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A dynamic model-based estimate of the value of a vanadium redox flow battery for frequency regulation in Texas

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HIGHLIGHTS

- A model is implemented to describe the dynamic voltage of a vanadium flow battery.
- The model is used with optimization to maximize the utility of the battery.
- A vanadium flow battery's value for regulation service is approximately \$1500/kW.

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ABSTRACT

Building on past work seeking to value emerging energy storage technologies in grid-based applications, this paper introduces a dynamic model-based framework to value a vanadium redox flow battery (VRFB) participating in Texas' organized electricity market. Our model describes the dynamic behavior of a VRFB system's voltage and state of charge based on the instantaneous charging or discharging power required from the battery. We formulate an optimization problem that incorporates the model to show the potential value of a VRFB used for frequency regulation service in Texas. The optimization is implemented in Matlab using the large-scale, interior-point, nonlinear optimization algorithm, with the objective function gradient, nonlinear constraint gradients, and Hessian matrix specified analytically. Utilizing market prices and other relevant data from the Electric Reliability Council of Texas (ERCOT), we find that a VRFB system used for frequency regulation service could be worth approximately \$1500/kW.

1. Introduction

In 2010, U.S. electric providers sold over 3.7 trillion kW h of electrical energy, generating nearly \$369 billion in revenue [1]. Despite the enormity of the electricity industry, the U.S. electric grid has very little capacity to store electricity. In 2011, the U.S. grid had only 22 GW of electric energy storage capacity, compared with over 1000 GW of generation capacity [1,2]. Because of the high cost of conventional electricity storage technologies (such as pumped-hydro energy storage [3]), it is typically more economical to generate 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 are sized to serve peak electric load. Furthermore, electric generators set aside capacity for grid ancillary services to reliably balance electric supply and demand in real time. These two aspects of the present electric grid represent a non-trivial component of the cost of electricity.

In recent years, high-performance electrochemical energy storage technologies such as sodium–sulfur, lithium–ion, and redox flow batteries (RFBs) have been developed to support grid applications. Despite advances in electrochemical energy storage technology, batteries have only been sparingly implemented on the U.S. electric grid. In 2011, there were less than 140 MW of batteries installed [2]. This fact can be attributed to the high cost of existing battery systems and uncertainty of their long-term reliability. Furthermore, there is uncertainty about the precise economic value of battery energy storage in grid-level applications. There are primarily two reasons for this uncertainty. First, unlike a traditional commodity storage facility, a battery cannot store electricity without losing some energy to conversion losses and other inefficiencies. Second, the value of energy storage in a grid application is directly affected by the external price of energy. Whether batteries are selling wholesale energy during peak hours or working to balance and control the electric grid, the energy they use to perform these services *must* come from somewhere, and the cost of this energy has a marked effect on the value of battery energy storage as it participates in the electricity marketplace. For these reasons, an assessment of the potential value of grid-based battery energy storage would benefit from two features: (1) an appropriate battery

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energy storage model to describe the particular capabilities of the battery in question and (2) a framework for showing how the battery could operate to produce the most value in an application.

The goal of this paper is to assess the potential value of a vanadium redox flow battery (VRFB) for frequency regulation service in Texas. Many researchers have highlighted the technical compatibility between electrical energy storage and frequency regulation service [4–7]. In order to show the value of a VRFB for regulation service, we perform a time-domain analysis of a VRFB's participation in Texas' organized electricity market that includes the detail of time-varying regulation capacity prices. We describe the instantaneous energy conversion capabilities of a VRFB using a dynamic, control-oriented battery model. To show how a VRFB could operate economically for regulation service, we incorporate this model into an economic optimization routine. The following section discusses past work that has assessed the value of energy storage in grid-based applications. Section 3 discusses the development of a control-oriented VRFB model, and how we implement this model with optimization. Section 4 uses the results of the optimization to assess the value of a VRFB for regulation service in Texas. Finally, Section 5 summarizes our work and discusses possible future research.

2. Background

Because electric energy storage has the potential to reduce utility costs associated with peak demand and power system control, a number of researchers have sought to demonstrate the benefits of grid-based battery energy storage. Early investigations focus on lead-acid battery applications for electric utilities [8,9]. These studies use utility-level knowledge to assess the economic benefit of grid-based energy storage. In recent years, organized competitive electricity markets have emerged in place of conventional vertically-integrated electric utilities. Rather than a single entity controlling a portfolio of generation, transmission, and distribution resources, competitive electricity markets permit diverse parties to offer their electric generation resources into a wholesale power marketplace. Numerous studies have highlighted the unique opportunity that these new markets present for energy storage [10–13]. Early studies by researchers from the U.S. Department of Energy's Energy Storage Systems Program identify new opportunities for storage in competitive electricity markets [10,11]. Following these studies, there have been detailed investigations of energy storage operating in the New York Independent System Operator (NYISO) market [12] and the California Independent System Operator (CAISO) market [13]. Both of these studies identify frequency regulation as a high-value application for grid-based energy storage [12,13]. A separate study of energy storage operating in the NYISO market analyzes the economics of storage for wholesale electricity arbitrage and regulation service [7]. It shows that energy storage for frequency regulation is more valuable than storage for energy arbitrage—even in transmission-constrained New York City [7]. Furthermore, studies of battery energy storage operating in the German electricity market identify frequency regulation as the highest-value application for battery energy storage [14,15]. We build on these studies by performing a time-domain analysis of the potential value of a VRFB used for regulation service from 2007–2009 in Texas' organized electricity market, which is administered by the Electric Reliability Council of Texas (ERCOT). By doing so, we capture the daily character of chronological regulation capacity prices and wholesale energy prices, and demonstrate how a VRFB could respond to those price signals.

Many estimates of the value of energy storage use a model-based time-domain analysis to show how a battery could participate in the electricity market [7,16–18]. The energy storage capabilities of a battery are conventionally described using a simple, black-box energy storage model, which describes a battery as a container for energy with regular losses anytime energy is added to or removed from the battery. With this sort of model, time-domain analysis of electricity market power flows is conducted by tracking the amount of energy stored in the device as it performs its duty on the grid. At each time step, k, the instantaneous amount of energy stored in the battery is tracked as a function of the power flowing to or from the battery as shown in the following equations [18]:

$$E_{batt,out}(k) = P_{batt,out}(k)\Delta t/\sqrt{\eta_{batt}} \tag{1}$$

$$E_{batt,in}(k) = P_{batt,in}(k)\Delta t\sqrt{\eta_{batt}} \tag{2}$$

$$E_{batt}(k) = E_{batt}(k-1) + E_{batt,in}(k) - E_{batt,out}(k) \tag{3}$$

The variable $P_{batt,out}(k)$ is the flow of power out of the battery; $P_{batt,in}(k)$ is the flow of power into the battery; and $E_{batt}(k)$ is the quantity of energy stored in the battery at each time step of duration Δt. The symbol η_{batt} represents the round-trip efficiency of the battery, and is treated as constant. The square root of η_{batt} is used in Eqs. (1) and (2) so that energy losses are imposed equally on discharging and charging power, respectively.

This model has been used for operational management of a battery using optimization [16,17]. The objective of the optimization problem is a function of the power flowing in and out of the battery at each time step ($P_{batt,in}(k)$, $P_{batt,out}(k)$) and a relevant electricity-market price signal. Bounds (see Eqs. (4)–(6)) are placed on the variables to find an optimal operation strategy for the battery that does not violate its technical limits.

$$\forall k \; P_{batt,out}(k) \leqslant P_{max,out} \tag{4}$$

$$\forall k \; P_{batt,in}(k) \leqslant P_{max,in} \tag{5}$$

$$\forall k \; 0 \leqslant E_{batt}(k) \leqslant E_{capacity} \tag{6}$$

The conventional model of a battery interfacing with the electric grid is limited because it tracks the real-time state of a battery with only one variable: $E_{batt}(k)$. This energy state variable effectively assumes a battery operates at a constant voltage. Because voltage varies with hysteresis and nonlinearly with a battery's duty cycle [19], the conventional model described in Eqs. (1)–(3) is an abstraction of a battery's real-time behavior. It is more accurate to consider voltage variations and decompose a battery's stored energy into two state variables: the terminal voltage and the state of charge (SOC), defined in Eq. (7) as the ratio of stored charge (q) to charge capacity (q_{max}).

$$SOC = q/q_{max} \tag{7}$$

While the conventional model is useful for energy storage economic analysis, its black-box description of a battery's state leads to difficulties in connecting operational strategies gleaned from the conventional model with real-time battery control. To overcome the shortcomings of the conventional model, we develop a control-oriented battery energy storage model, which encapsulates the real-time energy conversion capabilities of a battery within a dynamic relationship between current, voltage, and SOC. With this model, we describe battery voltage variations within an economic optimization framework, and help to connect system-level economic analysis with real-time optimal control of grid-connected battery energy storage.