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Energy dispatch schedule optimization and cost benefit analysis for grid-connected, photovoltaic-battery storage systems

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ABSTRACT

A linear programming (LP) routine was implemented to model optimal energy storage dispatch schedules for peak net load management and demand charge minimization in a grid-connected, combined photovoltaic-battery storage system (PV+ system). The LP leverages PV power output and load forecasts to minimize peak loads subject to elementary dynamical and electrical constraints of the PV+ system. Battery charge/discharge were simulated over a range of two PV+ system parameters (battery storage capacity and peak load reduction target) to obtain energy cost for a time-of-use pricing schedule and the net present value (NPV) of the battery storage system. The financial benefits of our optimized energy dispatch schedule were compared with basic off-peak charging/on-peak discharging and real-time load response dispatch strategies that did not use any forecast information. The NPV of the battery array increased significantly when the battery was operated on the optimized schedule compared to the off-peak/on-peak and real time dispatch schedules. These trends were attributed to increased battery lifetime and reduced demand charges attained under the optimized dispatch strategy. Our results show that Lithium-ion batteries can be a financially viable energy storage solution in demand side, energy cost management applications at an installed cost of about $400–$500 per kW h (approximately 40–50% of 2011 market prices). The financial value of forecasting in energy storage dispatch optimization was calculated as a function of battery capacity ratio.

1. Introduction

Adoption of advanced energy storage technologies as a means to integrate renewable energy resources into electric grids will dramatically increase in the next decade. 28 states in the United States of America have enacted mandatory renewable portfolio standards (RPS) and 5 additional states have adopted voluntary RPSs. RPSs require electricity providers to obtain a minimum percentage of their power from renewable energy resources by a certain date [1]. The state of California has set an ambitious RPS of 33% renewable electricity generation by the year 2020 [2] and passed legislation to determine energy storage procurement targets for both privately and publicly owned utilities [3]. Although critical applications for large scale energy storage (and the associated costs, benefits and market potentials) have been clearly identified [4,5], dispatch strategies for stored energy that maximize the financial value of combined renewable generation and energy storage systems (hereafter RSS) are not well quantified or understood in an operational context [6].

Many models have been developed to determine optimal scheduling for stored energy dispatch in RSSs. The objectives of these modeling studies can be broadly classified in two categories, utility side applications and demand side applications [7]. Utility side applications focus on optimizing properties of the RSS output that are economically beneficial to electric utilities (e.g. renewable capacity firming, transmission and distribution upgrade deferral, transmission support, etc.). The financial benefits associated with some utility side applications may be difficult to quantify (e.g. transmission support).

Demand side applications optimize the economics of the RSS when the system is installed “behind the meter”. In this case economic benefits are usually quantified in terms of energy bill savings for the RSS owner who purchases power from an electric utility (e.g. time-of-use energy cost management, demand charge management, etc.). Lee and Chen [8] used an advanced multi-pass dynamic programming (AMPDP) algorithm to optimize contract capacities and optimal energy storage capacity of stand-alone BESSs for utility customers that incur time-of-use (TOU) electricity rates. They found that optimal BESS capacity could be determined and varied significantly based on the customer’s load profile. A number of studies have investigated optimal energy storage

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Nomenclature

A	annual energy bill savings
E	energy
f	objective function
M	number of forecast update times
N	number of timesteps
NCC	number of charge cycles at 80% depth of discharge
NPV	net present value
OM	operation and maintenance costs
P	power (dE/dt)
R	power ramp rate (dP/dt)
r	discount rate
T	nominal battery lifetime
t	time.

Greek symbols

Δ	discrete change
ε	forecast accuracy (safety) factor.

Superscript

DC rating	DC nameplate rating of the PV array
m	forecast update index
max	maximum value
min	minimum value
n	time index
target	target value, objective
total	total energy capacity of the battery array.

Subscript

0	initial condition ($n = 0$)
l	load
lf	load forecast
o	PV+ output
opt	computed with LP optimization routine, i.e. Eqs. (1)–(3)
p	PV output
pf	PV output forecast
s	battery (storage)
update	time between forecast updates.

Symbols

<>	denotes a time average.

capacity and dispatch, and economics for PV+ systems.[1] Su et al. [9] implemented a closed-loop control system to modulate power output from a PV+ system for demand charge management, TOU energy price arbitrage, emergency power supply and transmission support. Su et al. concluded that the economic viability of PV+ systems is site specific and depends strongly on the end user load shape, utility rate schedule, PV+ capacity and choice of application. However, their evaluation only considered a single PV+ system with fixed PV nameplate rating and battery capacity. Hoff et al. [10] studied the economic benefits of PV+ for emergency power supply and demand charge management applications for typical industrial customers. Hoff et al. found that financial benefits from emergency power supply exceeded benefits from demand charge management; however, they assumed that the entire battery capacity would be devoted to one application and only considered two PV+ systems with fixed PV nameplate rating and battery capacity. Shimada and Kurokawa [11] modeled annual energy bill savings for a PV+ system over a range of battery capacities. They used an approximate insolation forecast and a load forecast to determine the amount of night time charging required to minimize the cost of energy purchased by the customer from the electric utility during the following day. Shimada and Kurokawa found that the value of the PV+ system was significantly increased by using day-ahead, hourly insolation and load forecasts to inform the energy storage dispatch scheduling algorithm, and they identified optimal battery capacities in terms of end user peak load. Ru et al. [12] used a mixed integer linear programming (MILP) framework to determine optimal battery energy capacity (in the context of marginal energy cost) for a PV+ system, and implemented a peak reduction objective assuming perfect net load forecasts. The most comprehensive model to quantify the economic value of general RSS in demand side applications is the Distributed Energy Resources Customer Adoption Model [13]. DER-CAM minimizes costs of operating on-site customer generation considering combinations of many different distributed generation technologies, dispatched in a variety of demand side applications, and electrical tariffs.[2] Stadler et al. [14] used DER-CAM to study demand charge management and CO_2 emissions minimization strategies in PV+ systems. Their results showed that for demand charge management it is most economically efficient to charge batteries from the electric grid during off-peak hours, while charging batteries directly from zero emissions PV generation for CO_2 minimization results in extraordinarily high energy costs to the customer.

In this paper we consider an idealized PV+ system in which a PV array and a Lithium-ion battery array are connected to the utility electric grid (Fig. 1). The goal is to determine the optimal dispatch schedule for the energy stored in the battery to achieve a preset amount of load peak shaving (i.e. demand charge management). The optimization algorithm is formulated as a linear program (LP) and leverages day-ahead PV power output and load forecasts with regular updates to determine the best time to charge or discharge the battery subject to basic dynamical and electrical performance constraints of the PV + system. System economics were quantified by the net present value (NPV) of the battery. The financial value of PV power output and load forecasts was calculated in an energy bill minimization application of the PV+ system. We also computed the market price at which large scale (240–1270 kW h), Lithium-ion battery energy storage becomes financially viable in demand side, energy bill minimization applications. The model formulation and structure are described in Section 2, results from analysis of model output are presented in Section 3. Sections 4 and 5 are a discussion of our results and conclusions.

2. Methodology

2.1. Linear optimization model

Fig. 1 shows a schematic of the idealized PV+ system in which a PV array, a Lithium-ion battery array, and a load are connected to

[1] The term PV+ was coined by Hoff et al. [10] and refers to combined photovoltaic and battery energy storage systems where the battery is placed “behind the meter”.

[2] The primary disadvantage of DER-CAM is that, due to its complexity and native software, the model is not yet suitable for widespread public release, although some DER-CAM functionality is available to end users through the Storage Viability and Optimization Web Service [15].