest of the energy operator and the government is to balance the grid and still have positive revenues, thereby ensuring grid stability, the main interest of the client is twofold: the total cost for electricity should be as low as possible and the power supply be as resilient as possible in the presence of power/grid outages. Clearly, these two objectives highly depend on the availability and capacity of local storage, and the overall strategy followed by the local controller.

We present a Hybrid Petri net model of a house that is mainly powered by solar energy with a local storage unit and subsequently analyze the impact of different storage strategies on the resilience of the power supply and the overall cost of electricity, for different production and consumption patterns.

## 3.9 Dynamics of Generic Wind Turbine Generator Models

*Ian Hiskens (University of Michigan – Ann Arbor, US)*

**Main reference** I. A. Hiskens, "Dynamics of type-3 wind turbine generator models," IEEE Transactions on Power Systems, Vol. 27(1):465–474, 2012.
**URL** http://dx.doi.org/10.1109/TPWRS.2011.2161347

The talk provides an analysis of a generic model describing the dynamic behaviour of type-3 wind turbine generators (WTGs). The behaviour of this model is governed by interactions between the continuous dynamics of state variables and discrete events associated with controls. It is shown that these interactions can be quite complex, and may lead to switching deadlock that prevents continuation of the trajectory. Switching hysteresis is proposed for eliminating deadlock situations. Various type-3 WTG models include control blocks that duplicate integrators. It is shown that this leads to non-uniqueness in the conditions governing steady- state, and may result in pre- and post-disturbance equilibria not coinciding.

## 3.10 Diagnostics and maintenance of HVAC systems

*Ondřej Holub (Honeywell Prague Laboratories, CZ)*

**Joint work of** Abate, Alessandro; Adzkiya, Dieky; Berka, Jan; Endel, Petr; Holub, Ondřej

Buildings consume more than 40% of energy in Europe. Smart building automation systems can considerably contribute to the balance in the grid at a neighborhood or district scale. In order to sustainably achieve this goal a continuous commissioning and maintenance of building automation systems is needed. Building maintenance typically includes many tasks solved by algorithms that are designed using different methodologies. Integration of the dedicated algorithms into one solution represents an ever more complex effort. A generic approach to the HVAC maintenance is presented in the talk, which solves this problem by formulating it in the framework of Stochastic Hybrid Systems.

## 3.11 Consensus + innovations based distributed optimization in electric power systems

*Gabriela Hug-Glanzmann (Carnegie Mellon University, US)*

**Joint work of** Hug-Glanzmann, Gabriela; Kar, Soummya; Mohammadi, Javad
**Main reference** J. Mohammadi, G. Hug, S. Kar, "Role of Communication on the Convergence Rate of Fully Distributed DC Optimal Power Flow," in Proc. of the 2014 IEEE Int'l Conf. on Smart Grid Communication (SmartGridComm'14), pp. 43–48, IEEE, 2014.
**URL** http://dx.doi.org/10.1109/SmartGridComm.2014.7007620

Traditionally, electric power is generated in bulk power plants and transmitted over a power grid with limited control capabilities to supply inflexible loads. With the trend moving towards more distributed generation and storage resources, flexible demand and increased power flow control capabilities, the number of control variables in the system increases significantly. For the coordination of the settings of these control variables, a more distributed control architecture may become more suitable than the traditional centralized approach. Hence, in this talk, the formulation of consensus + innovations based distributed optimization approaches applied to various optimization problems in power systems is discussed and simulation results which serve as a proof of concept are presented.

## 3.12 Provisioning of Energy Flexibility between Supply and Demand

*George B. Huitema (University of Groningen, NL)*

Currently we are facing the transition of the traditional Energy world to a Smart Energy System. Flexibility is key in Smart Energy. Flexibility here is not about the flow of energy itself but about the willingness or ability of energy units (i. e. households, generators, battery elements) to vary respectively in their consumption, production or storage. The variation thus may concern parameters like time (shifting loads), quantity, quality or e. g. type of energy (hybrid: electricity, heat, gas). Many Smart Grid business models, like Demand-response programs, deal with selling or buying flexibility. This is driven by revenues, savings or incentives. Related to the business relationships we have to take care of the corresponding (Smart Grid) Billing. No Billing is Killing. In this presentation I focus on the next step in the transition to Smart Energy Systems, that is not work anymore on implementation of single technologies but work on "Big Numbers" (1k–1M), and thus on complexity, i. e. system integration, aggregated flexibility and large scale business processes. In particular I describe the latest developments in

1. Smart Grid Coordination (2nd generation multi-stakeholder transactive energy algorithm for multi-objective optimization, example is the TNO PowerMatcher agent-based Energy Management System);
2. Active Customer Participation;
3. Flexible Power Architecture Interface (FPAI);
4. Hybrid System Integration (HESI) and
5. Smart Grid Billing (or SmarteBility).

Finally, I present the case of a Flexibility Provider, i. e. an aggregator who services to other parties the flexibility contracted with consumers. As a statement, I assume that the Flexibility Provider is a spin-doctor in this business proposition.

## 3.13 Thermal Loads for Ancillary Services

*Maryam Kamgarpour (ETH Zürich, CH)*

The increase in fluctuating weather-based renewable generation increases the need for the so-called ancillary services, which help in balance of supply and demand. Control reserves are the most important form of ancillary services and are today mainly covered by conventional generators, such as hydro power plants. I will discuss the use of thermal loads as additional means for ancillary services. Two main options for thermal loads will be discussed: first, control of Heating, Ventilation, and Air Conditioning (HVAC) systems of an aggregate of several office buildings; second, control of a large number of household appliances. I will discuss our modeling, optimization, and control tools developed to quantify the potential of these loads to serve in the ancillary service market.

## 3.14 Sooner is Safer than Later in Branching Time too

*Joost-Pieter Katoen (RWTH Aachen, DE)*

**Joint work of** Hermanns, Holger; Katoen, Joost-Pieter; Song, Lei; Zhang, Lijun

I present a formal characterization of branching-time safety and liveness properties for timed systems. As in the classical branching-time setting, I distinguish universally and existentially safe (and live) properties. I characterize these property classes topologically as well as by sound and complete fragments of timed CTL. For finitely branching timed properties, we present an algorithm that decomposes an arbitrary timed CTL formula into an equivalent conjunction of a safety and a liveness property, both represented by timed alternating tree automata.

## 3.15 Recharging Probably Keeps Batteries Alive

*Jan Krčál (Universität des Saarlandes, DE)*

**Joint work of** Hermanns, Holger; Krčál, Jan; Nies, Gilles

The kinetic battery model is a popular model of the dynamic behavior of a conventional battery, useful to predict or optimize the time until battery depletion. The model however lacks certain obvious aspects of batteries in-the-wild, especially with respect to (i) the effects of random influences and (ii) the behavior when charging up to capacity bounds.

This paper considers the kinetic battery model with bounded capacity in the context of piecewise constant yet random charging and discharging. The resulting model enables the time-dependent evaluation of the risk of battery depletion. This is exemplified in a power dependability study of a nano satellite mission.

## 3.16 Mosaik – a Framework for Smart Grid Co-Simulation

*Sebastian Lehnhoff (OFFIS – Oldenburg, DE)*

**Main reference** S. Rohjans, S. Lehnhoff, S. Schütte, F. Andrén, T. Strasser, "Requirements for Smart Grid Simulation Tools," in Proc. of the 23rd IEEE Int'l Symp. on Industrial Electronics (ISIE'14), pp. 1730–1736, IEEE, 2013.
**URL** http://dx.doi.org/10.1109/ISIE.2014.6864876
**URL** https://mosaik.offis.de

Future energy systems will have to integrate large varieties and numbers of active components (generation and consumption devices as well as operational equipment) into energy management or operating schemes allowing for an automated on-line optimization of appropriate systems. Although the necessary Information and Communication Technologies (ICT) and automation technologies are well known and established in other application domains, their implementation and prolonged use in (safety-critical) future Smart Grids is hitherto untested and thus fraught with potential risk for relevant stakeholders in the energy domain, e. g., Distribution and Transmission System Operators. Therefore, novel ICT-based systems e. g., for control and protection systems, adaptive ancillary service provision through decentralized units have to be tested rigorously in advance in order to minimize uncertainties in their prospective adoption.

When addressing the key question of how and on what parts of the system to test ICT components, the scope of future Smart Grids is hard to determine. Future energy systems will depend not only on unit (generation and consumption) commitment and on the utilization of the operating equipment in between but also on weather phenomena, user preferences or strategies, the utilization and thus availability of the underlying ICT system, market prices, regulatory constraints and governance to name but a few of the relevant facets. When taking complex interactions of these facets into account matters become even more complex. Omitting allegedly irrelevant facets might prove dangerous as even small effects quickly gain relevance through scaling a prominent example was the European 50.2Hz frequency problem. Formal analysis of such a system is not feasible anymore and realistic field tests or experimental hardware environments representative of the complex and interactive system too expensive. This paves the way for couplings of real hardware interacting with simulated environments (hardware-in-the-loop) or even pure software-based simulations in power system design and analysis. However, there is a need for proper simulation environments supporting the flexible integration of (oftentimes black- box-)models of various origin and representation (including hardware) into a functional environment.

In this talk we will present mosaik – a flexible Smart Grid co-simulation framework for reusing and coupling existing simulation models and simulators to create large-scale Smart Grid scenarios yielding thousands of simulated entities distributed across multiple simulator processes. These scenarios may then serve as a test bed for various types of control strategies (e. g., Multi-Agent Systems (MAS) or centralized control) in complex an realistic scenarios. Following mosaiks scenario design we will specify the state-of-the-art, identify current challenges with respect to modeling, simulation and uncertainty quantification in Smart Grid design and analysis.

## 3.17 Modeling, Validation, and Calibration of Power System Models.

*Bernard Lesieutre (University of Wisconsin – Madison, US)*

In this seminar we present results on power plant model validation. Using PMU measurements located at the point of interconnection, power plant models may be validated/invalidated. Simulations using dynamics models are compared to data from disturbances. When the models fail to match the measurements, the errors can be used to recalibrate the models. Issues involve the detection of discrete changes including control loop failures, and the non-uniqueness of parameter profiles to match data. Three illustrative examples are provided.

## 3.18 Mean field based decentralized control of power system components for a smoother integration of renewable sources

*Roland P. Malhame (Polytechnique Montreal, CA)*

The past years have seen a significant increase in the level of renewable energy sources in the power generation mix, and a number of countries have set for themselves ambitious goals in this respect. However, the intermittent character of most of the renewable sources creates particular challenges in terms of maintaining the balance between generation and load. In this context, energy storage becomes an important tool for making higher renewable penetration levels possible. Much energy storage of electrical origin is present in the power system; it is associated with temperature sensitive devices such as air conditioners, electric space heaters,electric water heaters, and refrigerators; also electric vehicle batteries could collectively represent an important energy storage capability. However besides the need for a communication link between the generation authority and the loads of interest, as well as the challenge of enlisting the agreement of customers, an important difficulty in tapping into the energy storage, remains the sheer number (in the millions) of devices which would have to be reached and properly coordinated for this purpose. Mean field control theory appears to be the right tool for dealing with such a challenge as it turns the complexity of large numbers into an ally, by harnessing the power of the law of large numbers to achieve predictability of aggregate load behaviors. It is a blend of the mathematical theory of Games with the Physics theory of Statistical Mechanics. We present a hierarchical control architecture with an upper scheduling level working with aggregate models of the devices to be controlled. Using all relevant macroscopic information, the upper level uses mathematical programming to calculate optimal mean power or energy trajectories for the average individual device in a given class. It is left up to a lower level mean field controller to synthesize the decentralized feedback control laws which will lead the group to track the desired aggregate behavior. The basics of the theory and simulation results are presented.

## 3.19 Learning and data based optimization with application to generation and load side control of uncertain power systems

*Kostas Margellos (University of California – Berkeley, US)*

**Joint work of** Margellos, Kostas; Prandini, Maria; Lygeros, John; Oren, Shmuel
**Main reference** K. Margellos, M. Prandini, J. Lygeros, "On the connection between compression learning and scenario based optimization," IEEE Transactions on Automatic Control, to appear; pre-print available as arXiv:1403.0950v2 [cs.SY].
**URL** http://arxiv.org/abs/1403.0950v2

Making optimal decisions in an uncertain environment is a challenging task. In the same time, advances in many engineering disciplines have led to a huge amount of easily accessible data. This big data trend, leads to a paradigm shift in control and optimization, rendering data driven control an alternative to deterministic or robust techniques. We first focus on the problem of designing a decision policy that optimizes a certain criterion and is immunized against data uncertainty. We show that the resulting decision can be accompanied with a performance certificate that is provided a-priori to the decision maker and encodes the confidence with which the decision maintains its robustness properties against uncertainty realizations other than those included in the data. We relate the issue of certificate provision with learning and generalization paradigms in machine learning and analyze the implications of this approach to optimization problems with certain structural characteristics. We next show how the developed machinery can be applied to different generation and load side control problems in power systems with renewable energy sources. We focus on the problem of stochastic unit commitment and on a novel paradigm and pricing analysis for demand side management. The proposed framework allows us to provide certificates regarding the performance of the underlying system and is in contrast to earlier approaches to such problems, that are typically restricted to rule based or ad-hoc methodologies.

## 3.20 Uncertain power system reserves from loads

*Johanna Mathieu (University of Michigan – Ann Arbor, US)*

**Joint work of** Mathieu, Johanna; Vrakopoulou, Maria; Andersson, Göran; Li, Bowen; Shen, Siqian; Zhang, Yiling
**Main reference** M. Vrakopoulou, J. L. Mathieu, G. Andersson,"Stochastic Optimal Power Flow with Uncertain Reserves from Demand Response," in Proc. of the 2014 47th Hawaii Int'l Conf. on System Sciences (HICSS'14), pp. 2353–2362, IEEE, 2014.
**URL** http://dx.doi.org/10.1109/HICSS.2014.296

Aggregations of electric loads can provide reserves (i. e. back-up capacity) to power systems, helping the system to manage real-time supply-demand mismatch. However, the amount of reserve capacity available from loads is a function of a variety of stochastic factors including weather and load usage patterns. In this talk, I will describe how aggregations of thermostatically controlled loads (each individually represented as a stochastic hybrid system) can be modeled as thermal energy storage. Using these models, we can tackle both control problems (e. g., energy price arbitrage) and planning problems (e. g., stochastic unit commitment). For the latter, I will describe recent work that proposed "uncertain reserves" where the possible reserve capacity is not known a priori. In that case, the system operator solves a stochastic optimization problem to manage uncertainty stemming from renewable generation, load consumption, and load control uncertainty. We explore a variety of methods to solve this problem including scenario-based methods, analytical reformulations that assume knowledge of uncertainty distributions, and distributionally robust optimization.

## 3.21 Electrical Transmission Grids: Needs and Challenges

*Patrick Panciatici (RTE Energy – France, FR)*

### 3.21.1 Needs from a Grid Operator Perspective

The electrical grids and their management become more and more complex. This state of affairs has different causes that will not disappear in the near future. In Europe, the first reason is the massive integration of renewable but generally intermittent generation in the system. Power flows in the grid are created by differences in the location of sinks and sources. With a significant amount of intermittent generation, the predictability of the sources (location and amount of power injections) decreases and affects the predictability of the flows. Furthermore, some of these new power plants could be small units (e. g. PV) connected to the distribution grid, changing the distribution grid into an active system. Moreover, Transmission System Operators (TSOs) have a poor observability of these power injections and have no control at all over them. Another factor is the inconsistency between the relatively short time to build new wind farms (2 or 3 years) and the time to go through all administrative procedures to build new lines (more than 5 years everywhere in Europe). In Europe, the best locations for wind farms are mostly along the coasts and offshore, while for photo-voltaic generation they are in the south of Europe. Since these locations do not generally match those of the large load centers, a transmission network is required and this network will have to cope with the variability of the flows induced by the stochastic nature of the novel generation subsystems. The second main reason is that it is more difficult than ever to build new overhead lines because of low public acceptance and "Not In My BackYard" (NIMBY) attitude. People are more and more afraid of hypothetical electromagnetic effects or just don't like to see big towers in the landscape and in particular in protected areas which are more and more numerous around Europe. It is very difficult to explain the need for new power lines to people who already have access to electricity at a reasonable price and with high reliability. An increase in the European Social Welfare with a positive feedback for the European economy and hopefully for all European citizens is a concept that is too theoretical compared to the negative local impact. Alternative solutions are technically complex, costly and need more time to be deployed. The third reason is linked to the setup of electricity markets crossing the administrative and historical borders. Generators, retailers and consumers view the transmission system as a public resource to which they should have unlimited access. This approach has the desirable effect of pushing the system towards maximization of the social welfare and an optimal utilization of the assets. However, this optimization is constrained by security considerations because widespread service interruptions spanning over long periods of time are unacceptable in our modern societies due to their huge economic and social costs. Since TSOs are responsible for maintaining the reliability of the electric power system, they must therefore define the operating limits that must be respected. As in any constrained optimization problem, the optimal solution towards which the market evolves tends to be limited by these security constraints. The stakeholders therefore perceive reliability management by the TSOs as constraining their activities and reducing the European Social Welfare rather than as enablers of this large physical market place, as it would be the case if the grid were a copper plate. The transparent definition and the precise assessment of the distance to these limits thus become more and more critical. The last reason is that the aging of grid assets needs increasing attention. A significant part of the European grids' assets are more than 50 years old. Asset management and maintenance in systems that can't be stopped, are extremely challenging and need to be precisely anticipated when large numbers of assets are approaching simultaneously the end of their expected life times. To maintain the security of the supply in this context, TSOs have to change the architecture of the system by considering the following technologies:

- Long distance HVAC underground cables with large reactive compensators.
- HVDC underground cables in parallel with the AC grid with smart controls of AC/DC converters.
- And, ultimately, HVDC grids, first to connect efficiently offshore wind farms and then to provide cheaper interconnections between distant areas.

Meanwhile, TSOs will try to optimize the existing systems by adding more and more special devices such as Phase Shifting Transformers, Static VAr Compensators and advanced controls and protection schemes, taking also advantage of the flexibility provided by HVDC links embedded in AC grids. At the same time, demand response or dispersed storage could offer new ways to control the system, even if business models and costs are still questionable. But in any case, this flexibility will require a rethinking of historical operating practices where grid operators made the assumption that the load is an uncontrollable exogenous stochastic variable. We have heard so often in conferences, seminars and workshops, that the power grid will soon be operated very near to its limits, so that this statement has become a cliché. This cliché is now a reality. To be more precise, it is no longer possible to respect the classical preventive N° 1 security standards during all hours in a year. The system is indeed no longer able to survive all single faults without post-fault actions, i. e. corrective controls. More and more corrective control strategies are hence elaborated and prepared to maintain the security of the system. The number of hours during which the system requires corrective actions to be secure is increasing, and that seems to be a natural trend associated with the massive integration of intermittent generation. More and more local or centralized Special Protection Schemes (SPS)/Remedial Actions Schemes(RAS) are deployed to implement automatically some of these corrective actions based on advanced measurement devices (Phasor Measurement Units, Dynamic Line Ratings, ...) and high bandwidth communication networks. Grid operators have to manage an extremely complex decision making process in order to ensure the reliability and quality of supply at minimal cost over different time horizons. For the sake of clarity, while not aiming at being exhaustive, the following problems need to be dressed by the grid operators:

- Long term (10–20 years): planning stage – where to build new power lines? which technology? which capacity?
- Mid term (2–5 years):
  - installation of control devices: substation design, var/reactive support, PSTs, replacement of conductors,SPS/RAS design;
  - asset management and maintenance: which equipment to upgrade, to replace, to repair and when?
- Short term (monthly–weekly): outage management, must-run generators, preparation of corrective actions, required margins.
- Real Time (two days ahead to real time):
  - interaction with energy markets: definition of grid capacities;
  - selection of substation's topology, settings of SPS/RAS, adjustment of generating units.

In all these contexts, the grid operators want to make “optimal” decisions over these different time horizons, even if some decision making processes are currently not formalized mathematically as optimization problems but are rather based solely on knowledge of experts. However, as complexity increases, decision support tools become mandatory to help these experts to make their decisions:

- For the long term planning, there is hyper uncertainty associated with the implementation of energy transition policies and long term market behavior (Priority to renewable energies, Demand Growth in context of efficiency promotion, Technology Costs: electrical batteries, Demand Response, EV, Distributed Generation, Carbon Tax, Fuel Costs) and Grid operators have to make robust decisions based on multi-scenario grid planning.
- In all these processes, the increasing level of uncertainty associated to wind and solar power must be taken into account, hence pushing towards the use of probabilistic methods.
- Operation nearest to the limits requires an accurate modeling of all pieces of equipment, of the corrective actions and of the dynamic behaviors, so as to allow an accurate enough assessment of security margins. Moreover, the active constraints could be related to voltage/reactive or stability issues and not only to thermal limits.

Grid operators must ensure an adequate consistency between these decision making processes. They are in fact multistage decision making processes considering all the different time horizons. At the planning stage, they have to consider the decisions which could be made in lower level problems: asset management and operation and the same between asset management and operation. The modeling of these lower level problems seems very challenging when these lower level problems become more complex. Approximations are required and relevant “proxies” must be found for this modeling. In this paper we defend the idea that in order to address all these different questions, it is valuable to explicitly formulate them as optimization problems. Most of these problems, once stated, are hard to solve exactly. On the other hand significant progress has been collected in the recent years both in computational and in mathematical respects. The goal of the paper is to highlight the main avenues of progress in these respects and explain how they can be leveraged for improving power systems management.

### 3.21.2 Taxonomy of Optimization Problems

The objective of this section is to dig into the different ways one can formulate and model optimization problems to be addressed in power systems (with a focus on system-wide problems, as those addressed by TSOs).

**A. Modeling the optimization problem from a formal viewpoint.** Based on examples, we discuss the intrinsic nature of the different optimization problems, by distinguishing different possible formulations. The general formulation can be summarized as a multistage decision making problem under uncertainty. But the formulation of this very general problem depends on the different time horizons and the type of decisions to make. We can divide these decisions in three classes, illustrated here by an analogy with IT systems. 1) Decisions changing the structure of the system (developing the hardware) 2) Decisions changing policies or control/protection schemes (developing the software) 3) Decisions modifying the operating points of the system (selecting input data to run the software on the hardware) We focus our discussion on the first problem which is the most challenging. This problem ideally requires the modeling of all the aspects of power systems: from possible long term energy policies to system operation using realistic modeling of the physical system and expectations of the grid users. The decisions related to the structure of the system

(”hardware”) take long time to be implemented, they have to go through long permitting processes and need quite long construction times. They are investment decisions. The objective is to optimize the associated capital expenditures (capex) by comparing them to future operational expenditures (opex) saving. The time frame is varying from around ten years for the construction a new power line to one year for changing conductors on existing power lines. A part of the problem is to choose the relevant mixture of technological options: ac overhead power lines, ac underground cables, hvdc links, phase shifter transformers (PSTs), new conductors for existing power lines, new reactive compensation devices, ... The problem can be formulated as stochastic dynamic programming problem. For long term expansion planning, scenario-based approaches seem the most attractive formulations in order to ensure some level of robustness as proposed in [1]. How to define reliability criteria and how to implement them, are key questions in these optimization problems. ”Energy Not Served” or ”Loss of Load” are generally used. An “artificial” monetization is performed and estimated costs are associated to these indexes. These large costs are simply added to operational expenditures. In stochastic formulations, generally only expected values are minimized without any cap on the maximum risk. This could be questionable and chance constraint programming or robust optimization could offer more relevant solutions. We could imagine that a generalization of Demand Response could change dramatically the definition of reliability and the foundations of power system design,pushing to less ”hardware” and more ”software” solutions as anticipated very optimistically in 1978 by F. C. Schweppe [2]. A review of the current formulation and associated optimization problem is mandatory as proposed for example in the two on-going European projects: e-HIGHWAY2050 [3] and GARPUR [4]. In this global optimization problem, the sub problem on selection of relevant technological options leads to a combinatorial optimization very similar to a ”knapsack” problem, increasing even more the complexity. We can identify three different dimensions: spatial, temporal and stochastic. The spatial complexity is increasing: ”more and more the electrical phenomena don’t stop at administrative borders”. We have to consider systems very extended (Pan- European Transmission System, Eastern or Western Interconnection in US, . . . ) and at the same time local active distribution grids. Time constants range from milliseconds to several years, leading to temporal complexity. Uncontrollable load and renewable energy sources implies to take into account more than ever stochastic behaviors. Considering spatial, temporal and stochastic complexity all together is still out of reach.Trade-offs must be made to take into account at most two of them in details at the same time and using approximation for third one. The appropriate modeling of uncertainties is also a key factor to find realistic optimal solutions. The spatial and temporal correlations between these uncertainties must be taken into account not to be too optimistic or too pessimistic. This pushes towards probabilistic methods and risk based approaches. When the probabilistic properties of the uncertainties are only partially known, generalized semi-infinite programming seems an appealing method proposing to find robust solutions when the uncertainties live in a defined domain. The objective function is related to satisfaction of the grid users (consumers and suppliers): maximization of social welfare. We need to estimate the expectations and the behaviors of the grid users. For long term decisions, it seems reasonable to simulate a “perfect market” leading to a global rational behavior minimizing the costs. For more short term decisions, it could be important to simulate the actual behavior of the market players and the imperfect market design. These estimations could be formulated as optimization problems based on game theory finding Nash equilibrium.In practice, we could have to formulate multi-objective optimization problems which are generally transformed in a single optimization problem using a weighted sum of the different objective functions

$\min(w1.f1(x) + w2.f2(x) + +wn.fn(x))$: (For example, we want to minimize the production costs and the amount of emitted CO2). Finding the associated weighting factors could be difficult and questionable. A more rational approach should be to formulate a true multi-objective function $\min(f1(x); f2(x); ; fn(x))$: But for a nontrivial multi-objective optimization problem, there does not exist a single solution that simultaneously optimizes each objective. In that case, the objective functions are said to be conflicting, and there exists a (possibly infinite number of) Pareto optimal solutions. A solution is called non dominated, Pareto optimal, Pareto efficient or non inferior, if none of the objective functions can be improved in value without degrading some of the other objective values. This leads to complex optimization problems which could be solved using meta-heuristics methods. We could see that power system management could lead to a large diversity of optimization problems. The proper formulation of each problem has to be well thought out before searching for computational solutions.

**Modeling the physics of the power system.** The objective of this section is to analyze the physics and technological constraints arising from the power system, and explain their implications in terms of the nature of the above formulated optimization problems. The quality of physical modeling of power systems used in optimization problems is essential in order to make “optimal” decisions. Solving optimization problems with a high accuracy based on not realistic enough modeling is useless. We need to find the right balance between realism and complexity. The usage of static and deterministic modeling using a linearization of the associated mathematical formulations should be questioned in the new context presented in the introduction. A significant number of controls in electrical grids are discrete: switch on/off of breakers, switch on/off capacitor or reactor banks, tap changers on transformers, generating units producing with non zero minimal active power when they are started. These controls become integer variables in optimization problems and their treatments require a special attention; with a naive relaxation (round off strategy) is not always possible even to find feasible solutions. Some controls and protection schemes implemented in local or centralized SPS/RAS are not event-based but measurement based. They acts conditionally when a measurement or a set of measurements don’t fulfill a given rule (for example, when a measurement value is beyond a given limit). This kind of behavior must be taken into account in optimization problem. This leads to conditional corrective actions and the modeling of this type of hybrid system (continuous and discrete) requires binary variable [5]. Some active constraints in power systems could be more and more related to stability and the system dynamic behavior. The ultimate solution should be to use a DAE-constrained optimization formulation but a reasonable first step could be to use ”proxies” to hide this complexity. The idea is to learn using Monte-Carlo simulation, rules which ensure that the study case has a very low probability to be prone to stability issues [6] and to introduce these rules in static optimization problems. Power system planning and operation raises many important decision making problems, which can generally be stated as large-scale, non-linear, mixed-integer continuous, non-convex, stochastic and/or robust optimization problems. In the last years, many progresses have been made in the theory and implementation of optimization algorithms, driven by research in applied mathematics and by multitudinous opportunities of application. The combination of these novel ideas to improve the state-of-the-art of power systems optimization is an important direction of future work. On the other hand, low cost information technology (HPC and Big Data) as well as progresses in machine learning and randomized algorithms offer other enabling approaches to apply optimization techniques in power systems. We suggest that the research community should further focus on the proper formulation of power system optimization problems with the help of power system experts, and develop more intensively fruitful collaborations with researchers in applied mathematics and computer science to determine the most effective solution strategies for these problems. At the same time, we think that more systematic investments in a more effective use of modern information technologies, especially in the context of high-performance computing and massive data exploitation should be made by the power systems industry.

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## 3.22 A classification-based perspective to optimal policy design for a Markov Decision Process

*Maria Prandini (Politecnico di Milano University, IT)*

**Joint work of** Prandini, Maria; Manganini, Giorgio; Piroddi, Luigi; Pirotta, Matteo; Restelli, Matteo
**Main reference** M. Pirotta, G. Manganini, L. Piroddi, M. Prandini, M. Restelli, "A particle-based policy for the optimal control of Markov decision processes," in Proc. of the 19th IFAC World Congress 2014, Part 1, pp. 10518–10523, 2014.
**URL** http://dx.doi.org/10.3182/20140824-6-ZA-1003.01987

Classical approximate dynamic programming techniques based on state space gridding become computationally impracticable for high-dimensional problems. Policy search techniques cope with this curse of dimensionality issue by searching for the optimal control policy in a restricted parameterized policy space. In this work, we focus on the case of discrete action space and introduce a novel policy parameterization inspired by the nearest-neighbor classification method. Particles are adopted to describe the map from the state space to the action space, each particle representing a region of the state space that is mapped into a certain action. The locations and actions associated to the particles describing a policy are tuned through the policy gradient method with parameter-based exploration. The task of selecting an appropriately sized set of particles is solved through an iterative policy building scheme, that adds new particles to improve the policy performance and is also capable of removing redundant particles. Experiments demonstrate the scalability of the proposed approach as the dimensionality of the state space grows.

## 3.23 Time Unbounded Search for Error Trajectories of Complex Dynamical Systems

*Stefan Ratschan (Academy of Science – Prague, CZ)*

**Joint work of** Kuřátko, Jan; Ratschan, Stefan
**Main reference** J. Kuřátko, S. Ratschan, "Combined Global and Local Search for the Falsification of Hybrid Systems," in Proc. of the 12th Int'l Conf. on Formal Modeling and Analysis of Timed Systems (FORMATS'14), LNCS, Vol. 8711, pp. 146–160, Springer, 2014.
**URL** http://dx.doi.org/10.1007/978-3-319-10512-3_11

We present an algorithm that searches for an error trajectory of a given dynamical system. An error trajectory is a trajectory that starts in a given set of initial states and ends in a given set of states that is considered not to be safe. Unlike other methods, we do not require a user-provided upper bound on the length of this trajectory in terms of time.

Our method takes a black box model of the dynamical system that allows us to simulate the system from a given starting point for a certain amount of time, and that, if available, also returns the sensitivity of the computed trajectory w.r.t. this starting point.

## 3.24 Meshed Data- and Model- Driven Frameworks for Stochastic Hybrid Network Dynamics

*Sandip Roy (Washington State University – Pullman, US)*

**Joint work of** Roy, Sandip; Jackeline Abad Torres; Justin Valdez; Mengran Xue; Rahul Dhal; Yan Wan

Management of electric power networks depends on tracking and forecasting complex stochastic hybrid dynamics at several different scales. Mathematical models have been developed for many of these complex phenomena, but often cannot by themselves provide accurate predictions and forecasts. However, as cyber- capabilities are being integrated into the power grid, a wealth of data – ranging from synchrophasor measurements to smart meters and weather forecasts – is becoming available to stakeholders. This talk will explore how such data sources can be used in tandem with formal models to achieve situational awareness (monitoring and forecasting), using two concrete examples at different scales. First, we will briefly discuss how stochastic automata models can be used along with weather forecast data for wide-area renewable-generation forecasting. Second, we will present a technique for locating line faults in a power network, using models for transient dynamics together with synchrophasor data. A common theory for network estimation and control underlying these results will be briefly overviewed.

## 3.25 Model checking probabilistic hybrid automata

*Jeremy Sproston (University of Turin, IT)*

This talk gives an overview of the probabilistic hybrid automata, which are classical (non-deterministic) hybrid automata extended with probabilistic choice over the discrete part of the system in question. This formalism can be used for the modelling of, for example, faulty components or timed, randomised protocols. Model-checking analysis of probabilistic hybrid automata is considered. It is shown that results on obtaining finite-state models that are equivalent to hybrid automata can be lifted to the probabilistic hybrid automata case. Furthermore, a method in which probabilistic hybrid automata can be used as abstract models for more general classes of stochastic hybrid system is presented.

## 3.26 Operation of a transmission network as a hybrid system

*Martin Střelec (UWB – Pilsen, CZ)*

**Joint work of** Střelec, Martin; Cerny, Vaclav; Janecek, Petr

Transmission grids are large power networks interconnecting power generation with consumption and mainly constitute backbone power grids on national levels. A network operator (e. g. TSO) ensures safe and reliable transmission of electricity and its desired quality. Balance between power generation and demand is one of most important indicator in network safety assessment. For power balancing, network operators rely on ancillary services, which eliminate power differences between generated and consumed power. The proposed presentation focuses on hybrid modeling of transmission network operations and associated Monte Carlo simulation techniques. Operation of a transmission network is modelled by evolution of the power difference which is a process affected by continuous (e. g. load evolution, automatic generation control), discrete (e. g. forced generators outages, power reserves activations) and stochastic factors (e. g. load and renewable generation volatility). Therefore stochastic hybrid systems represents promising framework for modeling of transmission grid operation. Introduced hybrid model is utilized in a traditional Monte Carlo approach for reliability assessment of ancillary services. Some of ancillary services are contracted on long term basis (typically secondary control reserves). Reasonable volume determination of these ancillary services has significant economic impact on operators. Each network operator has their own methodology for long term contracting of ancillary services. Reliability assessment consists in verification whether contracted ancillary services are sufficient for reliable operation of transmission networks.

### 3.27 Correct-by-construction synthesis of software-based protocols for open, networked systems

*Ufuk Topcu (University of Pennsylvania, US)*

We discuss specification and synthesis of software-based control protocols that dynamically reconfigure a network as the environment in which the network operates changes. We consider power networks on aircraft as a driving application. In this case, the network needs to reconfigure in order to guarantee, for example, satisfactory delivery of electric power to loads as the flight conditions and the health status of the generators and other equipment change. We present samples of our recent work on correct-by-construction synthesis formulated as two-player, temporal logic-constrained games and stochastic, two- player games along with experiments on an academic-scale testbed.

### 3.28 Lazy Determinisation for Quantitative Model Checking

*Lijun Zhang (Chinese Academy of Sciences, CN)*

**Joint work of** Ernst Moritz Hahn; Guangyuan Li; Sven Schewe; Andrea Turrini; Zhang, Lijun
**Main reference** E. M. Hahn, G. Li, S. Schewe, L. Zhang, “Lazy Determinisation for Quantitative Model Checking,” arXiv:1311.2928v1 [cs.LO], 2013.
**URL** http://arxiv.org/abs/1311.2928v1

The bottleneck in the quantitative analysis of Markov chains and Markov decision processes against specifications given in LTL or as some form of nondeterministic Buechi automata is the inclusion of a determinisation step of the automaton under consideration. In this paper we argue that applying this step in full generality is only required in some places, and can often be circumvented by subset and breakpoint constructions. We have implemented our approach – both explicit and symbolic versions – in a prototype tool. Our experiments show that our prototype can compete with mature tools like PRISM. Details can be found in our report [1].

#### References

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### 3.29 Revisiting the mathematical modeling of power networks

*Arjan van der Schaft (University of Groningen, NL)*

**Main reference** S. Fiaz, D. Zonetti, R. Ortega, J. M. A. Scherpen, A. J. van der Schaft, “A port-Hamiltonian approach to power network modeling and analysis”, European Journal of Control,19(6):477–485, 2013.
**URL** http://dx.doi.org/10.1016/j.ejcon.2013.09.002

Traditionally the power network engineering literature has refrained from developing ’complete’ structure-preserving models of power networks. Instead one has emphasized phasor descriptions of the network, swing equations for the generators and/or the modeling of generators as 'voltage sources behind a reactance'. There have been, and are, good reasons for doing this. On the other hand, with all the new questions posed in recent power network research developments, it seems promising to take a critical look at the modeling paradigms, in order to facilitate analysis and control. In this talk I will argue that a full time-domain modeling approach can be taken, which emphasizes the physical structure of the network and its components, and in particular makes 'energy' and 'power flow' explicit. Starting point of this approach will be a port-Hamiltonian formulation of the classical 8-dimensional model of the synchronous generator.

# 4 Working Groups

In the following we summarise the main points that have arisen from the breakout sessions and the final discussion. There have been three breakout sessions, focusing respectively on

- modelling issues in energy/power systems;
- simulation issues in energy/power systems;
- demand response: control and verification.

## 4.1 Modelling issues in energy/power systems

*Alessandro Abate, Martin Střelec*

The session has zoomed in on a number of topics, and raised related pressing issues.

### Gap in models

- Study of steady-state (power flow), and of optimal power flow (OPF)
- Communications
- Interactions with the physical system
- Interactions in the infrastructures for gas and electricity

### Uncertainty in models

- Presence of different forms of uncertainty: load amount and composition, load control availability, renewable generation, communication delays, random events (such as line and generator tripping), controllable resource in the case of demand response
- What are the right representations for power flow scheduling, analysis of its dynamics, its control?
- How can the effects of uncertainty on system dynamic performance be assessed (considering nonlinear, non-smooth behaviour)?

### Timescale of interest in models

- Adaption of models for different time scales
- Phasor versus time-domain modelling for dynamic analysis
- Timescale differences can be particularly troublesome for micro-grid analysis

### Load modelling

- Component models versus performance models, versus time-series models
- Distribution network models: aggregation of heterogeneous loads together with distributed generation
- Presence of uncertainty
- Models for control of individual loads, versus those for aggregated loads

### Power electronic devices

- Presence of AC/DC, DC/AC conversion
- Very fast response
- Control-based rather than physics-based behaviour

## 4.2 Simulation issues in energy/power systems

*Alessandro Abate, Martin Střelec*

This group has focused on a number of topics, as discussed below.

### Quality aspects of models

Model flexibility, namely the the ability to make user-defined changes to a model, is directly linked to the white-box vs. black-box dichotomy. Accuracy, namely the ability to show instabilities if the modelled system is unstable, is important, as much as computational complexity and portability are. The latter aspect in particular deals with the possible migration between simulation tools, platforms, and runtime environments.

### Purpose-specific views on models

The internal structure and the model representation (stochastic, deterministic etc.) has an impact on the processes of 1. testing validation of models, and 2. optimisation of/within the model.

### Determining the right models

This discussion focuses on a case-specific view on models. This can be based on the use cases or applications, where different model quality aspects become relevant, such as 1. planning vs. operation use cases; 2. design of control/protection systems; and 3. time-domain (non-linear) vs. frequency-domain aspects. In general, the more transient/dynamic the use case, the more transparent the model needs to be (from black- to grey- to white-box).

This theme has covered a discussion on the inclusion of noise into the models of power systems (in order to trigger certain effects that would otherwise be undetectable).

### Necessary tools

Starting from a discussion on how the engineering and the integration of models is quite expensive, the following aspects have been touched upon:
1. automatic reduction/abstraction/simplification of models;
2. merging/fusion of (white-box) models;
3. co-simulation; and
4. validation (benchmarking against reference models).

### Open questions

The following issues remain:
1. how do you validate or benchmark a system, without the data or the knowledge of the "real" underlying system (e. g. we are making highly detailed models of distribution systems that are currently not measured at all)?
2. can you derive model/application-specific characteristics or metrics?
3. can you tune models online as the data is gathered? Model-specific processes and tools are needed!

## 4.3 Demand response: control and verification

*Alessandro Abate, Martin Střelec*

Briefly stated, demand response has to do with the reaction within an energy-consuming building or by a consumer to requests to adjust consumption. The request can be direct (e. g. direct on/off control of HVAC system) or indirect (through pricing mechanisms).

Broadly, topics discussed have been the following:
- whether optimality issues can be properly addressed with optimal control or MPC techniques;
- how high-gain and delay in feedback loop in response to the pricing signal could result in instability;
- issues of privacy, due to load profiles being transmitted, particularly within bidirectional collaborative energy management;
- possible trade-offs between performance degradation and responsiveness to pricing stimuli;
- issues of faults diagnosis and of optimal control/scheduling for maintenance in HVAC systems;
- issues and opportunities in risk hedging/diversification of renewable sources;
- issues of predictability of renewables (in a short time scale), to be potentially matched by demand response?
- timely acquisition, processing and decision making based on "real-time" info.

Additional points raised in the discussions have touched upon the following themes:
- intelligent management/optimization and storage at local/global level;
- management of mobile assets (such as meters, devices, cars), with their user-friendliness;
- flexible policy for data management, dealing with security, privacy, and trust;
- the importance of interoperability and of open cross-layer collaborative approaches;
- issues of reliability and of scalability;

- the required support for and development of qualified open standards;
- the requirement of large-scale simulation, modelling, and risk analysis tools;
- the importance of business analytics (prediction, visualization, etc.);
- and finally the need for real-world trials and experiences.

## Participants

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