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Balancing autonomy and utilization of solar power and battery storage for demand based microgrids

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HIGHLIGHTS

- Microgrids with solar power and energy storage are studied through modeling.
- A single particle battery model was used to study microgrid battery storage.
- System demand effects for microgrids are examined.
- Results on microgrid autonomy and battery usage are report for differing demands.
- Seasonal solar variation reduces battery utilization from optimal levels.

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ABSTRACT

The growth of intermittent solar power has developed a need for energy storage systems in order to decouple generation and supply of energy. Microgrid (MG) systems comprising of solar arrays with battery energy storage studied in this paper desire high levels of autonomy, seeking to meet desired demand at all times. Large energy storage capacity is required for high levels of autonomy, but much of this expensive capacity goes unused for a majority of the year due to seasonal fluctuations of solar generation. In this paper, a model-based study of MGs comprised of solar generation and battery storage shows the relationship between system autonomy and battery utilization applied to multiple demand cases using a single particle battery model (SPM). The SPM allows for more accurate state-of-charge and utilization estimation of the battery than previous studies of renewably powered systems that have used empirical models. The increased accuracy of battery state estimation produces a better assessment of system performance. Battery utilization will depend on the amount of variation in solar insolation as well as the type of demand required by the MG. Consumers must balance autonomy and desired battery utilization of a system within the needs of their grid.

1. Introduction

In the past decade, distributed energy resources (DER) have seen rapid growth as more small scale technologies for power generation have become economically favorable. DER growth has driven more communities and individual entities to operate Microgrids (MG), which allow consumers greater control over their energy resources [1]. Many of the DERs that are present in MGs are intermittent, renewable based generation such as solar and wind power. In order to be used effectively, these systems must utilize energy storage to provide power during times when generation is not producing at full capacity.

Within the electric grid, power generation must match consumer demand in real-time. Since electricity is perishable (it must be used immediately upon creation) and consumer demand can fluctuate on a short (seconds and minutes) timescale, power generation is often run in excess of actual demand requirements in order to maintain the minimum level of electricity required by the grid [2,3]. Energy storage can help to remove the perishable nature of electricity [4]. Energy storage is already used within the electric grid in the form of flywheels and other short term storage methods (used for spinning reserve) which help alleviate some of the excess

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capacity requirements, maintaining a robust and flexible grid. This type of storage however has a very short discharge time, and due to friction and kinetic losses will lose most of its stored energy within 15 min [5]. Applications where energy storage is useful in the current electric grid and MGs include: system regulation (frequency and voltage), spinning reserve, peak shaving, peak shifting, load leveling, and transmission support [6,7].

MGs combine DER and energy storage, allowing consumers to set up local electrical networks where power is produced and consumed without being transmitted over long distances. Two types of MGs exist: islanded and grid-tied systems. Islanded systems are not connected to any regional or national grids and must generate all of their power within the MG [8]. Grid tied systems can operate in islanded modes (sometimes referred to as emergency mode), however, they maintain a connection to the grid and will typically draw power from the grid during times of high demand and low internal generation. They will send power to the grid during times of high internal generation and low demand [9]. A grid-tied system will only go into islanded mode when the external grid has a failure and cannot supply power to the MG [10]. Grid-tied systems are less strict in their requirements for generation and storage sources because they can use the grid to supplement any power shortfalls and will take energy directly from the grid when economically favorable.

When deciding the desired autonomy of the system (the amount of time that the MG output will match demand), islanded systems will need to operate near 100% autonomy to be effective, while grid-tied systems can operate at lower levels [11]. Autonomy is the inverse metric of Loss of Power Supply Probability (LPSP) used in similar studies [12]. The desire for 100% autonomy can lead systems to be overbuilt (only using their theoretical capacity a few days per year) [13]. This paper studies how to maximize capacity usage based on a combination of demand and generation requirements.

Sizing and system performance analyses of battery systems have been performed for grid applications in connection with conventional generation sources [14], single intermittent renewable sources [15–17] and combined hybrid renewable source systems [11,12,18–20]. Inclusion of system demand within MGs has increased the fidelity of simulations [21]. However, when accounting for battery systems, these simulations utilize simple empirical-based or equivalent-circuit based models (ECM). When sizing and analyzing system performance for battery storage within grid applications, accurate measurements of state-of-charge (SOC) are required for both controlling the battery and monitoring the depth-of-discharge (DOD). The previous work mentioned above has not utilized models rigorous enough to provide accurate measurements of battery utilization and SOC throughout long simulation periods. Using inaccurate models for battery systems forces underutilization of battery capacities in order to maintain safe and continuous operation. Previous work has restricted the operational SOC range and limited DOD during operation [22]. Additionally, empirically based models struggle to account for capacity fade and changes to operating conditions. We show that using the SPM, autonomy and battery utilization can be tracked accurately over the course of an entire year, avoiding the problem of refitting the ECM for changing seasonal insolation.

1.1. Common definitions

The following terms and metrics will be used in assessing the system operational characteristics.

- *State-of-Charge (SOC)*: The percentage of a full charge that remains stored in the battery. A fully charged battery will have a SOC of 100% and a completely discharged battery will have a SOC of 0%. Our studies use lithium anode concentration to track SOC:

$$SOC = \frac{C_n^s}{C_{\max,n}^s} \tag{1.1}$$

- *Depth-of-Discharge (DOD)*: The percentage of capacity used during a discharge cycle. We track DOD based on SOC:

$$DOD = SOC_{initial} - SOC_{final} \tag{1.2}$$

- *Battery Utilization*: The amount of storage capacity used during battery storage. If a battery experiences a full discharge during one daily cycle, the battery utilization will be 100%. To track this metric in the SPM, all discharge energy is summed and divided by the energy discharged during a single 100% DOD discharge. For systems that experience a single cycle per day, this term approximates to the average DOD for a battery. For real systems this value could be greater than one if multiple deep cycles are experienced on a daily basis.

$$\text{Battery Utilization}_{Annual} = \frac{\sum Energy_{discharged}}{365(Energy_{100\%DOD})} \tag{1.3}$$

- *Maximum Power Demand to Maximum Solar Power Output Ratio (MDMP)*: This metric measures how the power demand relates to the power output from the solar array. For a solar array that has a maximum power rating of 1 MW, a MDMP ratio equal to one would correspond to a maximum power demand of 1 MW. The amount of energy that is demanded will vary based on the shape of the demand curve. The ratio is used so that the demand can be studied independently of the solar array and battery size.
- *Battery Energy Capacity to Solar Energy Capacity Ratio (BCSC)*: This metric measures the energy storage capacity of the battery in relation to the amount of energy supplied from the solar array during a day of 12 h solar insolation with no cloud cover. A ratio of one would mean that all of the energy produced by a solar array during a 12 h day could be stored in the battery. The BCSC ratio accounts for the energy capacity of the battery storage system. For most studies that BCSC will remain constant because the size of the solar array and battery capacity will remain constant, while different levels of demand are studied by altering the MDMP ratio (increasing the MDMP will simulate a larger demand for the same sized system).

This paper has defined the MDMP and BCSC ratios as new terms which help the analysis of combined solar-battery systems by allowing comparison between systems, independent of a specific system (or demand) size.

2. Microgrid elements

Three important elements of the MG model are: demand, generation, and storage. The relationship between these three