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A logic-based geometrical model for the next day operation of PV-battery systems

Qianwen Zhong[a], Rajab Khalilpour[b], Anthony Vassallo[b,*], Yize Sun[a,**]

[a] School of Mechanical Engineering, Donghua University, China
[b] Faculty of Engineering & Information Technologies, University of Sydney, Australia

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ABSTRACT

This article presents a new control model for the optimal next day management of a PV-battery system using a geometrical analysis method under two electricity tariff schemes. The method is visual, simple and reduces calculation times by determining the control scheme only once a day, using 24-h forecasting of PV output and demand. The optimization goal of this method is to minimize the customer's daily expenditure on electricity from the grid. The cases studied in this work validate the effectiveness of this geometrical method which would be applicable in many countries with different tariff mechanisms. From a comparison of the control model under two tariffs, the results show that under a flat retail tariff (ReT), the battery needs only to store the surplus PV energy for later use, but under a Time-of-Use (ToU) ReT, the battery controller should optimize the battery state of charge according to the level of demand during peak and shoulder times.

1. Introduction

Renewable energy addresses two current energy-related crises, greenhouse gas emission and the fast growing demand for energy. Among new energy technologies, photovoltaic (PV) generation appears to be one of the most efficient and effective solutions, economically and environmentally [1].

Solar PV is one of the most plentiful and widely distributed sources of renewable power generation. However, one of the most critical problems hindering its development is the high variability of solar irradiation. This variation is not only associated with day/night regular cycles or seasonal changes, but is also influenced by the formation and movement of clouds. In fact the latter is the most critical challenge, due to the difficulty of forecasting. Moreover, demand variations become more complex with the increasing diversity of devices. To overcome the challenges generated from the above shortcomings, such as power fluctuations, voltage rises, high losses and low voltage stability, energy storage can be used to improve the dispatch of energy by storing PV surplus and shifting load [2]. Thus, efficient utilization of PV output and control of energy storage units in grid-connected PV-battery systems are key optimization issues.

Recent years have evidenced a fast-increasing rate of studies relevant to PV-battery system operation. Lu and Shahidehpour present a short-term scheduling of a battery in a grid-connected PV systems that applies an optimization method based on security-constrained unit commitment. The method uses a Lagrangian relaxation technique to schedule the battery's charging and discharging in a utility grid and a network flow programming algorithm for the dispatch of committed battery units [3]. Vasallo et al. propose a methodology based on an existing sizing tool called HOMER. The aim of this work is to obtain minimum life cycle cost system according to defined load and backup time data [4]. Two energy dispatch controllers are presented by Venayagamoorthy and Welch. [5]. One controller uses a critic neural network based on a class of adaptive critic designs called action dependent heuristic dynamic programming. The other controller uses an action neural network based upon expert knowledge, codified into a series of static rules. Castillo-Cagigal, et al. study on the effects of the Active Demand-Side Management and storage systems in the amount of consumed local electrical energy [6]. A self-sufficient solar house called "MagicBox" is developed with grid connection, PV generation, lead–acid batteries, controllable appliances and smart metering. However, the complexity of the system increases through considering information on local conditions. The economic and environmental impact of the application of lead-acid

* Corresponding author.
** Corresponding author.
E-mail addresses: Anthony.vassallo@sydney.edu.au (A. Vassallo), sunyz@dhu.edu.cn (Y. Sun).

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Nomenclature

ReT	Retail tariff
ToU	Time-of-use tariff
FiT	Feed-in tariff
x	Electricity from grid
y	Electricity from PV
η_{con}	Efficiency of the converter
η_c	Efficiency of the battery charging state
η_d	Efficiency of the battery discharging state
η_{in}	Efficiency of the inverter
B_0	Usable energy of the battery at time 0
B_t	Usable energy of the battery at time t
B_{max}	Maximum dischargeable energy of the fixed size battery
B_{size}	Battery capacity
A_1	Total energy difference between load and PV from the beginning of the day to the first intersection point
A_2	Total PV surplus energy
A_3	Total energy difference between load and PV from the second intersection point to end of the day
t_1	End time of the first off-peak period
t_2	Time of the first intersection point
t_3	Time of the second intersection point
t_4	End time of the peak period
t_5	End time of the second shoulder period
$A_{1.1}$	Total energy difference between load and PV from the beginning of the day to time t_1
$A_{1.2}$	Total energy difference between load and PV from time t_1 to time t_2
$A_{3.1}$	Total energy difference between load and PV from time t_3 to time t_4
$A_{3.2}$	Total energy difference between load and PV from time t_4 to time t_5
$A_{3.3}$	Total energy difference between load and PV from time t_5 to end of the day

batteries is assessed by McKenna et al. [7]. Their results unexpectedly show that, under current feed-in tariff arrangements in the UK, both economic and environmental benefits are negative, even when the battery is considered as an idealized lossless system. Nottrott et al. present a linear programming routine to model optimal energy storage dispatch schedules for peak net load management and demand charge minimization without considering the efficiencies of the inverter and converter [8]. Ru et al. obtain a criterion for considering charging loss of the battery by comparing the benefit of a battery with the purchases from the grid, while at the same time satisfying the load and reducing the peak electricity purchase from the grid [9]. Others have considered the battery degradation cost, seasonality change of data, and different pricing structures to optimize the scheduling and capacity of the battery [10]. Penangsang et al. introduce a method called ‘Interval type-2 fuzzy adaptive genetic algorithm’ which takes the annual cost of the system (consisting of annual capital cost, annual replacement cost, annual and annual operation cost maintenance) as the objective function [11]. Hanna et al. present a battery storage dispatch strategy using a linear programming routine that minimizes peak non-coincident demand that optimizes demand [12]. The method evaluated the robustness, reliability and consistency in the algorithm and is simulated for a summer and a winter month in an operational environment. Aghamohammadi and Abdolahinia present a control scheme for a DC/AC converter by considering overloading characteristics and limitations of the state of charge of the battery [13]. The difference of this method is its focus on the primary frequency control of a micro-grid for determining the optimal size of a battery energy storage system (BESS). Chen and Lan propose a “demand response” (DR) approach to a smart home with PV generators and a battery system [14]. The method gives a users’ load model and uses an interior point method for optimal scheduling with elastic power utilization to minimize power price [14]. Based on the latent reactive power capability and real power curtailment of single-phase inverters, Su et al. study a multi-objective optimal power flow problem that can simultaneously improve voltage magnitude and balance profiles [15]. The method minimizes network losses and generation costs that can be converted into an aggregated single-objective optimal power flow problem using the weighted-sum method, effectively solved by the global sequential quadratic programming approach with multiple starting points in MATLAB. A PV power generation and load-power consumption prediction algorithms are presented in [16], specifically designed for a residential storage controller. The proposed storage control algorithm is separated into a global control tier and a local control tier. The global tier is formulated and solved as a convex optimization problem at each decision epoch, whereas the local tier is analytically solved.

The optimization of hybrid new energy storage system is also being solved by researchers using a range of somewhat complex mathematical methods. New multi-objective index based analytical expressions with a self-correction algorithm have been proposed [17] to capture the size and power of the combination of PV and BES units. Bernardon et al. present a new methodology to perform an automatic reconfiguration of distribution networks incorporating distributed generation in normal operation [18]. A multi-criteria hierarchy process method has been employed to determine the best sequence of switching. The effects of different degrees of complementarity in time of the energy resources on the performance of hydro PV plants have been studied [19]. A method based on chance-constrained programming to determine the optimal size of hybrid renewable energy system components has been proposed, considering uncertainties in renewable resources. An efficient stochastic framework using the probability distribution function and the adaptive modified firefly algorithm has been proposed to investigate the effect of uncertainty on the optimal operation management of MicroGrids [20]. An economical approach has also been presented [21] enabling the calculation of break-even points for storage systems as a substitute to conventional grid reinforcements. A sizing methodology has been presented to optimize a hybrid energy system (HES) configuration based on a genetic algorithm [22]. A stochastic framework has been built for optimal sizing and reliability analysis of a hybrid power system including the renewable resources and energy storage system [23]. Uncertainties of wind power, photovoltaic power, and load are stochastically modeled using the autoregressive moving average. A multi criteria approach [24] uses a method called compromise programming and takes into account the technical, economic, environmental and social criteria. Garcia-Trivino et al. describe and evaluate an adaptive neuro-fuzzy inference system-based energy management system (ANFIS) of a grid-connected hybrid system [25]. Three energy management systems (EMSs) based on particle swarm optimization (PSO) for long-term operation optimization of a grid-connected hybrid system are discussed in [26]. Maleki and Askarzadeh evaluate the performance of different artificial intelligence techniques (PSO, tabu search, simulated annealing, and harmony search)for optimum sizing of a PV/wind/fuel cell hybrid system to continuously satisfy the load demand with the minimal total annual cost [27].

As evident from the above literature, there have been extensive studies of PV-storage modelling most of which require complex