Toward a Unified Modeling and Control for Sustainable and Resilient Electric Energy Systems

Marija D. Ilić
Carnegie Mellon University
United States
milic@andrew.cmu.edu

the essence of knowledge
Boston — Delft

Foundations and Trends® in Electric Energy Systems

Published, sold and distributed by:
now Publishers Inc.
PO Box 1024
Hanover, MA 02339
United States
Tel. +1-781-985-4510
www.nowpublishers.com
sales@nowpublishers.com

Outside North America:
now Publishers Inc.
PO Box 179
2600 AD Delft
The Netherlands
Tel. +31-6-51115274

The preferred citation for this publication is

Marija D. Ilić. *Toward a Unified Modeling and Control for Sustainable and Resilient Electric Energy Systems*. Foundations and Trends® in Electric Energy Systems, vol. 1, no. 1, pp. 1–141, 2016.

This Foundations and Trends® issue was typeset in LaTeX using a class file designed by Neal Parikh. Printed on acid-free paper.

ISBN: 978-1-68083-227-3

Foundations and Trends® in Electric Energy Systems

Volume 1, Issue 1, 2016

Editorial Board

Editorial Scope

Topics

Foundations and Trends® in Electric Energy Systems publishes survey and tutorial articles on the following topics::

- Advances in power dispatch
- Demand-side and grid scale data analytics
- Design and optimization of electric services
- Distributed control and optimization of distribution networks
- Distributed sensing for the grid
- Distribution systems
- Fault location and service restoration
- Integration of physics-based and data-driven modeling of future electric energy systems
- Integration of Power electronics, Networked FACTS
- Integration of renewable energy sources
- Interdependence of power system operations and planning and the electricity markets
- Microgrids: design, optimization, and stability
- Modern grid architecture
- Power system analysis and computing
- Power system dynamics
- Power system operation
- Power system planning
- Power system reliability
- Power system transients
- Security and privacy
- Stability and control for the whole multi-layer (granulated) network with new load models (to include storage, DR, EVs) and new generation
- System protection and control
- The new stability guidelines and control structures for supporting high penetration of renewables
- Uncertainty quantification for the grid
- System impacts of HVDC

Information for Librarians

Foundations and Trends® in Electric Energy Systems, 2016, Volume 1, 4 issues. ISSN paper version 2332-6557. ISSN online version 2332-6565. Also available as a combined paper and online subscription.

Foundations and Trends® in Electric Energy Systems
Vol. 1, No. 1 (2016) 1–141

DOI: 10.1561/3100000002

now
the essence of knowledge

Toward a Unified Modeling and Control for Sustainable and Resilient Electric Energy Systems

Marija D. Ilić
Carnegie Mellon University
United States
milic@andrew.cmu.edu

Contents

Abstract

In this paper cyber role in social-ecological energy systems (SEES) is formalized by using the language of large-scale dynamical systems. The key notion of interaction variables is introduced in support of their modeling as multi-layered dynamical systems. It is stressed that qualitatively different cyber designs are required for enabling performance of qualitatively different SEES architectures. In particular, it is proposed that composite control-based hierarchical control lends itself more naturally to supporting large-scale regulated monopolies, and that distributed multi-layered control with or without coordination is key to supporting SEES architectures comprising many decision makers. Today's hierarchical control is described as a particular case of hierarchical composite control. Having these formulations may help bridge R&D efforts across vastly multi-disciplinary communities working in the field of changing electric energy systems.

Marija D. Ilić. *Toward a Unified Modeling and Control for Sustainable and Resilient Electric Energy Systems*. Foundations and Trends® in Electric Energy Systems, vol. 1, no. 1, pp. 1–141, 2016.
DOI: 10.1561/3100000002.

1

Introduction

The electric power industry is reaching a tipping point at which technological, organizational and societal changes are extremely hard to reconcile. Different views are taken by different communities and the taxonomies used are hard to relate. Much progress is being made but the integration of piece-meal solutions at well-understood value remains quite elusive. This is not accidental nor intentional. The fundamental challenge to systematic integration in these rapidly changing systems calls for recognizing that the problem of interest is a classical wicked problem (Ostrom, 2009; Rittel and Webber, 1973; Camillus, 2008). Wicked problems have been subject of work by many leading institutional economists and business experts. I have convinced myself that it is worthwhile to think about innovation in electric energy systems while keeping in mind the gravity of the challenge captured as follows:

> "By now we are beginning to realize that one of the most intractable problems is the problem of defining the problem and of locating the problem." (Rittel and Webber, 1973)

> "There are no optimal solutions for wicked problems. There are only "satisficing" solutions–you stop when you have a solution that is "good enough"." (Simon, 1969)

Given these disclaimers, our paper attempts a more narrow task of establishing a modeling framework which could help pose the problem of providing future electric energy services more systematically so that it lends itself to innovation at value. This can only be done in systems whose initial complexity is truly overwhelming by establishing a relatively simple approach which is based on concepts common across different communities. Thanks to my affiliation with some of the friends outside my own community (Marrian Jelinek, Rolf Kunekke and John Groenewegen), I stumbled across thinking by Elinor Ostrom and many in her field. The following quote states the basic idea that has given me the encouragement to begin to relate what we do in engineering and the view by these industry economists.

> "Considerable theoretical and empirical research suggests that adaptive management of social-ecological systems requires networks that combine dense local informational flows with effective connections across groups and scales to foster the combination of local knowledge, cross-scale coordination, and social learning." (Ostrom, 2009)

This view taught me that in order to begin to relate our engineering innovations to the solutions needed by the society, we should perhaps begin to think about our physical engineering systems as multi-layered dynamical systems comprising intra- and inter-layers of very diverse components with local functional sub-objectives, and their dynamic interactions. This idea became a turning point for me as the connections with my own domain-specific systems-based research begun to emerge. My work with associates, notably my graduate students, over many years took another dimension in my mind. I concluded that if we rethink the engineering side of evolving electric power systems, including electricity markets, it quickly becomes clear that one must align functional objectives and technological solutions within a given governance environment. However, for this to be systematic, currently used physical models in electric power systems engineering must be transformed into models which are multi-layered themselves so that the functional objectives and technological solutions are aligned. After many years of thinking about this, and discussing it with my affiliates, I decided to formalize this unifying view in this paper as a possible framework for moving forward. The basic idea is to think of these multi-layered complex systems in terms of dynamical interactions between components belonging to layers, and in terms of dynamical interactions between the layers. The novel modeling proposed is a transformed state space for representing complex dynamics as a combination of internal dynamics specific to subsystems within the system layers and the interaction variables capturing the inter-dependencies between the subsystems. It turns out that the notion of interactions is well understood across disciplines by the engineers, economists and economists. The use of interaction variables makes it possible to innovate without being a true expert in every single aspect of the problem. I decided that we can at least begin to communicate to folks outside our own communities. What I have learned and would like to share in this paper with the broader community is that different communities already use notions of interaction variables, directly or indirectly. For power engineers they are stored energy and power exchanged with others; for economists these are prices associated with the same engineering variables; and for institutional economists, notably for Elinor Ostrom, they are means of qualitatively assessing how sustainable social-ecological systems will be. Notably, even more recent disciplines of social networks could have interpretation of their methods using interaction variables, as we discuss toward the end of our paper (Acemoglu et al., 2011, 2014). At the end, this paper became the first attempt to relate these multiple uses of interaction variables for solving wicked multi-disciplinary problems in the emerging electric energy systems.

1.1 The key role of cyber in enabling performance of SEES

Electric energy systems must become more digitized. The time has come for this to happen as the industry is beginning to use on-line data more proactively than in the past (Bennett and Highfill, 2008). The field of network cyber-physical systems (Net-CPS) is quickly emerging (Sztipanovits et al., 2012; Yang et al., 2013). However, here again, one must fully understand the role of cyber and the ways to embed it into physical system at value. Shown in Figure 1.1 is a sketch showing inter-dependencies between the functional objectives of an SEES, and its physical grid design and its cyber. In today's electric power systems integration of new resources and users does not systematically assess the role of CPS. However, by now there is sufficient evidence in particular sub-problems that it is possible to offset extensive investments in grid infrastructures by relying on data-driven decisions. It is also possible to enhance performance of the existing system by embedding right cyber. Keeping this evidence in mind and major moves toward "smart" grids, we must proceed with caution here as well. It is easy to run into different type of complexity when over-relying on cyber unless one fully understands the purpose of sensing, communications and control deployed. The following challenge was recently presented to the academic community in this context:

> "The systems most fitted for a purpose are those where the number of bits transferred between subsystems in achieving that purpose is minimised." David Hirst, consultant UK, August 2016.

This is, as I understand it, a pledge on behalf of many practitioners in the industry for avoiding cyber design complexity. The concern is well taken and one way forward is to have models and functional objectives defined keeping in mind multi-layered structure of an SEES for which cyber is being designed. As the first step, one must rethink electric power systems using well-understood taxonomies of dynamical systems and control. This paper is truly motivated by this need for modeling emerging electric energy systems as complex dynamical systems whose structure helps design effective cyber. Major part of the paper is devoted to rethinking models and their structures, and underlying assumptions in support of manageable analysis and cyber design.

Once this is done, we tackle the hidden theoretical problems created by non-convexity and non-linearities of models used. We propose the concept of "inner convexification" when designing cyber for provable performance in otherwise highly non-convex cyber design complex network problem (Caliskan and Tabuada, 2014; Ortega et al., 2013; Robinett and Wilson, 2010). Going back to the transformed state space, the inner convexification problem becomes the problem of designing local controllers so that specifications on interaction variables are met (Baros and Ilić, 2014; Ilić, 2011). Moreover, instead of asking for excessive control in each component the performance specifications are set for groups of collaborating components; we

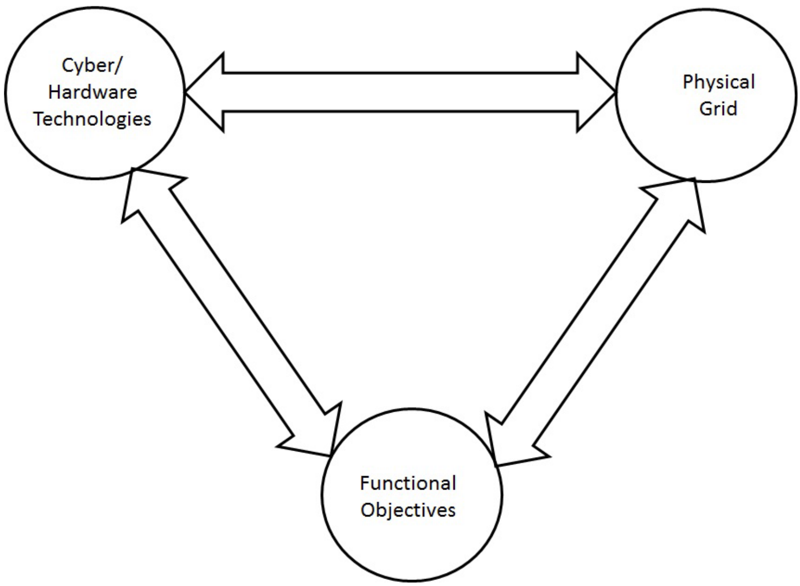

Figure 1.1: SEES inter-dependencies with cyber and physical grid design.

refer to these as the for intelligent Balancing Authorities (iBAs). The coordination problem becomes more straightforward, but the burden is on designing "smart" sensors and controllers at the iBA levels. We point out a long-standing open problem of directly controlling power generated/consumed by the local controllers which is key to implementing cyber for provable performance in electric energy systems. We suggest that major recent progress in theoretical nonlinear control design lends itself well to solving this major domain application problem (Caliskan and Tabuada, 2014; Ortega et al., 2013; van der Schaft and Jeltsema, 2014; Robinett and Wilson, 2011). Potential of utilizing this recent work in general dynamical systems for purposes of designing provable control for complex electric energy systems of an arbitrary architecture is discussed.

We contrast this idea of inner convexification with the efforts for convexifying system-level coordination problems presented by the nonlinearities of iBAs and components themselves (Low, 2014; Lavaei and Low, 2012).

An outstanding research problem concerns trade off between these two approaches. Here, again, no single solution fits all. Hotly debated issues about distributed vs. centralized control are briefly discussed and illustrated in this light. To return to David Hirst's quote above, one could transfer minimum bits (in other words make it almost fully distributed, along the lines of homeostatic control envisioned long ago by Fred Schweppe) (Schweppe et al., 1980), but this should not be a prescription for all SEES. Outer convexification ideas for coordinating power scheduling of otherwise nonlinear dynamic iBAs may lend itself better to some architectures and not to others. Herb Simon's quote on the impracticality of seeking perfect solution must be taken quite seriously as well.

At the end, our modeling framework helps design next generation physical grids and SCADA as a means of making electric energy systems sustainable and resilient. Based on modeling used, it is clear that SCADA must be enhanced to attempt specifications for desired solutions, including long overdue use of information from the system users themselves and not just from the system coordinators. This has led us to proposing Dynamic Monitoring and Decision Systems (DyMonDS) framework in support of this multi-directional multi-layered information exchange for next generation SCADA (Ilić, 2011). Notably, the same modeling framework can be used for designing man-made physical grids and their cyber for qualitatively different social-ecological energy systems (SEES). The new field of cyber-physical systems could fall real short unless one understands the objectives of cyber design given the physical structures to the level of detail needed but no more. We explain how the proposed unified modeling helps with this.

1.2 Major observations

Our proposed modeling and design principles needed to support sustainable and resilient electric energy services in the future in an environment where everything seems to be a moving target are a natural outgrowth of today's hierarchical control (Ilić and Liu, 2012; Ilić and Zaborszky, 2000). We have found it tremendously intriguing in our own research to go from this mathematical modeling approach and identify often hidden and implied assumptions made in today's operations. Once we know how to do this systematically, we can evolve technological solutions (physical and cyber) which gradually relax these assumptions where the value is the highest. To paraphrase former CEO of PJM, Terrence Boston, there is no way we can restart software solutions in today's energy management systems because the investments and best industry practices have been very costly; estimated cost of software related efforts in has been of the order of $ 800 M so far. The challenge is how to build on what already exists in the man-made side of electric energy systems. This paper wrote is about this challenge, and it is work in progress. I describe open problems whenever possible throughout the paper. Perhaps the most intellectually intriguing open area to me is further work on the relations of the proposed transformed state space and bond graph theory (Borutzky, 2010), nonlinear control design to shape systems into Hamiltonian closed-loop systems (Robinett and Wilson, 2011; Ortega et al., 2013; García-Canseco et al., 2010). While the relations in small two-component systems are straightforward to illustrate, scalability in bond graph representations has not been studied. Many open questions remain considering physical realizations of nonlinear controllers which meet specifications in bond graphs. Further formalization of the proposed transformed state space as bond graph version of multi-layering for large dynamical systems would be interesting and important. If this is understood, the indirect links with Dirac structures and more formal computer science languages becomes possible (Duindam et al., 2009). While these theoretical formalizations are beyond the objectives of our paper, we do illustrate the use of transformed state space for scalable modeling, control and simulations in the domain application of electric energy systems. The simulation platform for our Smart Grid in a Room Simulator (SGRS) utilizes the proposed modeling framework and can be used by the broader community to demonstrate concepts described in this paper (Wagner et al., 2015).

1.3 Paper organization

It has been broadly recognized that there exist tremendous challenges and opportunities on the way to modernizing operations of electric power systems. Changes are necessary to enable integration of many new technologies into existing electric power grids, as well as for better on-line utilization of the existing system. Today's industry practice does not readily lend itself to sustainable and resilient integration of new technologies. It also falls short of relying on data-driven utilization of the existing system according to well-defined operating protocols. In particular, connecting new equipment whose effects are not well-understood by the power system operators is not straightforward. Much innovation in on-line sensing, monitoring, predicting, decision making and automation methods is required for this to become possible. Perhaps the biggest challenge is the problem of abstracting the cyber design problems to the level necessary so that effective methods can be embedded with a clear understanding of their role within this very complex dynamical system. While much progress has been made in designing new hardware technologies their integration represents major challenge and roadblock. Also, recent progress has been made in proposing problem-specific and technology-specific control and optimization methods. Understanding the role of these solutions at value within an end-to-end energy system is the major remaining challenge.

The intent of this paper is to introduce technology-agnostic unified modeling foundations and to illustrate their use toward end-to-end cyber design for provable performance of complex electric energy systems. We start in Chapter 2 by recognizing that it would be real short-sighted to think of cyber design for the emerging electric energy system as a solely technical problem. Instead, we take a broader look at the objectives of deploying cyber into these physical systems in light of viewing them as general social-ecological systems (SES). We highlight that in the approach taken by Elinor Ostrom key metrics for assessing sustainability of any SES concern interactions between different system members. A basic sketch of a SES is used to illustrate how governance and regulatory/organizational rules set the stage for defining feasible cyber architectures. The new institutional (governance) design problem becomes the choice of different institutional designs which will have qualitatively different impacts. Options include: (a) Fully regulated monopolies and centralized planning and operations; (b) Complete, carefully designed markets; (c) Common set of interface standards and protocols; and, (d) Common regulator (Federal) level and/or lose cooperation of distributed State and Sub-State regulators. We suggest that cyber design for these vastly different institutional architectures should be based on common principles. However, the resulting cyber solutions are different, as described in the paper.

Next, we describe the electric power grid architectures which are rapidly transforming as renewable resources are being connected closer to the end users supported by organizational and technological drivers. In Chapter 3 we summarize these technological, societal and organizational changes. In Chapter 4 we describe the implications of these changes on the emerging architectures. In Section 4.4 general Dynamic Monitoring and Decision Systems (DyMonDS) framework is introduced for abstracting the basic cyber design problem which needs to be solved when adding "smarts" into the physical electric power grid. This framework is effectively a next generation Supervisory Control and Data Acquisition (SCADA) system enabled by advanced on-line sensing, monitoring, communication, decision-making and automation for the changing electric energy systems. It is explained why designing SCADA architecture for non-standardized physical system architectures represents a major challenge. This problem is made even harder by the fact that today's state-of-the-art modeling of electric power system dynamics has evolved under many strong assumptions many of which no longer hold, as described later in this paper. In Section 4.5 we tackle the key question regarding the information exchange needed to design DyMonDS and next generation SCADA so that provable performance becomes possible. We point out that a framework is needed for setting functional specifications across all industry layers to enable orderly industry unbundling. To arrive at such information exchange basis, we ask a long-overdue question regarding the existence of possible unified modeling approach for electric power systems which lends itself to a multi-layered representation of a complex dynamical system comprising different groups of components with their own performance goals interacting with other groups of components. We arrive at this answer in several steps.

First, in Chapter 5 we describe how each physical component can be represented as a dynamic component using standard state space formulation. The interconnection of dynamical components is modeled keeping in mind the ultimate need of viewing the problem as a multi-layered dynamic problem. This implies that when modeling the interconnected system a differentiation between internal states and port variables can be made which makes the structure of physical dynamics quite clear. The most powerful modeling and simulation approaches of multi-physics systems, such as Modelica and Dymola (Fritzson, 2010; Zauner et al., 2007), are fundamentally based on this approach. We briefly summarize a recently proposed approach to automated modeling specific to electric power systems (Bachovchin and Ilić, 2015). This is quite important for the purposes of lifting the very modeling of technology-specific and purpose-specific power grids to the process of automated, even symbolic, modeling. We observe that, no matter which way one arrives at these physical models, the port variables on the boundaries of components are modeled in the voltage-current ($v - i$) space because of the requirement that the interconnected components obey two basic Kirchhoff voltage and current laws. Appendix A.1 provides example state-space models of a few representative electric power system components. We use without loss of generality a small microgrid system to illustrate the inherent structure of models in standard state space form for the interconnected electric power systems. We point out that it is this structure which sets the basis for distributed control in these systems.

Second, in Chapter 6 we make the case for introducing a transformed state space modeling in order to enable multi-granular representation of very complex large-scale electric energy systems. The basic idea is the one of modeling interactions between components within a subsystem, or interactions between sub-systems within a large interconnecting system in terms of their net effects, instead of by representing each component in full detail. We propose that each module (stand-alone component, balancing authority (BA), intelligent Balancing Authority (iBA)) can be modeled as a combination of its internal states and the interaction variable which represents net stored incremental energy of the component and its rate of exchange (power) with the rest of the system. We derive models of stand-alone modules, and models of dynamical interactions of modules within an interconnected layer. Existence of such interaction variable is a result of most general conservation of power law, and, as such, it is applicable to any type of system modules (Penfield et al., 1970). Illustrations of models for representative electric power system components in this transformed state space are provided in Appendix A.7. While in this section a transformed state space is introduced for reasons of managing complexity brought about by the sheer complexity of very large number of diverse components, it is pointed out that this model helps understand causes and effects in terms of power production, delivery and consumption in its most natural way. This is done without having to understand the specifics of technologies embedded within the modules.

Third, in Chapter 7 we move on to defining general functional objectives of a complex electric energy system as a complex dynamic optimization problem. The performance objective (cost) of this optimization is expressed in terms of interaction variables and control. The equality constraints are complex dynamical models representing natural response of physical system. The inequality constraints are output variables associated with all components, which are needed to both account for safety constraints and for quality of service (QoS) required. Finally, the optimization is subject to physical control limits. To start with, this formulation is a benchmark optimal control formulation and, as such, it does not have pre-defined references for tracking output and interaction variables of interest. These are result of optimization. We also point out that it is generally necessary to differentiate between interaction variables and output variables associated with specific modules. If this is not done, many hidden assumptions in today's industry practices cannot be identified.

Next, in Chapter 8 we explain why the general benchmark optimal control problem is highly impractical to implement. Instead, a composite control based on temporal separation of disturbances driving power system dynamics is formalized as the basis for hierarchical control design at provable performance. Sub-objectives of primary, secondary and tertiary controllers are posed as separable optimization objectives which are integrated using systematic information exchange between these layers. Key observations are provided with regard to conditions under which such composite control would have provable performance. One of the key requirements concerns the ability of primary controllers to stabilize relevant output variables to their reference values given at the slower rate by the higher layer controllers. In Section 8.6 we review current state-of-the-art for primary control in electric energy systems and highlight typical assumptions made. Appendices A.10 and A.11 describe closed-loop modeling of representative power system components and point out the assumptions made. Notably, it becomes possible to design primary controllers capable of meeting specifications in terms of interaction variables using state-of-the-art energy-based nonlinear control design (Ilić, 2017). In Chapter 9 today's hierarchical control for a bulk power system (BPS) is summarized and explicit assumptions typically made are highlighted. These assumptions are no longer valid in some new SEES architectures, such as microgrids (Ilić, 2017).

The remaining material in this paper represents a qualitatively different approach to supporting evolution and operations of the emerging electric energy systems. In Chapter 10 a multi-layered distributed control with minimal coordination is proposed. This approach is not critically dependent on temporal separation of primary, secondary and tertiary controller sub-objectives required for composite control-based hierarchical control. Instead, distributed optimization is embedded into modules of the complex system and distributed model-predictive control (MPC) is carried out to create specifications regarding sensitivities of cost functions with respect to their own interaction variables. This information is provided to the iBAs responsible for meeting performance of components cooperating under the same iBA. At higher layers iBAs interact either multi-laterally or with the higher-layer iBAs within a general architecture shown in Figure 1.2. General underlying principles are stated for such distributed control to meet technical performance specifications. The problem effectively becomes the one of plug-and-play approach to complex systems (Doyle and Carlson, 2002). In Chapter 10 a general multi-layered decision making problem formulation using the proposed transformed state space is stated. It is claimed that in any given particular architecture dual variables associated with the dynamic constraints on physical interaction variables form sufficient information exchange basis. They are sensitivities of cost functions used by any iBA within the given architecture with respect to physical interaction variables. As such, they provide economic incentives which reflect the value of interaction variable between any iBA and the rest of the system. Once this is understood it becomes straightforward to define what must be exchanged in electricity markets, and one can interpret distributed bidding and market clearing using the higher-level interaction models only. In this sense electricity markets could and should become technology-agnostic. Using this approach it becomes possible to design protocols/standards for

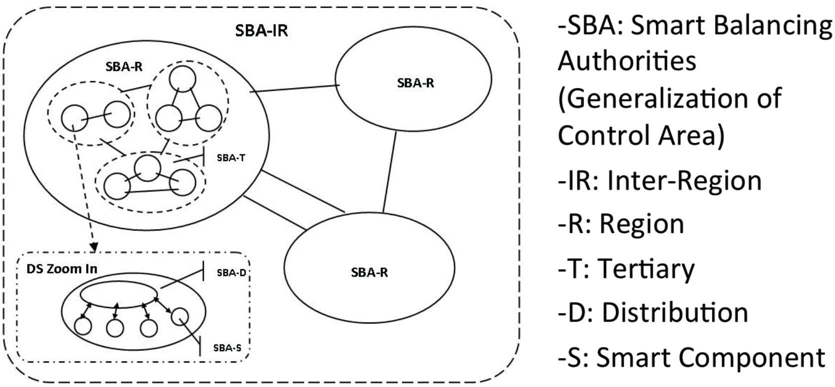

Figure 1.2: Nested hierarchies in the emerging electric energy systems.

cyber design to enable robust/resilient system operation over broad ranges of operating conditions and equipment status. These standards and protocols define information that should be exchanged in the next generation SCADA for the electricity services to be provided at value. The proposed unified multi-layered modeling has been used to design a computer platform for scalable simulation of smart grids named Smart Grid in a Room Simulator (SGRS) (Wagner et al., 2015). As such it sets the basis for simulating electricity markets, and their effects on physical system response.

In the closing Chapter 11 it is concluded that the proposed transformed state space provides a necessary level of abstraction for posing cyber design in future electric energy systems by accounting for their physical, economic and social governance objectives in a systematic manner. Notably, we illustrate how such modeling opens the opportunities for systematic cyber design with well understood rationale for the type and rate of information exchange required between modules within a multi-layered dynamical system. Several key open questions and next steps are suggested.

References

Daron Acemoglu, Munther A. Dahleh, Ilan Lobel, and Asuman Ozdaglar. Bayesian learning in social networks. *The Review of Economic Studies*, 78(4):1201–1236, 2011.

Daron Acemoglu, Kostas Bimpikis, and Asuman Ozdaglar. Dynamics of information exchange in endogenous social networks. *Theoretical Economics*, 9(1):41–97, 2014.

John Adams, Cathey Carter, and Shun-Hsien Huang. Ercot experience with subsynchronous control interaction and proposed remediation. In *IEEE PES Transmission and Distribution Conference and Exposition (T&D)*, pages 1–5. IEEE, 2012.

Muhamed Aganagic and Sasan Mokhtari. Security constrained economic dispatch using nonlinear dantzig-wolfe decomposition. *IEEE Transactions on Power Systems*, 12(1):105–112, 1997.

Eric Allen, Niels LaWhite, Yong Yoon, Jeffrey Chapman, and Marija D. Ilić. Interactive object-oriented simulation of interconnected power systems using simulink. *IEEE Transactions on Education*, 44(1):87–94, 2001.

Eric H. Allen, Jeff W. Chapman, and Marija D. Ilić. Effects of torsional dynamics on nonlinear generator control. *IEEE Transactions on Control Systems Technology*, 4(2):125–140, 1996.

Paul M. Anderson, Bajarang L. Agrawal, and James E. Van Ness. *Subsynchronous Resonance in Power Systems*, volume 9. John Wiley & Sons, 1999.

Anuradha M. Annaswamy and Massoud Amin. *IEEE Vision for Smart Grid Controls: 2030 and Beyond*. IEEE Press. 2013.

M. Araki. Stability of large-scale nonlinear systems–quadratic-order theory of composite-system method using m-matrices. *IEEE Transactions on Automatic Control*, 23(2):129–142, 1978.

Kevin D. Bachovchin and Marija D. Ilić. "Automated Computer-Aided Symbolic Derivation of Passivity-Based Control Law for Electrical Systems and Demonstration on Three-Phase AC/DC/AC Converter," EESG Working Paper No. R-WP-5-2014, 2014.

Kevin D. Bachovchin and Marija D. Ilić. Automated modeling of power system dynamics using the Lagrangian formulation. *International Transactions on Electrical Energy Systems*, 25(10):2087–2108, 2015.

Miao X., Jaddivada R., Ilić. M. and Bachovchin, K. *Dynamic Modeling and Primary Control of Components in Electric Energy Systems*. Cambridge University Press UK, 2017.

Stefanos Baros and Marija D. Ilić. Intelligent balancing authorities (IBAS) for transient stabilization of large power systems. In *IEEE PES General Meeting/Conference & Exposition*, pages 1–5. IEEE, 2014.

Stefanos Baros and Marija D. Ilić. Robust ectropy-based cooperative control of a wind DFIG for transient stabilization and MPPT. In *IEEE Power & Energy Society General Meeting*, pages 1–5. IEEE, 2015.

Alberto Bemporad and Manfred Morari. Robust model predictive control: A survey. In *Robustness in Identification and Control*, pages 207–226. Springer, 1999.

Coalton Bennett and Darren Highfill. Networking AMI smart meters. In *IEEE Energy 2030 Conference*, pages 1–8. IEEE, 2008.

Daniel Bienstock and Abhinav Verma. The NK problem in power grids: New models, formulations, and numerical experiments. *SIAM Journal on Optimization*, 20 (5):2352–2380, 2010.

Pandelis N. Biskas, Anastasios G. Bakirtzis, Nikos I. Macheras, and Nikolaos K. Pasialis. A decentralized implementation of DC optimal power flow on a network of computers. *IEEE Transactions on Power Systems*, 20(1):25–33, 2005.

Frede Blaabjerg, Remus Teodorescu, Marco Liserre, and Adrian V. Timbus. Overview of control and grid synchronization for distributed power generation systems. *IEEE Transactions on Industrial Electronics*, 53(5):1398–1409, 2006.

Radu Bojoi, Mario Lazzari, Francesco Profumo, and Alberto Tenconi. Digital field-oriented control for dual three-phase induction motor drives. *IEEE Transactions on Industry Applications*, 39(3):752–760, 2003.

Sina Yamac Caliskan and Paulo Tabuada. Compositional transient stability analysis of multimachine power networks. *IEEE Transactions on Control of Network Systems*, 1(1):4–14, 2014.

John C. Camillus. Strategy as a wicked porblem. *Harvard Business Review*, May 1, 2008.

Pedro M. S. Carvalho, Luís A. F. M. Ferreira, João C. Botas, Marija D. Ilić, Xia Miao, and Kevin D. Bachovchin. Ultimate limits to the fully decentralized power inverter control in distribution grids. In *Power Systems Computation Conference*, pages 1–7. 2016.

Anya Castillo, Xinyi Jiang, and Dennice F. Gayme. Lossy DCOPF for optimizing congested grids with renewable energy and storage. In *American Control Conference*, pages 4342–4347. IEEE, 2014.

Laijun Chen and Shengwei Mei. An integrated control and protection system for photovoltaic microgrids. *CSEE Journal of Power and Energy Systems*, 1(1):36–42, 2015.

Joe H. Chow, Felix F. Wu, and James A. Momoh. Applied mathematics for restructured electric power systems. In *Applied Mathematics for Restructured Electric Power Systems*, pages 1–9. Springer, 2005.

Charles Concordia. *Synchronous Machines: Theory and Performance*. Wiley, 1951.

Javier Contreras and Felix F. Wu. Coalition formation in transmission expansion planning. *IEEE Transactions on Power Systems*, 14(3):1144–1152, 1999.

Miloš Cvetković and Marija D. Ilić. Nonlinear control for stabilizing power systems during major disturbances. *IFAC Proceedings Volumes*, 44(1):9561–9566, 2011.

Miloš Cvetković and Marija D. Ilić. Ectropy-based nonlinear control of facts for transient stabilization. *IEEE Transactions on Power Systems*, 29(6):3012–3020, 2014.

E. J. Davison. Connectability and structural controllability of composite systems. *Automatica*, 13(2):109–123, 1977.

John Doyle and J. M. Carlson. Complexity and robustness. *Proceedings of the National Academy of Sciences*, 99:2538–2545, 2002.

Vincent Duindam, Alessandro Macchelli, Stefano Stramigioli, and Herman Bruyninckx. *Modeling and Control of Complex Physical Systems: The Port-Hamiltonian Approach*. Springer Science & Business Media, 2009.

D. Brian Eidson and Marija D. Ilić. Advanced generation control with economic dispatch. In *Proceedings of the 34th IEEE Conference on Decision and Control*, volume 4, pages 3450–3458. IEEE, 1995.

Abdallah Farraj, Eman Hammad, and Deepa Kundur. A systematic approach to delay-adaptive control design for smart grids. In *IEEE International Conference on Smart Grid Communications*, pages 768–773. IEEE, 2015.

Martin Fornage, Mudhafar Hassan-Ali, and Tibor Bolfan. Method and apparatus for anti-islanding of distributed power generation systems, March 1 2011. US Patent 7,899,632.

Peter Fritzson. *Principles of Object-Oriented Modeling and Simulation with Modelica 2.1*. John Wiley & Sons, 2010.

Eloísa García-Canseco, Dimitri Jeltsema, Romeo Ortega, and Jacquelien M. A. Scherpen. Power-based control of physical systems. *Automatica*, 46(1):127–132, 2010.

Kamal Garg, Lew Weingarth, and Saurabh Shah. Dynamic positioning power plant system reliability and design. In *Petroleum and Chemical Industry Conference Europe Conference Proceedings*, pages 1–10. IEEE, 2011.

Babak Hassibi and Thomas Kailath. A Krein space interpretation of the Kalman-Yakubovich-Popov lemma. Working paper. 1997.

Tim Heidel. Grid optimization workshop introduction. 2014. https://arpa-e.energy.gov/sites/default/files/B_Heidel_Workshop_Introduction.pdf.

Tobias Gybel Hovgaard, Kristian Edlund, and John Bagterp Jørgensen. The potential of economic MPC for power management. In *The 49th IEEE Conference on Decision and Control*, pages 7533–7538. IEEE, 2010.

Marija D. Ilić, P. Skantze, C. N. Yu, L. Fink, and J. Cardell. Power exchange for frequency control (PXFC). In *Power Engineering Society Winter Meeting*, volume 2, pages 809–819. IEEE, 1999.

Marija D. Ilić and Andrew Hsu. Autonomous methods, systems, and software for self-adjusting generation, demand, and/or line flows/reactances to ensure feasible ac power flow, June 17 2014. US Patent App. 14/307,145.

Marija D. Ilić and Shell Liu. *Hierarchical Power Systems Control: Its Value in a Changing Industry*. Springer Science & Business Media, 2012.

Marija D. Ilić, Francisco Galiana, Lester Fink, Anjan Bose, Pierre Mallet, and Hisham Othman. Transmission capacity in power networks. *International Journal of Electrical Power & Energy Systems*, 20(2):99–110, 1998.

Marija D. Ilić, Le Xie, and Qixing Liu. *Engineering IT-Enabled Sustainable Electricity Services: The Tale of Two Low-Cost Green Azores Islands*, volume 30. Springer Science & Business Media, 2013.

Marija D. Ilić, Sanja Cvijić, Jeffrey H. Lang, Jiangzhong Tong, and Diran Obadina. Operating beyond today's PV curves: Challenges and potential benefits. In *IEEE Power & Energy Society General Meeting*, pages 1–5. IEEE, 2015.

Marija D. Ilić. Dynamic monitoring and decision systems for enabling sustainable energy services. *Proceedings of the IEEE*, 99(1):58–79, 2011.

Marija D. Ilić and Andrew Hsu. Toward distributed contingency screening using line flow calculators and dynamic line rating units (DLRS). In *The 45th Hawaii International Conference on System Science*, pages 2027–2035. IEEE, 2012.

Marija D. Ilić and John Zaborszky. *Dynamics and Control of Large Electric Power Systems*. Wiley New York, 2000.

Marija D. Ilić, Xiaojun Liu, Gilbert Leung, Michael Athans, Christine Vialas, and Patrick Pruvot. Athans1995. *IEEE Transactions on Power Systems*, 10(4):1851–1862, 1995.

Marija D. Ilić, H. Allen, W. Chapman, Charles A. King, Jeffrey H. Lang, and Eugene Litvinov. Preventing future blackouts by means of enhanced electric power systems control: from complexity to order. *Proceedings of the IEEE*, 93(11): 1920–1941, 2005.

Marija D. Ilić, Jeffrey H. Lang, and Eric H. Allen. The role of numerical tools in maintaining reliability during economic transfers an illustration using the npcc equivalent system model. In *Bulk Power System Dynamics and Control-VII. Revitalizing Operational Reliability, 2007 iREP Symposium*, pages 1–13. IEEE, 2007.

Maria D. Ilić, R. Jaddivada, and X. Miao. Modeling for stability analysis of microgrids. *IEEE Transactions on Smart Grids*, submitted 2016.

Marija D. Ilić and Nipun Popli. Enabling convex energy bids for flexible ramp product via smart local automation. IFAC-PapersOnLine. 2015.

Jhi-Young Joo and Marija D. Ilić. Multi-layered optimization of demand resources using Lagrange dual decomposition. *IEEE Transactions on Smart Grid*, 4(4):2081–2088, 2013.

Thomas Kailath. *Linear Systems*, volume 156. Prentice-Hall Englewood Cliffs, NJ, 1980.

Matt Kamon, Frank Wang, and Jacob White. Generating nearly optimally compact models from krylov-subspace based reduced-order models. *IEEE Transactions on Circuits and Systems II: Analog and Digital Signal Processing*, 47(4):239–248, 2000.

David E. Keyes, Lois Curfman McInnes, Carol Woodward, William Gropp, Eric Myra, Michael Pernice, John Bell, Jed Brown, Alain Clo, Jeffrey Connors, Emil Constantinescu, Don Estep, Kate Evans, Charbel Farhat, Ammar Hakim, Glenn Hammond, Glen Hansen, Judith Hill, Tobin Isaac, Xiaomin Jiao, Kirk Jordan, Dinesh Kaushik, Efthimios Kaxiras, Alice Koniges, Kihwan Lee, Aaron Lott, Qiming Lu, John Magerlein, Reed Maxwell, Michael McCourt, Miriam Mehl, Roger Pawlowski, Amanda Peters Randles, Daniel Reynolds, Beatrice Riviere, Ulrich Rude, Tim Scheibe, John Shadid, Brendan Sheehan, Mark Shephard, Andrew Siegel, Barry Smith, Xianzhu Tang, Cian Wilson, and Barbara Wohlmuth. Multiphysics simulations: Challenges and opportunities. *International Journal of High Performance Computing Applications*, 27(1):4–83, 2013.

Charles A. King, J. W. Chapman, and Marija D. Ilić. Feedback linearizing excitation control on a full-scale power system model. *IEEE Transactions on Power Systems*, 9(2):1102–1109, 1994.

Natalia Kroutikova, C. A. Hernandez-Aramburo, and T. C. Green. State-space model of grid-connected inverters under current control mode. *IET Electric Power Applications*, 1(3):329–338, 2007.

E. S. Kuh and C. A. Desoer. *Basic Circuit Theory*. McGraw-Hill. 1969.

Jingang Lai, Hong Zhou, Xiaoqing Lu, Xinghuo Yu, and Wenshan Hu. Droop-based distributed cooperative control for microgrids with time-varying delays. IEEEXplore. 2016.

J. H. Lang, G. C. Verghese, and Marija D. Ilić. Opportunities in estimation and control of electrical machines. In *The 25th IEEE Conference on Decision and Control*, pages 379–387. IEEE, 1986.

E. V. Larsen and D. A. Swann. Applying power system stabilizers part ii: Performance objectives and tuning concepts. *IEEE Transactions on Power Apparatus and systems*, (6):3025–3033, 1981.

Javad Lavaei and Steven H. Low. Zero duality gap in optimal power flow problem. *IEEE Transactions on Power Systems*, 27(1):92–107, 2012.

Na Li, Lijun Chen, Changhong Zhao, and Steven H. Low. Connecting automatic generation control and economic dispatch from an optimization view. In *American Control Conference*, pages 735–740. IEEE, 2014.

Qixing Liu and Marija D. Ilić. Enhanced automatic generation control (E-AGC) for future electric energy systems. In *IEEE Power and Energy Society General Meeting*, pages 1–8. IEEE, 2012.

Steven H. Low. Convex relaxation of optimal power flow, part I: Formulations and equivalence. *arXiv preprint arXiv:1405.0766*, 2014.

Yuri V. Makarov, Viktor I. Reshetov, A. Stroev, and I. Voropai. Blackout prevention in the United States, Europe, and Russia. *Proceedings of the IEEE*, 93(11):1942–1955, 2005.

X. Miao, R. Jaddivada, A. Dowdle, and M. Ilić. Energy-based MPC for stabilizing microgrids during abnormal conditions. *IEEE*, 2017.

Richard H. Middleton, Graham C. Goodwin, David J. Hill, and David Q. Mayne. Design issues in adaptive control. *IEEE Transactions on Automatic Control*, 33(1):50–58, 1988.

J. R. Minkel. The 2003 northeast blackout–five years later. *Scientific American*, 13, 2008.

Jason C. Neely, Jay Johnson, Sigifredo Gonzalez, and Abraham Ellis. Integration of advanced inverters for increased pv penetration. Technical report, Sandia National Laboratories (SNL-NM), Albuquerque, NM (United States), 2015.

Romeo Ortega, Julio Antonio Loría Perez, Per Johan Nicklasson, and Hebertt Sira-Ramirez. *Passivity-based Control of Euler-Lagrange Systems: Mechanical, Electrical and Electromechanical Applications*. Springer Science & Business Media, 2013.

Elinor Ostrom. A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939):419–422, 2009.

P. Panciatici, F. Bena, P. Pruvot, N. Janssens, J. Deuse, and M. Stubbe. Centralized voltage control: a key point for optimal operation of power systems. *Cigre Paper*, pages 39–116, 1998.

Paul Penfield, Robert Spence, and Simon Duinker. A generalized form of Tellegen's theorem. *IEEE Transactions on Circuit Theory*, 17(3):302–305, 1970.

Sérgio Pequito, Soummya Kar, Clarance Agbi, A. Pedro Aguiar, Nipun Popli, and Marija D. Ilić. Designing decentralized control systems without structural fixed modes: A multilayer approach. *IFAC Proceedings Volumes*, 46(27):81–88, 2013.

Horst W. J. Rittel and Melvin M. Webber. Dilemmas in a general theory of planning. *Policy Sciences*, (4): 155–169, 1973.

Rush D. Robinett III and David G. Wilson. *Nonlinear Power Flow Control: Utilizing Exergy, Entropy, Static and Dynamic Stability and Lyapunov Analysis*. Springer-Verlag, 2011.

Rush D. Robinett III and David G. Wilson. Transient stability and control of renewable generators based on Hamiltonian surface shaping and power flow control: Part I-theory. In *IEEE International Conference on Control Applications*, pages 2196–2202. IEEE, 2010.

Jose Rodriguez, Marian P. Kazmierkowski, Jose R. Espinoza, Pericle Zanchetta, Haitham Abu-Rub, Hector A. Young, and Christian A. Rojas. State of the art of finite control set model predictive control in power electronics. *IEEE Transactions on Industrial Informatics*, 9(2):1003–1016, 2013.

A. Saberi and H. Khalil. Stabilization and regulation of nonlinear singularly perturbed systems–composite control. *IEEE Transactions on Automatic Control*, 30(8):739–747, 1985.

V. R. Saksena, J. O'Reilly, and P. V. Kokotovic. Singular perturbations and time-scale methods in control theory: Survey 1976–1983. *Automatica*, 20(3):273–293, 1984.

Fred C. Schweppe, Richard D. Tabors, James L. Kirtley, Hugh R. Outhred, Frederick H. Pickel, and Alan J. Cox. Homeostatic utility control. *IEEE Transactions on Power Apparatus and Systems*, (3):1151–1163, 1980.

Kazuto Seto and Shinji Mitsuta. A new method for making a reduced-order model of flexible structures using unobservability and uncontrollability and its application in vibration control. *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing*, 37(3):444–449, 1994.

Saurabh B. Shah, Kamal Garg, and Scott M. Manson. Systems and methods for protection of components in electrical power delivery systems, July 28 2014. US Patent App. 14/444,295.

Dragoslav D. Šiljak. *Large-scale Dynamic Systems: Stability and Structure*, volume 2. North Holland, 1978.

Dragoslav D. Šiljak. *Decentralized Control of Complex Systems*. Courier Corporation, 2011.

Herbert A. Simon. *The Sciences of the Artificial*. MIT Press, 1969.

John W. Simpson-Porco, Florian Dörfler, and Francesco Bullo. Droop-controlled inverters are kuramoto oscillators. *IFAC Proceedings Volumes*, 45(26):264–269, 2012.

John W. Simpson-Porco, Florian Dörfler, and Francesco Bullo. Synchronization and power sharing for droop-controlled inverters in islanded microgrids. *Automatica*, 49(9):2603–2611, 2013.

Mariya Soshinskaya, Wina H. J. Crijns-Graus, Josep M. Guerrero, and Juan C. Vasquez. Microgrids: Experiences, barriers and success factors. *Renewable and Sustainable Energy Reviews*, 40:659–672, 2014.

Janos Sztipanovits, Xenofon Koutsoukos, Gabor Karsai, Nicholas Kottenstette, Panos Antsaklis, Vijay Gupta, Bill Goodwine, John Baras, and Shige Wang. Toward a science of cyber–physical system integration. *Proceedings of the IEEE*, 100(1):29–44, 2012.

Arjan van der Schaft and Dimitri Jeltsema. Port-hamiltonian systems theory: An introductory overview. *Foundations and Trends in Systems and Control*, 1(2-3):173–378, 2014.

George C. Verghese, Marija D. Ilić, and Jeffrey Lang. Modeling and control challenges in power electronics. In *The 25th IEEE Conference on Decision and Control*, number 25, pages 39–45, 1986a.

George C. Verghese, Jeffrey H. Lang, and Leo F. Casey. Analysis of instability in electrical machines. *IEEE Transactions on Industry Applications*, (5):853–864, 1986b.

Jan von Appen, Martin Braun, Thomas Stetz, Konrad Diwold, and Dominik Geibel. Time in the sun: the challenge of high PV penetration in the German electric grid. *IEEE Power and Energy Magazine*, 11(2):55–64, 2013.

Martin R. Wagner, Kevin Bachovchin, and Marija D. Ilić. Computer architecture and multi time-scale implementations for smart grid in a room simulator. *IFAC-PapersOnLine*, 48(30):233–238, 2015.

Da Wang, Mevludin Glavic, and Louis Wehenkel. Distributed mpc of wide-area electromechanical oscillations of large-scale power systems. In *The 16th International Conference on Intelligent System Application to Power Systems*, pages 1–7. IEEE, 2011.

Hungjen Wang, Marija D. Ilić, and Ingo Vogelsang. Multilayered unbundled delivery of electricity service to customers under normal conditions. In *Power Engineering Society General Meeting*, pages 2257–2265. IEEE, 2004.

Youyi Wang, David J. Hill, Richard H. Middleton, and Long Gao. Transient stability enhancement and voltage regulation of power systems. *IEEE Transactions on Power Systems*, 8(2):620–627, 1993.

W. Borutzky. *Bond Graph Modelling of Engineering Systems*. Springer, 2010.

Allen J. Wood and Bruce F. Wollenberg. *Power Generation, Operation, and Control*. John Wiley & Sons, 2012.

Chenye Wu, Soummya Kar, and Gabriela Hug. Enhanced secondary frequency control via distributed peer-to-peer communication. *arXiv preprint arXiv:1403.1868*, 2014.

Felix Wu, Pravin Varaiya, Pablo Spiller, and Shmuel Oren. Folk theorems on transmission access: Proofs and counterexamples. *Journal of Regulatory Economics*, 10(1):5–23, 1996.

Le Xie, Pedro M. S. Carvalho, Luis A. F. M. Ferreira, Juhua Liu, Bruce H. Krogh, Nipun Popli, and Marija D. Ilić. Wind integration in power systems: Operational challenges and possible solutions. *Proceedings of the IEEE*, 99(1):214–232, 2011.

Shahan Yang, Baobing Wang, and John S. Baras. Interactive tree decomposition tool for reducing system analysis complexity. *Procedia Computer Science*, 16: 138–147, 2013.

Maojun Yao, Raymond R. Shoults, and Randy Kelm. AGC logic based on NERC's new control performance standard and disturbance control standard. *IEEE Transactions on Power Systems*, 15(2):852–857, 2000.

Chris S. K. Yeung, Ada S. Y. Poon, and Felix F. Wu. Game theoretical multi-agent modelling of coalition formation for multilateral trades. *IEEE Transactions on Power Systems*, 14(3):929–934, 1999.

D. Youla. Physical realizability criteria. *IRE Transactions on Circuit Theory*, 7(5):50–68, 1960.

Günther Zauner, Daniel Leitner, and Felix Breitenecker. Modeling structural-dynamics systems in MODELICA/Dymola; MODELICA/Mosilab and AnyLogic. In *Proceedings of the 1st International Workshop on Equation-Based Object-Oriented Languages and Tools*, number 024. Linköping University Electronic Press, 2007.

ZhengMing Zhao, Hua Bai, and LiQiang Yuan. Transient of power pulse and its sequence in power electronics. *Science in China Series E: Technological Sciences*, 50(3):351–360, 2007.