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A stochastic multiscale model for electricity generation capacity expansion

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ABSTRACT

Long-term planning for electric power systems, or capacity expansion, has traditionally been modeled using simplified models or heuristics to approximate the short-term dynamics. However, current trends such as increasing penetration of intermittent renewable generation and increased demand response requires a coupling of both the long and short term dynamics. We present an efficient method for coupling multiple temporal scales using the framework of singular perturbation theory for the control of Markov processes in continuous time. We show that the uncertainties that exist in many energy planning problems, in particular load demand uncertainty and uncertainties in generation availability, can be captured with a multiscale model. We then use a dimensionality reduction technique, which is valid if the scale separation present in the model is large enough, to derive a computationally tractable model. We show that both wind data and electricity demand data do exhibit sufficient scale separation. A numerical example using real data and a finite difference approximation of the Hamilton–Jacobi–Bellman equation is used to illustrate the proposed method. We compare the results of our approximate model with those of the exact model. We also show that the proposed approximation outperforms a commonly used heuristic used in capacity expansion models.

1. Introduction

The general problem of capacity expansion under uncertainty has been extensively studied both as a stochastic optimal control problem as well as a multistage stochastic programming problem. In many ways it is a prototypical example of an optimal control problem; as a result, it has been studied since the late 1950s (Luss, 1982). For electric power systems, long-term investment (capacity expansion) and short-term operations (generation dispatch and unit commitment) were traditionally treated as decoupled decisions, and numerical models of long-term planning used highly simplified models and heuristics to represent the short-term dynamics.

However, the environment in which generation capacity expansion decisions are being made is becoming increasingly complex. This complexity is driven in part by increasing pressure placed on the electricity industry to address the problem of meeting the projected growth in demand in a sustainable manner, including increased reliance on intermittent renewable generation and increased demand–response mechanisms. The variability on the short time scale has important implications for the optimal portfolio of technologies that should be built in the long-run. For example, more intermittent generation will require other dispatchable technologies such as natural gas generation that can ramp up or down quickly. The conventional simplifications in long-term models will not capture this effect and will lead to suboptimal investment strategies (Palmintier & Webster, 2011). Moreover the deregulation of the electricity industry means that utilities cannot pass on the risks of investment decisions to customers. Consequently advanced models are needed in order to capture the complexities of the new decision making environment. The model of the full system, explicitly resolving both short-term (e.g., hourly) and long-term (e.g., annual or decadal) time scales along with the stochastic processes associated with each, would be computationally intractable for any system of realistic size.

In this paper, we present an efficient method for coupling the multiple temporal scales in the capacity expansion problem using the framework of singular perturbation theory for the control of continuous time problems. We demonstrate that for power systems the relevant stochastic processes are highly structured in ways that can be exploited. In particular load demand uncertainty and uncertainties in generation availability can be accurately modeled using weakly connected Markov processes. We take advantage of the properties of weakly connected processes in order to perform dimensionality reduction on the original model and therefore allows useful computation to be performed.

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To make operational the uncertainty structures present in this class of problems we make use of the tools from singular perturbation theory for Finite State Markov Processes (FSMPs) in continuous time. In some respects some models already take advantage of this structure. For example, the widely used MARKAL model (Seebregts, Goldstein, & Smekens, 2001) uses the concept of a "load block" to overcome the onerous requirement of optimizing over all possible loads. Similarly (Palmintier & Webster, 2011) simplify an integrated unit commitment and capacity expansion model by aggregating different power generators together. These types of aggregation approaches can be useful in practice. However, it is also important to understand why heuristics work, when they fail, and what can be done instead. For example, it is not clear how to extend the concept of a "typical" load to handle wind intermittency, or demand elasticity (a major objective of demand response programs). Instead we use perturbation methods to derive an "aggregate" model based on the assumption that the fast processes in our system (e.g wind, demand uncertainty) follow their stationary distribution. The computational complexity of the aggregate model is much less then the exact model and based on initial numerical experiments the error associated with the solution is much less then the existing heuristics used in MARKAL.

The contributions of this paper can be summarized as follows:

1. We formulate the problem of energy planning over multiple scales as a stochastic optimal control problem with weakly interacting FSMPs. We then extend and adapt some existing results from the literature of singular perturbation theory to derive an approximate problem that is computationally more attractive than the original problem. We also establish the conditions under which the approximate problem will yield the same value function as the original problem.
2. We formalize the heuristics of widely used models such as MARKAL. Existing models are based on the assumption that the Markov processes that describe the stochastic intraday dynamics of power systems are regularly perturbed. This assumption is not supported by the data. We show how to relax this assumption, using standard results from singular perturbation theory.
3. We demonstrate the application of this approach using empirical observations. As our approach is based on perturbation theory, we need to make assumptions about the existence of sufficient scale separation. As will be shown in this paper, there is sufficient evidence to suggest that such scale separation is present in the data. We expect some of the statistical techniques we use to be useful in other problem classes as well.

The rest of this paper is structured as follows: in the next section we discuss related literature and outline in more detail the contributions of this paper. In Section 3 we introduce our capacity expansion model and discuss some of its properties. In Section 3.1 we reinforce the arguments that motivated this paper by looking at some real data. In Section 3.2 we review perturbation theory in the context of multiscale Markov processes and link our assumptions with the empirical observations of Section 3.1. We also show that existing models do not capture the correct asymptotic behavior of the uncertainties present in the intraday scale. In Section 4 we introduce an aggregate problem, and show that asymptotically the value function of the approximate problem converges to the value function of the original problem. We also establish the same result for the approximate optimal control. In Section 5 we illustrate how the proposed approach could be implemented in practice. We compare the results of the approximate model with those of the exact model. We also show that the proposed approximation outperforms a commonly used heuristic used in large models.

2. Related literature and contributions

Capacity expansion problems have generated a large amount of literature. This is mainly because expansion problems are applicable to many areas and also because they are a good testbed for new modeling ideas. We will only discuss models that address the effect of the different time scales. Even though some of the work discussed below does not address capacity expansion directly, we believe that the most relevant papers to this work are the ones that address multiple scales since their ideas could be used in a capacity planning problem.

In Sen, Yu, and Genc (2006) the problem of incorporating different scales for addressing risk management problems such as buying and selling forward contracts for fuel are addressed in conjunction with the intraday unit commitment problem. Their model does not address intraday effects from intermittent sources. They formulate the problem as a multistage stochastic programming problem. The resulting large scale mixed integer linear programming problem is solved using a nested column decomposition algorithm. In Epe et al. (2009) the authors do address the problem of dealing with the intermittency of wind. Again a multistage stochastic programming approach is taken and the resulting large scale optimization problem is solved using a recombining tree methodology. In Pritchard, Philpott, and Neame (2005) the operation of a hydro-electric reservoir is addressed. Their problem also has multiple scales since the supply of power occurs intraday, in hourly intervals, but the management of the reservoir occurs over monthly scales. The problem is formulated as a dynamic programming problem. By approximating the decision to have some desirable properties the different scales can be decomposed. In Powell, George, Lamont, and Stewart (2009) the intermittency of wind and solar are addressed by approximate dynamic programming. We refer to the review article in Wallace and Fleten (2003, chap. 10) and the recent book (Weber, 2005) for a more complete overview of stochastic programming approaches as well as approaches based on dynamic programming. What all these papers have in common is that they address the existence of multiple scales using some sort of algorithmic framework. They either use a decomposition algorithm, approximate dynamic programming, or find some way to relax the non-anticipativity constraints in order to make the problem tractable. In this paper we take a different approach from the work described above. We posit that the uncertainties that exist in energy planning problems, in particular load demand uncertainty and uncertainties due to the power source, are highly structured. This structure can be exploited to a great advantage that provides insight into the nature of the problem. It also allows us to construct a reduced order model that is based on model primitives. The main aim of this paper is not to produce more accurate numbers by incorporating intraday variations, but rather define the representational structures that will allow qualitative and quantitative reasoning about the effects of different time scales.

The main results for multiscale FSMPs are summarized in two excellent books (Sethi & Zhang, 1994; Yin & Zhang, 1998). Therefore we only comment on the relations between the analysis here and the literature. In Jiang and Sethi (1991) a similar model to ours is proposed. The model is motivated by a manufacturing system with machines that have failure events that occur on different time scales. However, their model does not address the issue of capacity expansion and demand is deterministic. In Zhang, Yin, and Boukas (1997) another model similar to ours is proposed and is again studied in the context of manufacturing systems. Their model also has fixed capacity and deterministic demand. Even though the problem of capacity expansion with multiple scales has been studied (see chap. 10 in Yin & Zhang (1998)) we address capacity expansion for Markov Chains with weak interactions and multiple scales. This