Guest Editorial
Modeling, Simulation, and Application of Cyber-Physical Energy Systems

CYBER PHYSICAL systems (CPSs) are the systematic combination of physical processes and information and communication technology (ICT). They constitute the next generation of networked, embedded systems that explicitly consider the physical parts during their design and operations.

CPS applied to the energy system leads to the possibility of more sophisticated controls, the interworking of different energy types [1], cooperative loads [2], smart factories [3], the interaction of markets and infrastructure [4], smart integration of renewable energy sources [5], automated [6] and grid-friendly buildings [7], more knowledge about the system due to sensor networks and analytics [8], multiagent systems [9], usage of smart storage [10], information technology (IT) security challenges [11], and many other aspects of what is sometimes called smart grids [12].

Combining such different aspects like physical infrastructure, communication systems, markets, and people leads to heterogeneous systems that are difficult to deal with. Their inherent complexity stems from its many autonomous subsystems and their very different nature with respect to timing or size. Dynamic models of such systems can help to understand the mechanisms, to check for robustness and stability, to estimate and anticipate problems and to optimize them for performance and efficiency. Unfortunately, modeling of hybrid systems is not easy. Traditional methods quickly reach their limits if the systems are heterogeneous and large, which is typically the case with cyber-physical energy systems (CPESs). New methods and tools are needed. The annual workshop on "Modeling and Simulation of Cyber Physical Energy Systems" (Berkeley 2013, Berlin 2014, Seattle 2015), technically cosponsored by the IEEE Industrial Electronics Society, serves as a forum for researchers in this area. This special section is the result of these meetings, bringing together the latest research in CPES.

The dominating topic of this community of researchers is to find new and effective ways of modeling and simulation of CPESs. Morais *et al.* [13] describe the Secure Operation of Sustainable Power Systems Simulation Platform for Real-Time System State Evaluation and Control (SOSPO) Simulation Platform, a framework to test and assess power system properties like stability in real time. Phasor measurement units (PMUs) and power-hardware-in-the-loop (P-HIL) equipment is used to create an experimental setup for power system operator training and research. Various stability aspects (rotor angle, voltage, transient, and frequency stability) can be analyzed.

The focus of [14] lays on the communication part of an intelligent energy system. Control applications massively depend on the quality of service provided by the communication system. The paper describes a cosimulation setup based on power system computer aided design (PSCAD). Using this simulation setup, it is shown how control applications can be designed in order to be more robust and resilient with regards to communication problems such as a stochastic latency.

In addition to interfacing the electricity grid to communication systems, other energy systems can be the source of heterogeneity. Molitor *et al.* [1] present a cosimulation setting, based on existing simulators, to be used for city- and district-level analysis of hybrid energy systems. The interactions of the electricity systems and for instance a gas or heat network can be modeled in a cosimulation fashion. The various individual parts of the simulator are integrated by means of a commercial run time infrastructure (RTI).

A use case with on-load tap-change (OLTC) transformers in an automated grid is given in [15]. A cosimulation setting for power systems and ICT systems is used to analyze the properties of a multiagent-based control algorithm and its behavior in case of packet loss and the differences in using user datagram protocol (UDP) or transmission control protocol (TCP) as a transport.

Calculating a large number of scenarios or large systems pose is a challenging task. The performance of simulators can be improved by using parallel computation wherever it makes sense. Anderson *et al.* [16] present GridSpice, a simulator platform that loosely coupled engines like GridLab-D or MATPOWER, plus providing a comfortable user interface for things like GIS information.

Another cosimulation framework for power and ICT systems is presented in [17]. The high-level architecture (HLA) is the basis of connecting OPNET and DIGSILENT PowerFactory with a multiagent core that implements the controls. A focus in on event handling and time management, one of the still not completely solved problems in cosimulating hybrid systems.

Another work that covers the handling of asynchronous events in the case of power system and ICT system cosimulation is given in [18]. It provides a systematic overview of the existing solutions and their differences.

An automated demand side is a prerequisite for cooperative and grid-friendly loads, whether it is the buildings [19], industry [3], or private homes [8], [20]. Demand response (DR) is the dynamic variant of an intelligent load side. Safdarian *et al.* [20] describe a distributed algorithm for load management of buildings and homes, having the grid needs and the house owners'

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needs in its focus. Flexible loads are scheduled according to their individual requirements and according to a collective load chart.

Ding *et al.* [3] describe DR for industrial facilities, formulated as a mathematical optimization problem. Tasks and production procedures are expressed in mixed linear integer program. Day-ahead prices are used to evaluate the various schedules.

Load management naturally has an influence on the customers' processes, may it be indoor comfort or production output. Palensky [8] addresses the dilemma of keeping the energy system robust and stable, while satisfying customer needs. Data from demonstration projects show the benefits of load shifting, but also the impact on the customers' processes.

In [5], the Paravalos *et al.* propose a methodology for the design optimization of photovoltaic (PV) plants, which can be executed using high time-resolution values of the meteorological input data and allows for the precise assessment of the performances of the PV plant during its operational lifetime period. The design optimization is able to include in the design process both the meteorological conditions and the operational characteristics of the PV plant components and to evaluate their impact on the PV plant energy production and cost.

In [10], a hybrid model is developed for spatiotemporal estimation of temperature distribution in lithium ion batteries. Time/space separation method is used to develop an effective nominal model suitable for real-time thermal management applications. Then, in order to compensate the model-plant mismatch caused by the spatial nonlinearity and other model uncertainties, a data-based neural model is adopted. Numerical simulations demonstrated that the hybrid method is able to estimate the spatiotemporal temperature distribution also in presence of real-time changes of the working environment. The model can be easily integrated into existing battery management systems for estimation of other temperature dependent battery states.

In [9], a method based on multiagent system for a distributed real-time coordination of power flow control is presented. The distributed control concept, relying on a powerful communication infrastructure, is easy to implement by installing simple software agents at each substation in a controlled network area. The paper outlines the essential algorithms of the agent-based coordination, proposes the concept of adaptive control increments, and evaluates the performance of the adaptive power flow control. The system, located at the substation level, has been developed only relying on local measurements and inter-agent communication in contrast to global system models and centralized computations. The agents are able to rapidly adapt to changing network situations by updated information received from neighboring agents and relieve overloads by coordinated action of power flow controlling devices.

The complexity of the studied systems and the variety of cyber attacks make the role of traditional intrusion detection systems (IDS) more problematic. The huge use of information and communication technologies in Supervisory Control and Data Acquisition (SCADA) systems opens new ways for carrying out cyber attacks against critical infrastructures relying on SCADA networks. In [11], the authors investigate the use of l_p-norms in radial basis function (RBF) kernels for intrusion detection in SCADA systems. Two distinct approaches are investigated by the authors, the support vector data description (SVDD) and the kernel principal component analysis (KPCA). In each approach, the description boundary of the normal behavior of the system is found, and the one-class classifier discriminates the data between normal or abnormal, using two one-class classification algorithms, SVDD and KPCA. Tests have been conducted on real data from a SCADA gas pipeline and water treatment plant for verifying the effectiveness of both approaches. Real data included several types of cyber attacks showed that the variation of the norm affects the distribution of the data in the feature space and the ability of the classifier in detecting the intrusions.

CPESs are a hot research topic, and this is not likely to change in the near future. Still, there are white spots in this domain, especially in scalability, analytic description, and numeric handling of the used models. This collection of research papers shall serve as a help for researchers on their way to mastering these important but difficult systems.

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