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Optimal switching renewable energy system for demand side management

Zhou Wu *, Xiaohua Xia

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

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Abstract

Renewable hybrid systems with small capacities are widely installed for joining demand response in modern communities. Based on hybrid systems, renewable energy generation can be stored and used for power supply during peak load period. It is impractical to control power flow in such small-scale systems, because power flow dispatching asks for extra investment of expensive regulators and adaptors. In this paper, a switching grid connected photovoltaic system is studied for simplifying system installation. Optimal switching control model is proposed to sufficiently utilize the solar energy and to minimize electricity cost under the time-of-use program. As shown in results, optimal scheduling of the PV system can achieve promising cost savings.

Keywords: Optimal switching control; Solar energy; Renewable energy; Distributed generation; Demand side management

1. Introduction

Due to globally increasing energy consumption, fossil fuel resources suffer from risks of over exploration and possible distinction in the near future. Meanwhile carbon and pollutant emissions caused by burning of fossil fuel have been growing over the last decade with great threat to environment (Wu et al., 2015). To control fossil fuel consumption and carbon emissions, exploration of new clean energy resources is necessary to decelerate the increasing rate of fuel consumption and reduce it if possible. Renewable energy (RE) resources have become an increasingly significant part of power generation for reducing fossil fuel consumption and pollutant emission (Esen and Yuksel, 2013). Among available RE technologies, wind and solar energy sources are the most promising options, as they are omnipresent, freely available, and environmental friendly.

Wind and solar generators usually require storage components (battery, ultra-capacitor, and so on) due to their drawback of intermittent nature. Combination of multiple power sources and storage components can provide a stable power supplier, which is the so-called renewable hybrid system. One common application of hybrid systems is the installation in remote areas for stand-alone supply (Nema et al., 2009; Shaahid and El-Amin, 2009). Especially, the photovoltaic (PV) systems are widespread due to universal availability of solar energy. Researchers have great interests on stand-alone or grid connected PV systems, including various topics like PV sizing (Arun et al., 2009), scheduling (Gabash and Li, 2013; Kanchev et al., 2011), and maximum power point tracking (MPPT) (Soto et al., 2006).

Life cycle cost and power generation efficiency are two main criteria to evaluate performance of exploring

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

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Nomenclature

$P_1(t)$	power flow from the diesel generator to the load at time t (kW)
$P_2(t)$	power flow from the PV to the load at time t (kW)
$P_3(t)$	power flow from the PV array to the load at time t (kW)
$P_4(t)$	power flow from the battery to the load at time t (kW)
$P_{pv}(t)$	power output from the PV generator at time t (kW)
$P_L(t)$	load demand at time t (kW)
$P_G(t)$	power output from the grid to the battery at time t (kW)
$u_1(t)$	status of switch on the line connecting the PV and the battery charger at time t
$u_2(t)$	status of switch on the line connecting the grid and the battery charger at time t
$u_3(t)$	status of switch on the line connecting the battery inverter and the load at time t
$u_4(t)$	status of switch on the line connecting the grid and the load at time t
$u_5(t)$	status of switch on the line connecting the PV and the load at time t
$S(t)$	the state of charge (SOC) of battery (kW)
S^{max}	the maximum capacity of battery (kW)
S^{min}	the allowable minimum SOC of battery (kW)
DoD	the depth of discharge
η_C	the charging efficiency of battery
η_D	the discharging efficiency of battery
$rho(t)$	the price of electricity (\$/kW h)

renewable energy (Shaahid and El-Amin, 2009; Wies et al., 2005; Esen et al., 2006; Esen et al., 2007). Simulation model for economic analysis and environmental impacts is proposed for a PV–diesel–battery (PDB) system (Wies et al., 2005), in which the fuel cost is calculated over a one-year period and simple payback is evaluated. The PDB hybrid system is proven with ability of reducing the operation costs and the emission of greenhouse gases. In Tazvinga et al. (2013), daily energy consumption variations between winter and summer are considered into scheduling the PDB system. The authors have evaluated operational efficiency of the hybrid system over a 24-h period and optimal solutions can be found to reduce the corresponding fuel costs. Their conclusion is that 73–77% fuel savings in winter and 80.5–82% fuel savings in summer can be achieved by the optimal control method. In Tazvinga et al. (in press), two objectives of fuel cost and battery wear cost have been considered in the optimal management of the PDB hybrid system.

Nowadays, a rising number of individuals take part in demand response (DR) programs, such as peak shaving, load shifting, power reduction and time-of-use (TOU) (Aalami et al., 2010). Small-capacity hybrid systems installed in more families or small communities can play significant roles in demand side management (DSM). On the other hand, some remote areas, where customers used to rely on stand-alone hybrid systems for supplying power, are getting connection to the grid as part of network upgrade. The installed hybrid system is necessarily modified to earn benefits in DSM. For controlling such hybrid systems, some rule-based strategies about power flow dispatching (Wang and Nehrir, 2008; Jain and Agarwal, 2008; Teleke et al., 2010) can obtain promising but not optimal solutions that can ensure practical constraints satisfied. Optimal control is a useful method to schedule power flows of hybrid systems with minimum cost and maximum benefit (Tazvinga et al., 2013; Riffonneau et al., 2011; Tazvinga et al., 2014). However, power flow control is impractical for small-capacity hybrid systems that have been widely equipped individually, because power control asks for extra investment of expensive regulators and adaptors. Therefore, a simple but practical switching model of grid connected PV system with storage is proposed at demand side. The scheduling of the PV system for DSM is based on an optimal switching control approach. To our best knowledge, few works emphasize on optimal switching control of hybrid system to reduce the power consumption and the electricity cost at demand side. In this paper, the optimal switching control will be studied for the grid-connected PV system in the framework of TOU, in which the electricity price is high in the peak hours and is low in the off-peak hours (Aalami et al., 2010). As the electricity prices are fixed in advance for the customer reference, day-ahead optimal switching control is applicable to minimize the electricity cost under the TOU program.

The main contributions of this work include three aspects. Firstly, a switching model of the grid connected PV system with storage is proposed with simple structure. The PV system can be newly installed or modified from other existing hybrid systems with low construction cost. Secondly, the PV system is analyzed in the viewpoint of control system theory. System state-space equations are deduced, and optimal control is proposed to schedule the PV system for DSM. Thirdly, the optimal control approach can minimize the electricity cost and ensure all practical constraints satisfied. The performance of optimal control is better than an intuitive control method.