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Battery capacity determination with respect to optimized energy dispatch schedule in grid-connected photovoltaic (PV) systems

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A R T I C L E I N F O

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This paper describes an approach to optimize the capacity of battery used in a grid-connected photovoltaic system (PV/storage system). Scheduling of the battery after installation has to be considered for the optimal design; because battery degradation cost is mainly a function of system operation. In this paper, peak shaving and load shifting which are important applications of PV/storage systems are studied. Load shifting is mostly implemented when time-of-use pricing is in effect and peak shaving is beneficial when utility customers are charged for peak of demand. In order to account for seasonality in system net load, data clustering techniques are implemented to produce scenarios for net load of the customer. Then, the proposed Mixed Integer Programming (MIP) model of the optimization problem is solved. To illustrate the important cost of battery degradations, a model of non-ideal battery is also studied and the results are compared with the case which ideal model of battery is used. Results show that sizing determination of the battery highly depends on the exact pricing structure. In addition, it is illustrated that, considering real assumptions for battery ageing is necessary to reliably estimate financial benefits of storages in PV/storage systems.

1. Introduction

With the global economic development and population growth, large amount of energy is required to meet the present electricity demands. Global warming, environment pollution and the rapid depletion of fossil fuel resources, culminated in an increase in the use of renewable energy sources as a viable alternative to fossil fuels. Among renewable energy technologies, grid-connected photovoltaic application has gained a great attention in research because it appears to be one of the most efficient solutions to these environmental problems [1].

In most of countries, the maximum output power of photovoltaic (PV) systems may not be consistent with the period of system peak load. Energy storage systems combined with grid-connected PV systems (PV/storage system), store electricity generated from PV systems during off-peak hours for discharging during peak load hours [2]. Battery energy storage systems are used most commonly as storage devices in grid-connected PV systems [3–5]. The above mentioned potential of storage systems provides benefits for the customers with grid-connected PV system through various applications [6]. Customers with PV/storage system can reap benefits by charging the storage with excess generation of the PV early in the day to support a load later (i.e. load shifting). If a customer is charged for peak of the requested power (i.e. demand charge), the PV/storage system preserves required power above a specified threshold and provides benefits for the system owner (i.e. peak shaving). PV/storage system also allows the customers to contribute to energy load reduction in response to market prices, with little or no effect on local operations; and utilize financial incentives offered by the utilities (i.e. demand response strategies). The financial benefits of PV/storage systems are mostly achieved through the above mentioned applications. However, these benefits highly depend on the exact tariff structure and policies where the consumer lives. Recently with increased implementation of smart meters, net metering policies and electric vehicles, some utility companies introduced time-of-use rates and peak demand charges for their customers. Customers who purchase electricity under these tariffs are more interested to install PV/storage system and achieve financial benefits through load shifting (especially under time-of-use rates) and peak shaving (especially under a demand charge based tariffs) [6].

In addition to the price structure, the sizes of system components and system operation affect the performance of the PV/storage system. This article deals with optimization of battery capacity in a grid-connected PV system for the customers who

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Nomenclature

A. Abbreviations

BESS	battery energy storage system
FCM	Fuzzy Clustering Method
TOU	time-of-use
TOUD	time-of-use with specifying demand charge
MIP	Mixed Integer Programming

B. Indices

k	data point
j	cluster
i	day
t	time-step

C. Parameters

N	number of data point
c	number of clusters
m	degree of fuzziness
η_{Bi}	battery inverter efficiency [%]
η_{pi}	photovoltaic (PV) inverter efficiency [%]
I	global horizontal irradiation [W/m^2]
A	total area of PV modules [m^2]
η_{pv}	solar conversion efficiency of PV modules [%]
Δt	sampling interval [h]
t_0	initial time of the optimization process [h]
Z	ageing coefficient
C_{ref}	the nominal capacity of battery [Wh]
η_B	conversion efficiency of battery [%]
η_{BR}	round-trip efficiency of battery [%]
E_P	electricity price [$/kWh]
nu	number of days of month
D_C	demand charge [$/kW]
B_{FC}	battery investment cost [$]
SOH_{min}	minimum state of health of the battery [%]
P_L	the electricity load of the customer [W]
$E_{B\ min}$	minimum stored energy in the battery [Wh]
$P_{Bdc\ min}$	minimum charge/discharge rate of the battery [W]
$P_{Bdc\ max}$	maximum charge/discharge rate of the battery [W]
t_H	minimum charge/discharge time of the battery [h]
b	indicator variable
n	number of studied days
N_{year}	number of years in studied dataset
N_{data}	number of days in studied dataset
P	probability of each cluster
PDT	peak demand target [W]

D. Variables

P_{Bdc}	charge/discharge rate of the battery [W]
P_{Bac}	charging/discharging rate of the battery on AC bus [W]
E_B	stored energy in the battery [Wh]
ΔC	cumulative battery capacity loss [Wh]
C	the usable battery capacity [Wh]
BCL	battery capacity loss [Wh]
ECB	energy cost and benefit [$]
PDC	peak demand cost [$]
C_{BCL}	cost of battery capacity loss [Wh]
P_{Net}	net power of the grid [W]
P_{demand}	peak of the electricity demand [W]
ANP	annual net profit [$]
ΔC_{year}	battery capacity loss during one year [Wh]
ΔC_{day}	battery capacity loss in ith studied day [Wh]
A_C	annual cost of the system operation [$]

purchase electricity on a time-of-use basis or a demand charge based tariff. Optimization of battery capacity with respect to operation of the battery after installation in the system is necessary to fully achieve financial benefits of battery storage in a grid-connected PV/storage system. An effective scheduling strategy should be capable of responding to frequent and dynamic load changes [2]. Also, cost of battery ageing should be taken into account in the optimization of energy dispatch schedule of the battery.

To determine optimal battery capacity for a typical customer equipped with PV system, the customers load and PV output through several years should be taken into account. Because, several years of data existing, using data clustering method is the most reasonable approach to determine battery capacity with respect to optimal scheduling of battery [7,8]. In this paper, Fuzzy Clustering Method (FCM) is utilized to produce scenarios for the battery sizing problem. To illustrate the effectiveness of this method under time-varying pricing structures, time-of-use (TOU) and time-of-use with specifying demand charge (TOUD) tariffs proposed by Duke Energy Progress North Carolina [9] are evaluated. A typical customer is considered and optimal battery capacity under each of pricing structures is obtained and important effects of electricity tariff on optimal battery capacity are evaluated. Also, an ideal and a non-ideal model of battery ageing are studied and the importance of battery ageing cost is investigated.

2. Related work

There is a wide literature on battery scheduling and sizing for PV systems, but mostly focused on stand-alone applications. Simulation and optimization of stand-alone systems with PV and battery energy storage have been the subject of several publications [10–14]. Recently, optimization of storages in grid-connected PV systems attracted increasing interest. However, there is little in the way of guidance on battery sizing with respect to optimal scheduling of the battery. Ref. [15] presents a predictive control system based on a dynamic programming approach, which optimizes the power flow management into a grid-connected PV system with energy storage system. In Ref. [2] a short-term optimized dispatch schedule of energy stored in the battery is presented and the effect of grid-connected PV/battery system on locational pricing, peak load shaving, and transmission congestion management is analyzed. Ref. [16] presents the construction and the performance of a distributed power generating system of PV/storage. Accordingly, financial benefit and load-levelling capacity of the system have been studied. The sizing problem is not studied in the mentioned papers. Ref. [17] presents the modelling, simulation, and sizing results of battery energy storage systems for residential electricity peak shaving, with the objective of reducing the peak electricity demand seen by the electricity grid. The model simulates and provides performance results of a range of battery and inverter sizes specific to a variety of residential houses. However, battery life is not considered in daily operation and the economics effects of peak shaving on residential customer bills are not investigated. Paper [18] studies the problem of the battery size determination used in grid-connected PV systems for the purpose of load shifting and peak shaving under time-of-use rates. The optimization problem is modelled to obtain the optimal energy dispatch schedule which minimizes the cost associated with net power purchase from the electric grid and the battery capacity loss.