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Demand side management of photovoltaic-battery hybrid system

Zhou Wu *, Henerica Tazvinga, Xiaohua Xia

Department of Electrical Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa

HIGHLIGHTS

- Hybrid system under TOU with power selling is modeled to minimize electricity cost.
- Optimal control is developed to dispatch power flow economically.
- Model predictive control is applied to ensure economic and robust operation of hybrid system.

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ABSTRACT

In the electricity market, customers have many choices to reduce electricity cost if they can economically schedule their power consumption. Renewable hybrid system, which can explore solar or wind sources at low cost, is a popular choice for this purpose nowadays. In this paper optimal energy management for a grid-connected photovoltaic-battery hybrid system is proposed to sufficiently explore solar energy and to benefit customers at demand side. The management of power flow aims to minimize electricity cost subject to a number of constraints, such as power balance, solar output and battery capacity. With respect to demand side management, an optimal control method (open loop) is developed to schedule the power flow of hybrid system over 24 h, and model predictive control is used as a closed-loop method to dispatch the power flow in real-time when uncertain disturbances occur. In these two kinds of applications, optimal energy management solutions can be obtained with great cost savings and robust control performance.

1. Introduction

Renewable energy (RE) sources, including wind, solar and their hybrid systems, have become attractive options of providing energy globally for reasons such as low cost, no pollutant emission, energy security, easy accessability and reduction fossil fuel consumption [1–4]. Photovoltaic (PV) array, which is the main technology to convert solar energy into electric power, can be stand-alone installed for providing electricity in some remote areas or be connected to the grid for selling power generated. Because of instantaneous and unstable nature of solar energy, PV usually works with battery storage to provide continuous and stable power, i.e., the PV-battery hybrid system. Battery storage can reduce the risk of PV's intermittent power supply, and always ensure demand satisfaction. Generally, grid-connected PV systems without battery storage do not require sophisticated management strategies. Prioritizing use of PV power is the only rule when the PV power is less than the load demand. In contrast, battery storage brings more challenges to energy management, as more complicated scenarios must be considered, such as charging the battery from the grid or PV and discharging when necessary. As a result, controllers are required for hybrid PV-battery systems, such that the performance of solar usage can be significantly enhanced and the grid regulation can be improved in terms of safety and efficiency.

For grid-connected hybrid PV-battery systems, the changing electricity price, the timing of power transaction, and the mismatch between solar power generation and load demand are main challenges in application [5,6]. From the perspective of demand side management (DSM), solar energy or grid power may be stored when the PV can generate surplus power or when the grid electricity is inexpensive. The stored energy can be managed for economic usage in future when the electricity price is high over peak load periods, or when the PV power is unavailable [7]. The grid-connected hybrid system with DSM can help customers to reduce electricity cost, and also can help utility to regulate the grid in terms of security and efficiency issues, such as peak shaving, direct load control (DLC), and capacity market programs [8].

* Corresponding author.
E-mail addresses: wuzhsky@gmail.com (Z. Wu), henerica.tazvinga@up.ac.za (H. Tazvinga), xxia@up.ac.za (X. Xia).

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Therefore, at both sides of electricity market hybrid systems may introduce new opportunities to smart grid but also cause many challenges in the following DSM programs.

(1) Peak shaving: it is necessary to decide when and how much to charge the battery from the grid or PV before peak hours, so that power consumed from the grid at peak hours can be reduced to satisfy the requirement of shaving.
(2) Direct load control (in which a utility operator remotely shuts down or cycles a customer's electrical equipment at short notice to address system or local reliability): customers have to control the operation of hybrid system to ensure their demand is satisfied at the shutting time based on the frequency and time of shutting at DLC.
(3) Capacity market programs (in which customers commit to respond pre-specified load reduction when system contingencies arise and are subject to penalties if they do not curtail power consumption when directed): such programs involve issues such as how to decide on the amount of power stored in the battery, how to use the instantaneous and stored power cooperatively to complete the pre -specified load reduction, and how to minimize the penalty if the customer demand exceeds the pre-specified demand.
(4) Time-of-use (TOU, where the electricity price is high in the peak load time and low in the off-peak time): scheduling problems arise, such as determining how to optimally operate the hybrid system in peak and off-peak periods for minimizing electricity cost and satisfying the customer demand as well.

It must be noted that the hybrid systems with battery storage may have potential to take part in every DSM program or combined programs, which can help the utility to regulate the grid and help customers to reduce energy cost. For simplicity, this paper will mainly focus on evaluating a grid-connected PV-battery system under the TOU program with contracted selling as an example. It will be answered how customers optimally schedule the hybrid system to earn cost savings with varying prices in the TOU program, and how they manage their consumption to sell surplus power to the grid over peak period.

Although storage systems are not common in large generation farms, for residential and small-scale power producers many storage systems (battery, ultra-capacitor and so on) have been incorporated in energy supply systems. Nair and Garimella [9] argued that battery storage systems will have a significant impact on the small-scale integration of renewable sources into the commercial and residential sectors. For hybrid systems with battery storage, energy management is a vital and difficult issue that has attracted great interest among researchers [7,10]. Many energy management systems (EMS) have been developed for the utility to regulate micro-grids and reduce generation cost. Some rule-based strategies were designed for energy management of hybrid systems [11–13], which can obtain promising but not optimal solutions to ensure practical constraints are satisfied. In [14], a deterministic planning method was proposed to perform robustly day-ahead power flow scheduling for conventional and renewable generators. To improve the performance of EMS, optimal control is a useful method to schedule power flows of hybrid systems with minimum cost and maximum benefit [15,16]. In [17], an EMS for a virtual power plant was proposed to minimize the electricity generation cost and to utilize renewable energy sufficiently. Authors in [18] presented a dynamic optimal power flow control for power and heat generation scheduling while considering PV generations coupled with storage systems. A flexible battery management system was developed to optimize the duration (hours) of charging and discharging battery for optimal power flow control in distribution networks [19].

Beyond existing work, more emphasis should be made on two important issues of renewable hybrid systems. Firstly, most researchers have considered energy management and demand response for large-scale integration of renewable energy at the utility side [20,21]. There is lack of comprehensive work in consideration of optimal planning and DSM for small-scale hybrid systems at the demand side, because many customers install hybrid systems for stand-alone or back-up usage without any participation of DSM program. DSM can be studied more in appliance scheduling of household [22] than in scheduling of small-scale hybrid system. Secondly, uncertainties within forecast errors of renewable energy and demand have been studied for large-scale integration of renewable energy [23], but uncertainties at the demand side are not well evaluated. Most related optimal scheduling methods cannot handle complicated cases when hybrid systems experience external disturbances; only a few closed-loop control methods have been designed [7,24]. Therefor, it is necessary to model the small-scale hybrid system, to comprehensively study optimal schedule with DSM over different seasons, and to analyze uncertainty and robustness for the closed-loop control. This paper will be organized to respond to the above two issues.

Some remote areas, where customers used to rely on stand-alone hybrid systems for generating power, are being connected to the grid as part of network upgrade. Now a new problem is how to use such installed small-scale system efficiently. Based on our previous work [16], we consider DSM, scheduling and uncertainty handling of the grid-connected hybrid system in this paper. The diesel generator is now excluded, as the power its power generation is less green and more costly than the grid. DSM of the hybrid system is expected to help customers earn some payback and reduce electricity cost. Another by-product advantage of DSM is the reduction of emissions by utilization of clean PV technologies.

The main contributions of this paper are listed below. Firstly, as an example of DSM, the hybrid system under TOU with power selling is modeled to minimize the electricity cost while matching the customer demand and the PV output. Secondly, optimal control is developed as an open loop method to dispatch power flows of the hybrid system stably and economically. A comprehensive study has been conducted to evaluate different situations over weekend and weekday of winter and summer. Thirdly, in case of uncertainties in the PV output and the customer demand, model predictive control (MPC) is applied as the closed-loop control to ensure economic, robust and safe operation of the hybrid system. MPC is a feedback control strategy that uses an explicit model of plant to predict the future response of the plant over a finite horizon. Only "the first part" of the sequence is applied to control at the next state [25,26]. MPC has been widely used in the closed-loop control for adaptively changing control variables according to external disturbances [26–28]. MPC is applied in this work because of its capability to explicitly handle constraints and to adjust the power flows when disturbances occur.

In this paper, an optimal power flow management algorithm of a grid-connected PV-battery hybrid system is developed. The objective is to minimize the electricity cost within the DSM framework by optimal power flow control. Literature review is conducted on energy management of stand-alone and grid-connected systems in Section 2. The structure of the grid-connected PV-battery system and its sub-models are described in Section 3. The mathematic DSM model of the hybrid system is given in Section 4. Some results of the optimal control are discussed in Section 5. In Section 6 based on the steady state model an MPC approach is proposed as the closed-loop control, while the last section is the conclusion.