Chapter 7
Unified Modeling for Emulating Electric Energy Systems:
Toward Digital Twin That Might Work

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ABSTRACT

Large-scale computing, including machine learning (MI) and AI, offer a great promise in enabling sustainability and resiliency of electric energy systems. At present, however, there is no standardized framework for systematic modeling and simulation of system response over time to different continuous- and discrete-time events and/or changes in equipment status. As a result, there is generally a poor understanding of the effects of candidate technologies on the quality and cost of electric energy services. In this chapter, the authors discuss a unified, physically intuitive multi-layered modeling of system components and their mutual dynamic interactions. The fundamental concept underlying this modeling is the notion of interaction variables whose definition directly lends itself to capturing modular structure needed to manage complexity. As a direct result, the same modeling approach defines an information exchange structure between different system layers, and hence can be used to establish structure for the design of a dedicated computational architecture, including AI methods.

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INTRODUCTION

This chapter is motivated by a central recognition: electric energy systems could have much better performance than what is achieved today if they are enabled by rich data (appropriately collected and processed) and on-line decision-making based on learning from history and predictions. Taking this recognition a step further, we argue that novel approaches are needed for next generation modeling and computing for managing complex on-going major organizational and technological changes. Clearly, this should not be done from scratch, since there have been major investments in current information technology by entities such as the Pennsylvania-Jersey-Maryland (PJM) independent system operator (ISO), estimated at $800 million (Boston, 2020). This makes it even harder to move forward with the next generation Supervisory Control and Data Acquisition (SCADA) system (Ilic, 2010). An additional subtle challenge comes from the need to almost instantaneously balance supply and demand. This means supporting control and decision making for "guaranteed" Quality of Service (QoS), which is in sharp contrast with Internet protocols where targeting "best efforts" is sufficient. Imagine having to operate a system like Puerto Rico's during a hurricane or an earthquake, when lots of electric system equipment is damaged and disconnected. It is crucial to have a flexible digital twin for simulating such complex systems, both in support of autonomous self-adaptation to the changing conditions and for assessing impact of previously unused technologies and system disturbances, such as intermittent power. This chapter is written with such challenges and opportunities in mind.

Background and History

Computing and simulations in electric power systems enjoy a long history. Generally speaking however, the approach has been rather piece-meal software development for basic applications and computational tasks, such as state estimation (Clements et al., 1981), power flow analysis in a large grid (Stott, 1974), optimal power dispatch for minimizing generation fuel cost when supplying predicted demand (Stott et al., 2009), short circuit analysis (Zhang et al., 1995), and numerical simulation of system response to sudden large equipment failures (Pavella and Murthy, 1994). All of these applications and tasks are used in a feed-forward way with the human-in-the-loop, while relying on local embedded automated feedback to ensure stable and feasible dynamic response in near real-time.

In the early 1970's, utilities worldwide begun to experience major widespread blackouts, and this called for more reliance on computing. These needs motivated active R&D on large-scale numerical methods, such as solving sparse matrix problems (Tinney et al., 1985; Rose, 2012), waveform relaxation for numerical integration of multi-rate differential equations (Ilic et al., 1987), small-signal stability analysis (Verghese et al., 1982) and, more generally, parallel computing for large-scale systems (Betancourt and Alvarado, 1986). In turn, these efforts resulted in computer applications used routinely by control centers for dispatching generation to supply predicted power demand (Fu and Shahidehpour, 2007; Stott, 1974; Cvijic et al., 2018). However, emulation of system dynamics has only been done in an off-line mode for select deterministic scenarios because centralized numerical integration of high-order differential-algebraic equations (DAEs) cannot be done in near real-time (Pavella and Murthy, 1994; Crow and Ilic, 1994). Only a handful of forward-looking utilities have designed a hybrid analog-digital simulators of their own power systems for the purposes of better understanding their performance, particularly during abnormal conditions, and also for simulating potential of system control and protection (Do et al., 2001; Doi et al., 1990).