EDA for Cyber-Physical Energy Systems Design

Mohammad Abdullah Al Faruque
Department of Electrical Engineering and Computer Science
University of California, Irvine
e-mail: alfaruqu@uci.edu

Abstract

This position statement paper highlights the importance of Electronic Design Automation (EDA) tools and system-level design methodology e.g., Model-Based Design (MBD) for the Cyber-Physical Energy Systems (CPES) to tackle the heterogeneous design complexity coming from multiple domains including power-flow dynamics, market conditions, weather, infrastructure, control, communication, consumer demand responses, etc. In addition to discussing the importance of EDA tools and its associated research challenges, this paper also showcases an exemplary EDA tool developed by the author and his group that may perform a cyber-physical co-simulation of a residential microgrid as well as potentially expedite the design of various control algorithms efficiently and interactively [3]. Furthermore, this paper proposes a novel way of abstracting a CPES model by means of a functional abstraction level that is coded through a Functional Basis language [5]. Finally, a discussion on how high-level synthesis algorithms and EDA tools may be developed to generate high fidelity simulation models quickly and efficiently is presented.

1 Introduction

Currently in the power systems industry, there is a paradigm shift from the traditional, non-interactive, manually-controlled, power grid to the tight integration of both cyber information (computation, communications, and control - discrete dynamics) and proper physical representations (the flow of electricity governed by the laws of physics - continuous dynamics) at all scales and levels of the power grid network. This new grid which features this cyber and physical combination is termed as *Cyber-Physical Energy Systems* (CPES) [4], and it is expected to improve the reliability, flexibility, efficiency, cost-effectiveness, and security of the future electric grid [7, 8]. However, the introduction of *Distributed Energy Resources* (DERs) which include renewables and new types of loads (specifically *Electric Vehicles* (EVs)) in the residential distribution grid presents the challenge of multi-level monitoring and control for supply and demand management to an already complex and heterogeneous grid. A consequence of the rapid addition of these DERs would be that traditional power system design methodologies become more time-consuming to perform and that the ability to preempt grid problems would be more difficult.

Various research challenges have been already identified in the 2009 NSF Workshop "*Research Recommendations for Future Energy Cyber-Physical Systems*", of which various funding and research efforts from the past few years have been performed towards meeting these challenges. It is the author's understanding that now would be a good time to further identify research challenges of interest in the area of CPES due to the introduction of more heterogeneity in the grid, such as through the addition of DERs. Energy systems is an integral part of the overall Utility service package (water, gas, transportation etc.) that is necessary for the consumer and industrial demand sector to continue thriving, and the work done towards researching and building the models and tools that drive CPES to meet the aforementioned challenges will have a positive impact towards both improving the overall system design and to meeting these important consumer end-goals. This paper advocates that to solve this rising complexity new research has to be performed for automation and synthesis algorithms, tool and methodology design, and development similar to what has been performed in the semiconductor industry.

2 Rationale: Why EDA for Energy

The semiconductor industry has been driven by *Moore's law* for more than 40 years. Over that time period, constant and aggressive scaling of device dimensions has resulted in: i) **Device Dimensions** decreasing in scale by a factor of 10^3, ii) **Device Density** increasing in scale by a factor of 10^6, iii) **CPU Frequency** increasing in scale by a factor of 5×10^4, and iv) **CPU Performance** improving by a factor of 3×10^6 [9]. These dramatic improvements came as a direct result of large amounts of R&D investments by the government agencies, e.g. NSF, DoD, DOE, etc. and key industry players such as Intel, IBM, TSMC and many others. *Electronic System Level* (ESL) design methodology and various *Electronic Design Automation* (EDA) tools (including high level synthesis, logic synthesis, etc.) have been successfully used to revolutionize the semiconductor industry thanks in part to their combined ability to tackle both the increasing complexity that comes with smaller and more efficient semiconductor designs, as well as to meet the short deadlines that exist due to the quick time-to-market pressure. EDA tools and algorithms are based on rigorous analysis and optimization algorithms that are the results of many decades of work, and they are well-trusted by the industry due to them being frequently compared to existing published benchmarks.

Though electricity has been around since 1800's and has influenced our daily life in a multitude of ways including: lighting, refrigeration, entertainment, transportation, communication, and etc., many sectors of the population take its existence for granted and rely on the government (and, thanks to the increased push towards market deregulation, the private sector) for its operation. However, with the rise of new technologies and issues ranging across different fields (be it physical limitations, environmental, political, or economical), the development and design-work of energy grid systems will require more optimization work with data cross-disciplinary fields as well as more participation by the consumers. Therefore, the author strongly believes that design automation techniques are a strong future research area for the CPES; a concept that could tackle this additional complexity in an economic way.

3 Cyber-Physical Co-Simulation

Simulation is heavily used across industries during development of complex systems because it is an economical and effective way to design, validate, and test. Various domain-specific simulation tools are available for power systems and they, too, are capable of identifying at an early stage domain-specific problems. However, with the added complexity that comes from new grid technology such as DERs, problems may not be identifiable through these existing domain-specific simulation tools. As an example, a steady-state voltage analysis tool may not be able to explain by itself the reason for why a feeder that services multiple DERs (such as electric vehicles) is overloaded; information about the load charging times, or behavioral information about the decision-making done by electric vehicle owners may be needed to properly explain the issue. To present the planning and design engineers with all the needed information, the CPES will need models and tools that support multi-domain simulation.

While various domain-specific power system simulation tools currently exist, there is a critical gap of advanced system-level design methodology and tools in the modeling and simulating (of both discrete and continuous dynamics) of the cyber and physicals portions of CPES concurrently. Therefore, research will be required to develop novel, efficient, flexible, and interactive cyber-physical simulation tools. Moreover, simulation will need to be achieved at various abstractions of the CPES design and therefore design automation algorithms should be used for synthesizing between differing abstraction levels of greater or lesser complexity before final deployment in the real implementation. In 4, one of the research challenges of automating the simulation model from a higher abstraction level is shown. To solve the complexity of developing an optimal grid at different scales, a system level design methodology, *Model-Based Design* (MBD) has been demonstrated in recent publications [1, 6, 10]. Of critical importance is the fact that MBD allows modeling of the physical and cyber components concurrently. Moreover, it allows cyber-physical co-simulation to explore for various design alternatives required for designing, validating, and testing in an economical and effective way. The author of this position paper has recently developed a MBD methodology for a residential microgrid which is an example of a CPES. Moreover, in [3] the author has presented a MATLAB/Simulink toolbox (GridMat) where

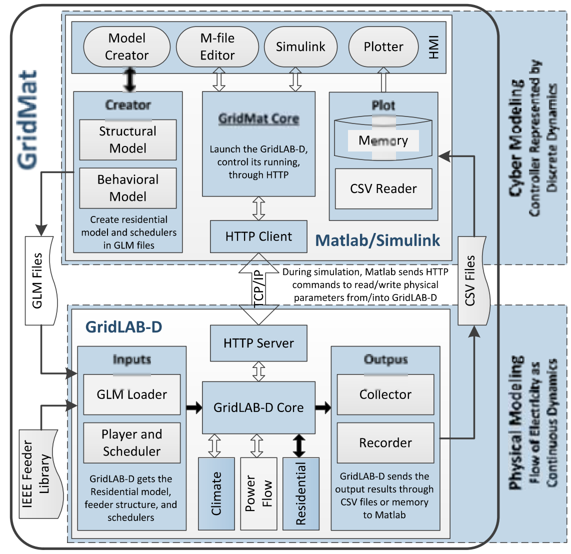

Figure 1: An example of a cyber-physical co-simulation platform: GridMat for residential microgrid modeling, simulation, debugging, and validation

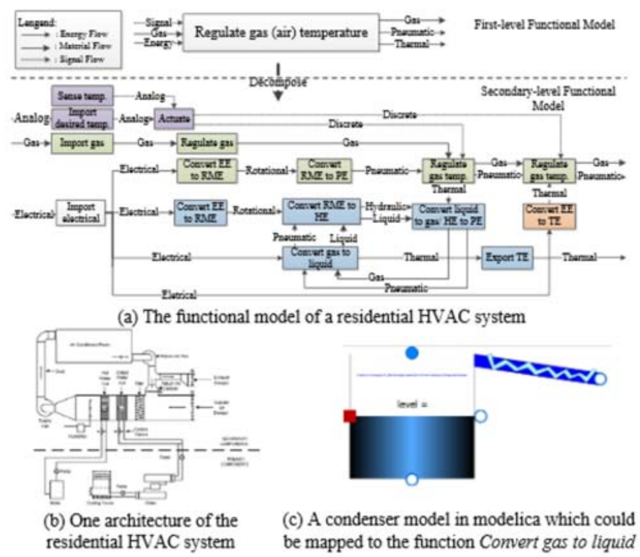

Figure 2: An example of high-level synthesis of a building energy management CPES from its Functional model

structural and behavioral aspects of a residential microgrid are modeled using GridLAB-D through the *Graphical User Interface* (GUI) of the GridMat tool and various control algorithms may be modeled using the graphical language of the Simulink. Moreover, using this GridMat tool, the developed cyber-physical model may be simulated, debugged, and analyzed (see Figure 1). More details about this method and tool may be found in [3].

4 High-Level Synthesis

Both the modeling at higher abstraction layers and the simulation at various levels of abstractions for early design space exploration have been the key to success of ESL methods for semiconductors. As mentioned earlier, similar methods, algorithms, and tools are now required to develop CPES in an economic and efficient way. Today, tools like Matlab/Simulink, which are typically developed for *Model-In-the-Loop-Simulations* (MILS) which in turn is a methodology for designing control algorithms, partially supports design automation algorithms that automatically convert the control algorithm into various higher level programming languages (e.g. C, IEC 61131-3, etc.). This automation is due to the embedded code generator built-into these tools and it supports a high fidelity *Hardware-In-Loop-Simulation* (HILS) for CPES. However, the capability of such automation algorithms are very limited. Active research is required to develop new algorithms (also may be new intermediate languages) for such synthesis mechanisms.

The author of this paper is currently working on abstracting a CPS specification in a higher abstraction level where both cyber and physical components may be described simultaneously without going into great detail. In [2] the author has presented how a CPS system may be abstracted using Functional Basis language.

Functional models describe *what the system does* in terms of basic physical properties: energy, material, and signal transformations are some examples. The Functional Basis language [5] is a high-level language that integrates natural language elements to facilitate the inter-disciplinary communication of engineering problems; it has been in use in the mechanical engineering community but so far has remained unexploited by the CPES community.

Energy systems engineers who are developing various solutions (for example HVAC systems for a commercial entity) typically rely on informal functional models that use an inconsistent vocabulary (verbs and nouns) to describe power system functions. However, current practice is even worse, most of the time engineers just use manual processes and prior knowledge and do not use any sort of evaluation for optimizing the operations (e.g. HVAC architecture) based on the installation facility and other constraints. Accomplishing such a solution will require an early design space exploration tool and capability. Therefore, in this paper, the author advocates that such a solution may be achieved using Functional modeling. Informal description of functions by the engineers will not be appropriate as informal functions like maintain the server room temperature to 60□F, it is very expressive for humans but it is difficult for computers to parse. For this reason, the Functional Basis language provides a good compromise between expressiveness for humans and ease of processing for compilers.

Figure 2 (a) is an example of using functional modeling to describe the functionality of a HVAC system. The first-level of the functional model shows the main function of the HVAC system. It will regulate the air temperature based on the given control signal. However, the first-level of the functional model is too abstract that it would be extremely hard for a tool to synthesis it. Thus a second-level of the functional model which comes from the decomposition of the first-level needs to be introduced in this example. In the second-level of the functional model of this example, there are four major flows. The main flow is the flow of the air (shown in green blocks) which is our target material. The flow of coolant (shown in blue) will help to absorb the thermal energy from the main flow and export it out of the system. The heating flow (shown in red) will use electricity to generate thermal energy and help the main flow to regulate the temperature of air. The fourth flow (shown in purple) is the control flow which will guide the regulation process. Moreover, an HVAC architecture that may be used for implementing such function is shown in Figure 2 (b). In Figure 2 (c), we show the Modelica simulation model. Synthesis from one abstraction level to another abstraction level of such a CPES is possible through an EDA tool, though research into this topic is required to establish the appropriate science and build the tools for such high level synthesis.

5 Conclusion

This paper strongly advocates further need of research for EDA for CPES. Moreover, some current research activities by the author in the domain of EDA for CPES and various future research challenges that need to be solved are presented here. The author of this paper is going to organize a special session at the 19th Asia and South Pacific Design Automation Conference (ASP-DAC'2014) in Singapore January 20-23 together with IBM and other academic experts on the topic of "EDA for Energy". The purpose of this special session is to identify the possibility of using existing EDA algorithms and to find and understand the existing gap in energy network design in order to develop new EDA algorithms, methods, and tool for CPES as it is a highly distributed, real-time, heterogeneous, multi-domain, multi-physics, and complex system.

References

[1] W. Bernal, M. Behl, T. Nghiem, and R. Mangharam. "MLE+: a tool for integrated design and deployment of energy efficient building controls". *SIGBED Rev.*, 10(2):34–34, July 2013.

[2] A. Canedo, E. Schwarzenbach, and M. A. A. Faruque. "Context-sensitive Synthesis of Executable Functional Models of Cyber-Physical Systems". *in ACM/IEEE 4th Internationl Conference on Cyber-Physical Systems (ICCPS'13)*, pages 99–108, 2013.

[3] M. A. A. Faruque and F. Ahourai. "A Model-based Design of Cyber-Physical Energy Systems". *IEEE/ACM 19th Asia and South Pacific Design Automation Conference (ASP-DAC'14)*, 2014.

[4] H. Gill. "Cyber-Physical Systems:Beyond ES, SNs, SCADA". *Trusted Computing in Embedded Systems (TCES'10) Workshop*, 2010.

[5] J. Hirtz, R. B. Stone, S. Szykman, D. A. McAdams, and K. L. Wood. "A functional basis for engineering design: Reconciling and evolving previous efforts". *Technical report, NIST*, 2002.

[6] J. Jensen, D. Chang, and E. Lee. "A model-based design methodology for cyber-physical systems". In *Wireless Communications and Mobile Computing Conference (IWCMC)*, pages 1666–1671, 2011.

[7] S. Karnouskos. "Cyber-Physical Systems in the SmartGrid". In *IEEE International Conference on Industrial Informatics (INDIN)*, pages 20–23, 2011.

[8] T. Morris, A. K. Srivastava, B. Reaves, K. Pavurapu, S. Abdelwahed, R. Vaughn, W. McGrew, and Y. Dandass. "Engineering future cyber-physical energy systems: Challenges, research needs, and roadmap". In *North American Power Symposium (NAPS)*, pages 1–6, 2009.

[9] S. Nassif, G. Nam, J. Hayes, and S. Fakhouri. "Applying VLSI EDA to Energy Distribution System Design". *IEEE/ACM 19th Asia and South Pacific Design Automation Conference (ASP-DAC'14)*, 2014.

[10] G. Simko, T. Levendovszky, M. Maroti, and J. Sztipanovitz. "Towards a Theory for Cyber-Physical Systems Modeling". *Third Workshop on Design, Modeling and Evaluation of Cyber Physical Systems (CyPhy'13)*, 2013.