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Combining a dynamic battery model with high-resolution smart grid data to assess microgrid islanding lifetime

Robert L. Fares *, Michael E. Webber

Department of Mechanical Engineering, The University of Texas, Austin, TX 78712, United States

HIGHLIGHTS

- A dynamic battery model is used to describe a transformer-level grid battery system.
- Smart grid data is used to simulate the battery system operating in islanded mode.
- Thousands of islanding events are simulated to show the expected islanding lifetime.
- 50 kW h transformer-level storage alone can endure 93% of average-duration outages.
- Adding rooftop solar does not increase islanding lifetime during peak hours.

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ABSTRACT

In this paper, we use experimental data collected from an Austin, Texas smart grid test bed with a system-level battery energy storage model to assess the lifetime of batteries in a microgrid operating in islanded mode during a distribution-level outage. We consider a hypothetical microgrid consisting of 21 single-family detached homes and three transformer-level community energy storage (CES) battery units ranging in size from 25 kW h to 75 kW h. To describe the performance of CES batteries, we implement a dynamic behavioral circuit model capable of describing voltage transients and rate-capacity effects. We use one-minute electricity production and consumption data collected from the smart grid test bed in 2012 to assess how the timing of an electric outage affects the islanding lifetime of a residential microgrid. We contrast our results with the average outage duration reported by U.S. electric utilities to quantify how often a residential microgrid could withstand a typical outage. Our results show that increasing the amount of rooftop PV in a residential microgrid does not significantly increase how often it can withstand an average-duration outage. However, combining PV with CES extends the median islanding lifetime by up to 11.6 h during morning outages. Based on our results, 50 kW h CES provides the best tradeoff between the cost of a CES system and its reliability benefit, allowing downstream loads to withstand an average-duration outage approximately 93% of the time.

1. Introduction and motivation

With the rapid development of battery energy storage devices and the rising implementation of intelligent electricity distribution technologies, there has been growing interest in distribution-level battery energy storage systems [1–3]. Energy storage located at the distribution level of the grid can provide useful control services, reduce the cost of delivering electricity during peak-demand hours, integrate local intermittent renewable energy, and isolate a node of the distribution system during an electric outage to form a microgrid [1–3]. The U.S. Department of Energy defines a microgrid as “a group of interconnected loads and distributed energy resources (DERs) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [and can] connect and disconnect from the grid to enable it to operate in both grid-connected or island mode.” [4].

One proposed distribution-level energy storage technology is community energy storage (CES), a 25 kW battery system located at the distribution transformer [1]. The goal of this paper is to model the state of CES used to isolate downstream electric loads, so that we can approximate how long CES could provide backup power during an outage. It is difficult to gauge how long CES could

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* Corresponding author. Address: Department of Mechanical Engineering, The University of Texas at Austin, 204 E. Dean Keeton Street, Stop C2200, Austin, TX 78712-1591, United States.

E-mail address: robertfares@utexas.edu (R.L. Fares).

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isolate downstream loads because electric demand often varies widely with ambient temperature, time of day, and other factors. Furthermore, the power load placed on a battery affects its available capacity [5,6]. To approximate how long a battery could power a microgrid, information must be known about the power load on the battery and the battery's real-time performance.

To model the performance of CES, we use a dynamic behavioral circuit model [7]. The model has the capability to describe how the voltage and capacity of a battery vary with its duty cycle. These features are important for the purpose of this paper, because a battery powering a microgrid would have a variable load applied to it.

To approximate the load that would be applied to CES powering a microgrid during an electric outage, we use high-resolution electricity data collected by Pecan Street Inc. [8] of Austin, Texas as part of its ongoing smart grid demonstration study [9]. The study utilizes a test bed of 250 modern, green-built homes constructed after 2007, and 160 homes ranging from 10 to 92 years in age [10]. The homes are instrumented with electricity, gas, and water metering equipment. Of the 250 homes in the study, 185 are outfitted with rooftop solar photovoltaic (PV) panels [10], which are metered separately from electric demand. For the purposes of this paper, we utilize electric demand and PV generation data with a one-minute time resolution collected from 21 of homes with PV panels over the entirety of 2012.

The remainder of this paper is organized as follows: Section 2 introduces the concept of microgrids and discusses the dynamic battery performance modeling literature; Section 3 discusses how we implement a dynamic battery model to approximate the state of CES powering a microgrid; Section 4 shows how we combine the battery model with empirical electricity data to calculate the islanding lifetime of a microgrid powered by CES; Section 5 shows the results of our analysis; and Section 6 discusses our results and prospects for future work.

2. Background

2.1. Distributed energy resources and microgrids

For many years, the electric grid has operated within a centralized, energy-on-demand paradigm. Electric power is typically produced in a large power station located far away from electricity end users, and then sent over a long distance using high-voltage transmissions lines (electric "highways"). Transmission lines deliver electric power to a substation, which transfers the power to distribution lines (electric "roads") that deliver electricity to end users. The entire grid operates on demand; electricity is instantaneously generated, delivered, and consumed in real-time.

The physical separation between energy sources and energy users is a primary vulnerability that affects electric reliability. Temporary distribution equipment failures that disrupt the flow of current cause all downstream electric customers to lose power. Because these failures are difficult to avoid, a typical U.S. electric customer experiences 1–2 power outages a year, with each outage lasting approximately 2.5–3 h on average [11].

Beyond the issue of power reliability, today's grid sometimes lacks sufficient power quality for some end users. Transmission and distribution lines behave as inductors when they carry electric power over long distances. Their inductive reactance must be compensated for using banks of capacitors, power electronics, or other equipment to avoid excess reactive power flow, which can potentially cause voltage sags, voltage collapse or even a system-wide blackout [12].

Issues such as power quality and reliability have driven interest in a grid with a larger share of DERs, such as energy storage, demand response, microturbines, fuel cells, and PV panels [13–15]. Because they are located close to electricity customers, DERs have the potential to fundamentally increase electric reliability and power quality. Nevertheless, centrally coordinating and controlling a fleet of DERs poses a challenge to grid operators [13,14]. One solution is to lump groups of DERs and electric loads into microgrids [13,16–18], which can behave as a single entity capable of operating in both grid-connected and island mode [4].

In this paper, we build on our previous work [19] to evaluate the impact of transformer-level CES coordinating with local PV generation and electric loads to form an islanded microgrid during an electric outage.

2.2. Battery modeling

Researchers have developed numerous models to describe the performance of a battery. The literature divides battery models into three major categories: electrochemical models, mathematical models and electrical models. Electrochemical models use fundamental electrochemical and chemical 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 [20]. Electrochemical models are primarily used as a design tool to optimize the performance of a battery. Newman and Dees have developed models of this kind for lithium-ion batteries [21,22].

Mathematical models use semi-analytical or empirical equations 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 mathematical models [5,6]. Other mathematical models describe a battery's non-linear capacity/recovery effects [23–26] or energy efficiency [27].

Electrical models are equivalent circuit models that describe the system-level behavior of a battery using a combination of variable voltage sources, resistors, and capacitors. A number of electrical models have been developed in the literature including Thévenin equivalent circuit models [28–30], impedance-based models [31–33], and runtime-based models [34,35]. A behavioral circuit model developed by Chen and Rincón-Mora combines the benefits of many of these models [7]. It accurately describes the nonlinear voltage of a battery, short-term and long-term transient effects, and nonlinear rate-capacity effects.

The objective of this paper is to describe the capabilities of a battery energy storage unit used to isolate downstream loads and provide emergency backup power during a distribution-level outage. In doing so, a large power load in excess of the battery's capacity might be applied for a short period of time. Furthermore, unlike a battery used in typical applications, a battery used for islanding will continue to discharge until its minimum cutoff voltage is reached, where the terminal voltage behavior is highly nonlinear. Thus, it is important to utilize a model capable of describing dynamic rate-capacity effects and end-of-discharge voltage behavior. Chen and Rincón Mora's model combines the benefits of a number of dynamic behavioral circuit models to describe both of these phenomenon without significant added complexity [7]. Thus, we select the behavioral circuit model from [7] for our analysis.

3. Model development and transformation

Chen and Rincón-Mora's model describes the state of a battery using two coupled electrical circuits, as shown in Fig. 1. The "battery lifetime circuit" on the left-hand side of Fig. 1 estimates a