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Analytical sizing methods for behind-the-meter battery storage☆

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ABSTRACT

In behind-the-meter application, battery storage system (BSS) is used to reduce a commercial or industrial customer's payment for electricity use, including energy and demand charges. The potential value of BSS in payment reduction and the optimal size can be determined by formulating and solving standard mathematical programming problems. In such mathematical programming methods, users input system information such as load profiles, energy/demand charge rates, and battery characteristics to construct a standard programming problem, which typically involves a large number of constraints and decision variables. The problems are then solved by optimization solvers to obtain numerical solutions. Such kind of methods cannot directly link the obtained optimal battery sizes to input parameters and requires case-by-case analysis. In this paper, we present an objective quantitative analysis of costs and benefits for customer-side BSS, and thereby identify key factors that affect optimal sizing. We then develop simple but effective guidelines for determining the most cost-effective battery size. The proposed analytical sizing methods are innovative, and provide engineering insights on how the optimal battery size varies with system characteristics. We illustrate the proposed methods using practical building load profile and utility rate. The obtained results are compared with the ones using mathematical programming based methods for validation.

1. Introduction

The operation of electric power sector requires flexibility to realize instantaneous balance between generation and constantly changing demand. Wind and solar power have been developed rapidly in recent years world-wide. With their natural variability and uncertainty, these renewable energy resources introduce additional variation to power systems and present difficulties and challenges to system operators. Energy storage system (ESS) has been a candidate for meeting flexibility and reserve requirement from power grid for years. Recent developments and advances in energy storage and power electronics technologies are making the application of energy storage a viable solution for increasing flexibility and improving reliability of power systems. When delivered via behind-the-meter application, energy storage can play an even more significant role in increasing operation flexibility and reducing energy cost.

Many studies have been devoted to various ESS technologies for grid applications. The technical and economic characteristics of an array of ESS technologies are reviewed and compared in [1–3], including pumped hydro, battery storage, flywheel, compressed air, superconducting magnetic energy storage, and advanced capacitors. Studies [4,5] are dedicated to various battery technologies and methods of assessing their economic viability and impacts on power systems. The identified grid applications include energy arbitrage/load leveling, frequency regulation, load following, spinning and non-spinning reserves, T&D deferral etc. A review of several ESS technologies for wind power applications is provided in [6]. There are also many studies focusing on the optimal operation and sizing for BSS, and can be categorized into transmission, distribution and customer-side applications.

- Transmission: In [7], the authors evaluate the economic performance of NaS batteries for energy arbitrage and flywheels for regulation services based on fixed utilization factors for NYISO and PJM systems. Ref. [8] incorporates realistic CAISO regulation signals and battery responses to yield more granular results. In [9], the authors investigate the application of battery

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Nomenclature

a	battery equivalent capital cost with respect to energy size ($/kWh)
b	battery equivalent capital cost with respect to power size ($/kW)
E_{cycle}	the maximum amount of load that can be shifted from peak hours to off-peak hours considering battery storage power capacity
$E_{offpeak}$	the amount of energy charged during off-peak hours
E_{max}	battery storage energy capacity
E_{peak}	the amount of energy discharged during peak hours
N_D	number of days in a year
N_M	number of months in a year
p_{max}	battery storage power capacity
$r_{offpeak}$	off-peak rate ($/kWh)
r_{peak}	peak rate ($/kWh)
$T_{offpeak}$	duration (in h) of off-peak period
T_{peak}	duration (in h) of peak period
α	capital recovery factor (levelized annual fixed-charge rate)
β	monthly demand charge rate ($/kW/month)
Δr	saving in energy charge by cycling per unit energy from off-peak to peak time period
η_{round}	battery round-trip efficiency
ρ_{opt}	optimal ratio of energy size to power size for a battery storage system

storage system (BSS) for relief of transmission line thermal constraints, and therefore increase the transfer capability. Based on a case study, an economic analysis of benefits and costs is provided. Ref. [10] presents control algorithms and sizing strategies for using BSS to manage energy imbalance for variable generation resources. The authors in [11] develop an optimal control strategy of BSS for smoothing out the intermittent power from the wind farm. In [12], an evaluation framework and co-optimization are proposed to assess BSS economic performance considering multiple grid applications simultaneously, including energy arbitrage, balancing services, capacity value, distribution upgrade deferral, and outage mitigation. In [13], a method is proposed for identifying the sites where BSS should be located to perform spatial-temporal energy arbitrage most effectively and the optimal size of these systems.

- Distribution and microgrid: The authors of [14] present an optimal sizing method for BSS in a microgrid, where the unit commitment problem with spinning reserve for microgrid is formulated as a mixed linear integer problem. Ref. [15] investigates the potential of using BSS in the public low-voltage distribution grid, to defer upgrades needed to increase the penetration of photovoltaics, where a multi-objective optimization method is proposed to visualize the trade-offs between three objective functions: voltage regulation, peak power reduction, and annual cost. An optimal scheduling and cost-benefit analysis for microgrid applications is developed in [16]. Dynamic programming is used to solve the optimal scheduling problem and determine the optimal BSS power and energy ratings for both isolated and grid-connected microgrids. The authors in [17] formulate an optimization problem to minimize microgrid energy cost using BSS subject to operational constraints. A recent optimization technique called grey wolf optimization is then applied to solve the problem and determine the optimal BSS size. In [18], the authors develop a primary frequency control scheme for islanded microgrid using BSS. Then based on maximum mismatch power and permissible durations in the control scheme, the optimal battery sizing procedure is proposed. In [19], the authors develop a frequency-based approach to size a battery-supercapacitor energy storage system for maintaining power balance of an isolated system with high penetration of wind generation, thus to maintain the grid frequency stability with the stochastic wind power fluctuations.
- Customer-side: Customer-side BSS is gaining popularity among commercial and industrial businesses as a cost-effective solution to reduce energy and demand charges. In such an application, the battery is utilized by customers for saving energy cost, rather than by system operators for improving distribution system operation. This is also referred to as behind-the-meter BSS because the battery is literally "behind-the-meter", on the owner's property, not on the side of the electric utility. This market is predicted to grow rapidly. In California Public Utilities Commission's mandatory energy storage procurement targets, its IOUs are required to collectively procure 200 MW energy storage in the customer-side domain by 2020 [20]. According to GTM Research, over 700 MW of distributed energy storage will be deployed in the U.S. between 2014 and 2020 [21]. However, only few studies have been carried out for economic analysis and optimal sizing of battery storage in behind-the-meter application. In [22], the authors develop a peak-shaving control algorithm to determine battery charging and discharging operation, and then calculate the economic benefits in demand charge reduction for a few given battery sizes. Ref. [23] considers an application bundle including both energy and demand charge reduction. One application is treated as primary and determined first, and then the other application is evaluated. Ref. [24] explicitly formulates a co-optimization problem considering both the energy and demand charges. Dynamic programming technique is used to solve the problem to obtain the optimal charging schedule. The charging and discharging efficiencies have not been modeled. These papers provide different methods in evaluating economic benefits for a given size of battery storage, but have not addressed the optimal sizing problem considering the trade-off between economic benefit and cost. Therefore, the authors [25] study optimal sizing of a solar-plus-storage system for utility bill savings and resiliency benefits. Rather than formulating explicit optimal sizing problem, a number of simulations are carried out to obtain the economic and resiliency benefits for different solar-plus-storage sizes, and then select the optimal one. In [26], the authors formulate linear optimization problems for economic analysis and optimal sizing of behind-the-meter BSS. This method explicitly models the charging and discharging efficiencies and co-optimizes the battery operation for both energy and demand charge reduction. No analytical expression is given for optimal battery sizes as functions of key factors such as load magnitude, energy/demand charge rate, peak/off-peak time periods, and therefore cannot provide much engineering insights on how the optimal battery size varies with those factors. This motivates the work presented in this paper.

This paper presents analytical sizing methods for behind-the-meter battery storage. The main contributions of this paper are summarized as follows.

- Developing analytical sizing method for battery storage is a challenging problem. Existing methods rely on standard mathematical programming for battery operation and sizing analysis, which cannot explicitly directly link the output to input parameters and requires case-by-case analysis. This paper proposes an innovative objective quantitative analysis of costs