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Exact sizing of battery capacity for photovoltaic systems

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ABSTRACT

In this paper, we study battery sizing for grid-connected photovoltaic (PV) systems. In our setting, PV generated electricity is used to supply the demand from loads: on one hand, if there is surplus PV generation, it is stored in a battery (as long as the battery is not fully charged), which has a fixed maximum charging/discharging rate; on the other hand, if the PV generation and battery discharging cannot meet the demand, electricity is purchased from the grid. Our objective is to choose an appropriate battery size while minimizing the electricity purchase cost from the grid. More specifically, we want to find a unique critical value (denoted as E^c_{max}) of the battery size such that the cost of electricity purchase remains the same if the battery size is larger than or equal to E^c_{max}, and the cost is strictly larger otherwise. We propose an upper bound on E^c_{max}, and show that the upper bound is achievable for certain scenarios. For the case with ideal PV generation and constant loads, we characterize the exact value of E^c_{max}, and also show how the storage size changes as the constant load changes; these results are validated via simulations.

1. Introduction

Installations of solar photovoltaic (PV) systems have been growing at a rapid pace in recent years due to the advantages of PV such as modest environmental impacts (clean energy), avoidance of fuel price risks, coincidence with peak electrical demand, and the ability to deploy PV at the point of use. In 2010, approximately 17,500 megawatts (MW) of PV were installed globally, up from approximately 7500 MW in 2009, consisting primarily of grid-connected applications [2]. Since PV generation tends to fluctuate due to cloud cover and the daily solar cycle, energy storage devices, e.g., batteries, ultracapacitors, and compressed air, can be used to smooth out the fluctuation of the PV output fed into electric grids (capacity firming) [14], discharge and augment the PV output during times of peak energy usage (peak shaving) [16], or store energy for nighttime use, for example in zero-energy buildings.

In this paper, we study battery sizing for grid-connected PV systems to store energy for nighttime use. Our setting is shown in Fig. 1. PV generated electricity is used to supply loads: on one hand, if there is surplus PV generation, it is stored in a battery for later use or dumped (if the battery is fully charged); on the other hand, if the PV generation and battery discharging cannot meet the demand, electricity is purchased from the grid. The battery has a fixed maximum charging/discharging rate. Our objective is to choose an appropriate battery size while minimizing the electricity purchase cost from the grid. We show that there is a unique critical value (denoted as E^c_{max}, refer to Problem 1) of the battery capacity (under fixed maximum charging and discharging rates) such that the cost of electricity purchase remains the same if the battery size is larger than or equal to E^c_{max}, and the cost is strictly larger otherwise. We first propose an upper bound on E^c_{max} given the PV generation, loads, and the time period for minimizing the costs, and show that the upper bound becomes exact for certain scenarios. For the case of idealized PV generation (roughly, it refers to PV output on clear days) and constant loads, we analytically characterize the exact value of E^c_{max}, which is consistent with the critical value obtained via simulations.

The storage sizing problem has been studied for both off-grid and grid-connected applications. For example, the IEEE standard [11] provides sizing recommendations for lead-acid batteries in stand-alone PV systems. In [18], the solar panel size and the battery size have been selected via simulations to optimize the operation of a stand-alone PV system. If the PV system is grid-connected, batteries can reduce the fluctuation of PV output or provide economic benefits such as demand charge reduction, capacity firming, and power arbitrage. The work in [1] analyzes the relation between available battery capacity and output smoothing, and estimates the required battery capacity using simulations. In addition, the battery sizing problem has been studied for wind power applications [21,5,12] and hybrid wind/solar power applications [4,8,20]. Most previous work completely

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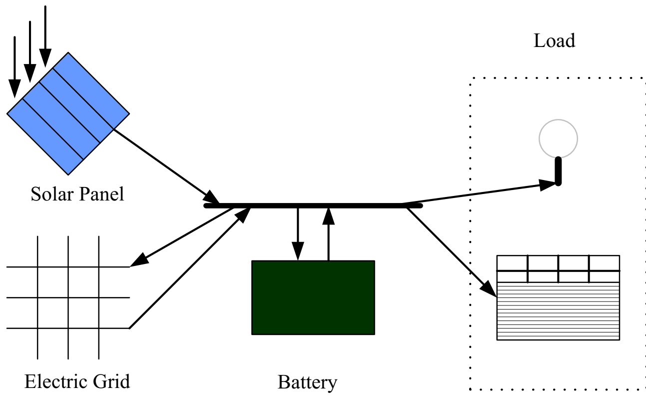

Fig. 1. Grid-connected PV system with battery storage and loads.

relies on trial and error approaches to calculate the storage size. Only very limited work has contributed to the theoretical analysis of storage sizing, such as [13,9,17]. In [13], discrete Fourier transforms are used to decompose the required balancing power into different time-varying periodic components, each of which can be used to quantify the physical maximum energy storage requirement. In [9], the storage sizing problem is cast as an infinite horizon stochastic optimization problem to minimize the long-term average cost of electric bills in the presence of dynamic pricing as well as investment in storage. In [17], we cast the storage sizing problem as a finite horizon deterministic optimization problem to minimize the cost associated with the net power purchase from the electric grid and the battery capacity loss due to aging while satisfying the load and reducing peak loads. Lower and upper bounds on the battery size are proposed that facilitate the efficient calculation of its value. The contribution of this work is the following: exact values of battery size for the special case of ideal PV generation and constant loads are characterized; in contrast, in [17], only lower and upper bounds are obtained. In addition, the setting in this work is different from that of [9] in that a finite horizon deterministic optimization is formulated here. These results can be generalized to more practical PV generation and dynamic loads (as discussed in Remark 10).

We acknowledge that our analysis does not apply to the typical scenario of "net-metered" systems,[1] where feed-in of energy to the grid is remunerated at the same rate as purchase of energy from the grid. Consequently, the grid itself acts as a storage system for the PV system (and E^c_{max} becomes 0). However, from a grid operator standpoint it would be most desirable if the PV system could just serve the local load and not export to the grid. This motivates our choice of no revenue for dumping power to the grid. Our scenario also has analogues at the level of a balancing area by avoiding curtailment or intra-hour energy export. For load balancing, in a balancing area (typically a utility grid) steady-state conditions are set every hour. This means that the power imports are constant over the hour. The balancing authority then has to balance local generation with demand such that the steady state will be preserved. This also corresponds to avoiding "outflow" of energy from the balancing area. In a grid with very high renewable penetration, there may be more renewable production than load. In that case, the energy would be dumped or "curtailed". However, with demand response (e.g., loads with relatively flexible schedules) or battery storage, curtailment could be avoided.

[1] Note that in [17], we study battery sizing for "net-metered" systems under more relaxed assumptions compared with this work.

The paper is organized as follows. In the next section, we introduce our setting, and formulate the battery sizing problem. An upper bound on E^c_{max} is proposed in Section 3, and the exact value of E^c_{max} is obtained for ideal PV generation and constant loads in Section 4. In Section 5, we validate the results via simulations. Finally, conclusions and future directions are given in Section 6.

2. Problem formulation

In this section, we formulate the problem of determining the storage size for grid-connected PV system, as shown in Fig. 1. Solar panels are used to generate electricity, which can be used to supply loads, e.g., lights, air conditioners, microwaves in a residential setting. On one hand, if there is surplus electricity, it can be stored in a battery, or dumped to the grid if the battery is fully charged. On the other hand, if there is not enough electricity to power the loads, electricity can be drawn from the electric grid. Before formalizing the battery sizing problem, we first introduce different components in our setting.

2.1. Photovoltaic generation

We use the following equation to calculate the electricity generated from solar panels:

$$P_{pv}(t) = \mathrm{GHI}(t) \times S \times \eta, \tag{1}$$

where GHI ($\mathrm{W\,m^{-2}}$) is the global horizontal irradiation at the location of solar panels, S ($\mathrm{m^2}$) is the total area of solar panels, and η is the solar conversion efficiency of the PV cells. The PV generation model is a simplified version of the one used in [15] and does not account for PV panel temperature effects.

2.2. Electric grid

Electricity can be drawn from (or dumped to) the grid. We associate costs only with the electricity purchase from the grid, and assume that there is no benefit by dumping electricity to the grid. The motivation is that, from a grid operator standpoint, it would be most desirable if the PV system could just serve the local load and not export to the grid. In a grid with very high renewable penetration, there may be more renewable production than load. In that case, the energy would have to be dumped (or curtailed).

We use $C_{gp}(t)$ (¢/kW h) to denote the electricity purchase rate, $P_{gp}(t)$ (W) to denote the electricity purchased from the grid at time t, and $P_{gd}(t)$ (W) to denote the surplus electricity dumped to the grid or curtailed at time t. For simplicity, we assume that $C_{gp}(t)$ is *time independent* and has the value C_{gp}. In other words, there is no difference between the electricity purchase rates at different time instants.

2.3. Battery

A battery has the following dynamic:

$$\frac{dE_B(t)}{dt} = P_B(t), \tag{2}$$

where $E_B(t)$ (W h) is the amount of electricity stored in the battery at time t, and $P_B(t)$ (W) is the charging/discharging rate (more specifically, $P_B(t) > 0$ if the battery is charging, and $P_B(t) < 0$ if the