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A flexible model for economic operational management of grid battery energy storage

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ABSTRACT

To connect energy storage operational planning with real-time battery control, this paper integrates a dynamic battery model with an optimization program. First, we transform a behavioral circuit model designed to describe a variety of battery chemistries into a set of coupled nonlinear differential equations. Then, we discretize the differential equations to integrate the battery model with a GAMS (General Algebraic Modeling System) optimization program, which decides when the battery should charge and discharge to maximize its operating revenue. We demonstrate the capabilities of our model by applying it to lithium-ion (Li-ion) energy storage operating in Texas' restructured electricity market. By simulating 11 years of operation, we find that our model can robustly compute an optimal charge-discharge schedule that maximizes daily operating revenue without violating a battery's operating constraints. Furthermore, our results show there is significant variation in potential operating revenue from one day to the next. The revenue potential of Li-ion storage varies from approximately \$0–1800/MWh of energy discharged, depending on the volatility of wholesale electricity prices during an operating day. Thus, it is important to consider the material degradation-related "cost" of performing a charge-discharge cycle in battery operational management, so that the battery only operates when revenue exceeds cost.

1. Introduction

Because of the high cost of conventional large-scale electricity storage technologies (such as pumped-hydro energy storage [1]), it has typically been more economical to produce electricity on demand, generating and then delivering it to the end user in real time. To reliably deliver electricity on demand, generation, transmission, and distribution equipment must have the capacity to serve peak electric load, which only occurs for a small portion of the year. Furthermore, electric generators must set aside reserve capacity for grid ancillary services to ensure electric supply consistently equals demand, even in the case of a contingency. These two aspects of today's electric grid represent a non-trivial component of the cost of electricity. At the same time, concerns about air pollution, sustainability, and anthropogenic climate change have driven an increase in the amount of intermittent renewable energy resources connected to the grid. Because of the grid's on-demand design, it would benefit from the integration of more flexible electricity resources as the penetration of intermittent resources increases [2].

Grid energy storage is an appealing technology because it temporally decouples electricity supply from demand, which means generation can occur at a time other than when there is demand. Doing so adds new flexibility to grid operations with the potential to reduce grid capital expenditures, integrate higher fractions of intermittent renewable energy, and increase electric reliability. For these reasons, recent advances in battery technology have driven renewed interest in grid-based battery energy storage. Nevertheless, batteries have only been sparingly implemented on the U.S. electric grid. In 2011, there were less than 140 MW of batteries installed [3]. This fact can be attributed to the high cost of existing battery systems and uncertainty surrounding the revenue potential of battery energy storage operating on the electric grid.

The revenue potential of grid battery energy storage is uncertain for primarily two reasons. First, because a battery cannot store electricity without incurring energy losses and material degradation from electrochemical conversion, the performance and lifetime of a battery in grid applications is uncertain. Second, because an energy storage plant uses grid electricity as its "fuel," the external price of electricity has a strong effect on its revenue potential. To generate revenue from the sale of electric energy, a grid

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battery must charge when the real-time price of electricity is low and discharge when the price is high. Thus, the profit maximization problem for a grid battery system is considerably more difficult than the profit maximization problem for a conventional power plant. For these reasons, it is desirable to develop a tool that integrates two features: 1) a battery model capable of describing complex battery performance characteristics within a real-time control framework, and 2) a decision-making framework to show how a battery should operate to maximize its revenue potential from the sale of electric energy.

To augment the existing literature, this paper connects a behavioral-circuit model capable of describing nonlinear battery performance characteristics with an optimization algorithm for grid battery operational management. The remainder of this paper is organized as follows: Section 2 reviews past literature that has sought to develop models to describe battery performance and manage the operation of grid energy storage. Section 3 discusses how we discretize a dynamic behavioral circuit model from the literature for use with optimization. Section 4 describes the formulation of a model-based optimization problem for operational management of grid battery storage, and application of the model to simulate lithium-ion (Li-ion) battery energy storage used for wholesale energy arbitrage in Texas' restructured[1] electricity market. Section 5 shows the results of our case study, and discusses the implications of our results for economic operational management of a grid battery. Finally, Section 6 draws conclusions from our results and proposes future work.

2. Background

2.1. Battery modeling

Researchers have developed a number of models to describe a battery. These models can be broadly classified into two major categories: first-principles electrochemical models and empirical behavioral models. First-principles models use physical equations to describe the transport and reaction of active species inside a battery. They describe how the concentration of active species at the electrode surface affects the overpotential required to drive an electrochemical reaction to store or release energy [4–8]. Empirical behavioral models use mathematical equations or physical analogs (e.g. electric circuits) to describe the system-level characteristics of a battery, such as capacity, efficiency and voltage. Peukert's law, which describes the relationship between rate of discharge and discharge capacity, is one of the earliest empirical models [9,10]. Other models describe a battery's non-linear capacity/recovery effects [11–14], or energy efficiency [15]. Many empirical models use an electric circuit analog to describe the system-level behavior of a battery using a combination of variable voltage sources, resistors, and capacitors. A number of these models have been developed in the literature including Thévenin equivalent circuit models [16–18], impedance-based models [19–21], and runtime-based models [22,23]. More recent electric circuit analog models combine the benefits of many of these models to empirically describe a number of complex battery characteristics [24,25].

Empirical models are advantageous for real-time battery control because they can be designed to describe complex battery characteristics without significant computational complexity. In particular, electric circuit analog models have proven to be a flexible tool for empirically describing battery performance under diverse operating conditions, including temperature, state of charge, and charge-discharge rate [24–29]. These models describe a battery's open circuit voltage using a variable potential source, and then use a combination of series resistors and parallel resistor-capacitor couples to describe a battery's ohmic potential drop and dynamic voltage behavior at various time scales. Numerous studies have developed methods to experimentally extract the electrical parameters required to describe a battery's dynamic state using these models [24,28–31].

2.2. Operational management of grid energy storage

A number of researchers have sought to analyze the value of electricity storage in the context of restructured electricity markets. Early studies use simple assumptions about energy storage system performance, operating revenue, and cost to assess the value of electricity storage in a restructured electricity market from a largely qualitative perspective [32–34]. More recent studies utilize multiple years of dynamic electricity price data that have become available since restructured electricity markets opened to quantitatively assess the value of electricity storage [35–48]. Typically, studies focus on assessing the techo-economic performance of one specific technology in a given market and system context using optimization and other techniques for energy storage operational management.

A principle limitation of existing studies is that they assume a storage device has a constant roundtrip efficiency, energy capacity, and power capability, regardless of its instantaneous operating state. While this assumption might not have a strong influence on the overall economic assessment of a given energy storage device, it makes it difficult to connect economic assessments with real-time control to maximize the daily operating revenue of an energy storage device deployed on the grid. To connect operational management of grid energy storage with real-time battery control, we develop an optimization model that uses a flexible behavioral circuit model developed previously [24] to describe the dynamic operating state of a grid battery system and decide how it should charge and discharge to maximize its daily operating revenue without violating its operating constraints.

3. Battery model transformation

Chen and Rincón-Mora's model describes the state of a battery using two coupled electrical circuits, as shown in Fig. 1 [24]. The "battery lifetime circuit" on the left-hand side of Fig. 1 approximates a battery's state of charge based on the current input, I. The capacitor C_c integrates the charge flowing into and out of the battery to approximate state of charge, and the resistor R_{sd} models the

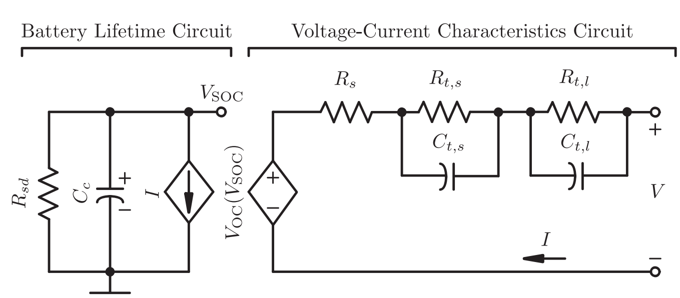

Fig. 1. The battery lifetime circuit describes the dynamic nature of a battery's state of charge, and the voltage-current characteristics circuit describes how the terminal voltage of a battery is dynamically affected by state of charge and current load. Figure adapted from Ref. [24].

[1] Modern competitive electricity markets are often described as "deregulated," despite the fact that numerous regulations still exist. This work will use the term "restructured" to describe competitive electricity markets.