Solar Energy 144 (2017) 707–720

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Optimal switchable load sizing and scheduling for standalone renewable energy systems

Abdulelah H. Habib *, Vahid R. Disfani, Jan Kleissl, Raymond A. de Callafon

Department of Mechanical and Aerospace Engineering (MAE), University of California, 9500 Gilman Drive MC 0411, La Jolla, San Diego, CA 92093-0411, United States

ARTICLE INFO

Article history:
Received 4 July 2016
Received in revised form 1 January 2017
Accepted 29 January 2017

Keywords:
Inequality-constrained least square
Load management
Mixed-integer linear programming
Off-grid solar energy

ABSTRACT

The variability of solar energy in off-grid systems dictates the sizing of energy storage systems along with the sizing and scheduling of loads present in the off-grid system. Unfortunately, energy storage may be costly, while frequent switching of loads in the absence of an energy storage system causes wear and tear and should be avoided. Yet, the amount of solar energy utilized should be maximized and the problem of finding the optimal static load size of a finite number of discrete electric loads on the basis of a load response optimization is considered in this paper. The objective of the optimization is to maximize solar energy utilization without the need for costly energy storage systems in an off-grid system. Conceptual and real data for solar photovoltaic power production provides the power input to the off-grid system. Given the number of units, the following analytical solutions and computational algorithms are proposed to compute the optimal load size of each unit: mixed-integer linear programming and constrained least squares. Based on the available solar power profile, the algorithms select the optimal on/off switch times and maximize solar energy utilization by computing the optimal static load sizes. The effectiveness of the algorithms is compared using one year of solar power data from San Diego, California and Thuwal, Saudi Arabia. It is shown that the annual system solar energy utilization is optimized to 73% when using two loads and can be boosted up to 98% using a six load configuration.

1. Introduction

Increasing global energy demand and human population growth have triggered a need for standalone renewable applications. Recent estimates show that 1.4 billion people do not have access to energy services and one billion are suffering from unreliable electricity services (IEA, 2013). Standalone application of clean energy, (e.g., fresh water pumping), has become more critical for humanity (IEA, 2013; Universal Access to Modern Energy for the Poor, http://www.undp.org/content/undp/en/home/ourwork/environmentandenergy/focus_areas/sustainable-energy/universal-access.html). Often such systems are powered by solar photovoltaic (PV) due to ubiquitous high solar resource availability and scalability. However, solar production exhibits high variability over a broad range of time scales (Wan, 2012). Power variability is the main obstacle facing solar energy in standalone or islanded mode applications. High penetrations of solar power sources create large power swings which influence electric power quality (Nguyen et al.) and can cause loss of load or generation curtailment (Energy, 2010, http://www.nrel.gov/docs/fy10osti/47434.pdf). Variability of solar PV generation is a result of seasonal and diurnal changes in the sunpath as well as short-lived cloud cover. Solar variability limits the operation of off-grid loads at maximum capacity (Saber and Venayagamoorthy, 2012; Egido and Lorenzo, 1992; Sreeraj et al., 2010).

Optimal load switching can be applied to microgrids with any hybrid forms of renewable energy resources such as solar and wind (Mohammadi et al., 2012; Kobayakawa and Kandpal, 2015; Lee et al., 2014; Atia and Yamada, 2015) to capture as much renewable energy as possible. Although partial or modulated load operation is conducive to the problem, there are numerous types of load units which can only be switched on or off, such as non-dimmable lighting, standard electric motors, and Magnetic Resonance Imaging (MRI) machines at hospitals and load aggregation such as demand side management (Shafie-khah et al., 2016; Negnevitsky and Wong, 2015). Dispatching such binary load units, which are referred as switchable loads hereafter, to follow available renewable energy resources have been discussed in the literature for different microgrid applications such as water desalination (Smaoui et al., 2015), pumping systems (Bakelli et al., 2011), irrigation systems (Olcan, 2015), and cooking appliances(Mandelli et al., 2016; Fux et al., 2013; Bouabdallah et al., 2015).

* Corresponding author.
E-mail addresses: ahhabib@ucsd.edu (A.H. Habib), disfani@ucsd.edu (V.R. Disfani), jkleissl@ucsd.edu (J. Kleissl), callafon@ucsd.edu (R.A. de Callafon).

http://dx.doi.org/10.1016/j.solener.2017.01.065
0038-092X/

Nomenclature

$S(t_k)$	solar power data sampled at t_k and normalized by the maximum solar generation S_{max}
S_{max}	maximum solar generation
Δ_T	is the sampling rate
T	is the length of the solar power data
k	is an array of size T
x^i	static load size unit
n	is the number of loads
$E(t_k)$	power mismatch or difference of solar power $S(t_k)$ and power used by the loads $u(t_k)x$
u^i_k	binary number represent the switching of the loads
N	Number of possible combination of units
U	is the permutation matrix of size $[n, N]$

Different optimization techniques are used for planning and design of such systems. For instance, mixed-integer linear programming (MILP) has been used in many fields, such as unit commitment of power production (Viana and Pedroso, 2013) and power transmission network expansion (Bahiense et al., 2001; Zhang et al., 2012), as well as scheduling problem of the generation units in off-grid in order to maximize supply performance of the system (Morais et al., 2010). Nonlinear approaches have also been applied to load scheduling (Hung and Robertazzi, 2008). For example, neural networks and genetic algorithms have been applied to size stand-alone PV (Mellit et al., 2010,; Mellit and Kalogirou, 2008). The on/off control optimization problem is similar to the unit commitment problem in power systems and bio-fuel (Chen et al., 2015; Amir et al., 2008).

However, limited studies have been conducted on the optimal load sizing in a standalone (islanded) grid application with switchable loads. Most of other research has been in the demand/supply side while very few looked into the unit/load sizing for many reasons, such as, the load is assumed to be fixed and has to meet by any supply way (Ashok, 2007) or the accessibility of designing load for certain application is harder and not easy process. This work focuses on optimal load sizing for standalone applications in rural areas or off-grid sites. While the present paper assumes an off-grid system, similar challenges exist for a power system with a weak grid connection, i.e. with a line carrying capacity that could only balance variability that is a small fraction of local solar generation or load capacity.

Energy storage systems (ESS) have been applied to solve the variability challenges (Pickard and Abbott, 2012; Kousksou et al., 2014). An alternative or complementary approach is optimal sizing and scheduling of load units which follow power generation variability to maximize solar energy utilization and load uptime. Clearly, the solar energy utilization could be improved with an ESS, but an ESS that eliminates solar variability would need to be large enough to store several days' worth of solar power which is uneconomical at present. Smaller ESS would experience significant cycling and deep discharge events if not properly maintained, increasing maintenance costs and requiring replacement much before the end-of-life of a PV system. Our objective is to improve solar utilization without an ESS and use load demand response only and show that high efficiencies can still be obtained. In practice, a combination of a small ESS with high cycle life such as an ultracapacitor ESS and the proposed load sizing and scheduling system would probably be the best solution. The ESS would absorb solar variability at time scales of seconds to minutes while the loads would balance variability at longer time scales. This approach would allow limiting ESS energy capacity making it more economical. While practical challenges of implementing such a system are significant, e.g. in maintaining system stability during switching, this paper focuses on the critical algorithmic work that permits such a system to operate efficiently and economically.

In a properly planned system, the solar system would be optimally sized to power the load required for the intended application. This paper does not consider this scenario. Often in practice, the conditions are not as plannable. Load growth will occur and a solar power system may be initially oversized to accommodate such growth. Sizing the solar system may also be limited by land ownership and topographic constraints. The solutions proposed in this paper apply in such a context where solar capacity is fixed and loads are sized to optimize solar energy utilization.

This paper proposes an optimization model to capture the maximum amount of variable solar generation, which sizes and schedules a finite number of loads to track available solar PV power. The objective is to maximize solar utilization, given the projected power generation of the renewable energy resources. Here, solar utilization is defined as a percentage of energy captured by the units over total solar energy produced. This is akin to terms such as solar utilization factor (Vermeulen and Nieuwoudt, 2015) and loss of power supply (LPS) (Gupta, 2011) which are commonly used in the literature. The loads are assumed to switch between a binary "on" or "off" statuses, where both the switching times and the size of the static power demand (static load size) determines the ability to track available solar power.

The main contribution of this paper is to develop both analytical solutions and computational approaches based on Equality Constrained Least Squares (ECLS), Inequality Constrained Least Squares (ICLS), and Mixed-Integer Linear Programming (MILP) in order to solve the optimization problem. The rest of the paper is organized as follows. The mathematical formulation is given in Section 2 along with an analytical example and the motivation for a computational procedure for optimal load size selection. One year of solar resource data for San Diego is analyzed and discussed in Section 3. Section 4 presents different computational procedures for optimal load size selection based on a bi-linear optimization problem involving a mix of binary and real numbers. The simulation results are presented and discussed in Section 5. Finally, Section 7 concludes the paper.

2. Problem formulation

The sizing and scheduling problem computes the distribution of the optimal load size of a finite number load units, given an available (solar) power profile. For the optimal load size selection, the loads are assumed to operate in a binary manner, on or off, and therefore only the static load size is optimized.

2.1. Static load response optimization problem

To formalize the notation for the optimization approach presented in this paper, we assume knowledge of the (solar) power delivery $S(t)$ sampled at regular time intervals $t = t_k = k\Delta_T$, where $1/\Delta_T$ is a fixed sampling frequency and k is the sample index. In this way, we have a data set of T points on the solar power production $S(t_k), k = 1, \ldots, T$. Typically, $S(t_k)$ is close to a daily periodic function and $S(t_k) \geqslant 0$ over a daily time interval $t_k \in [t_b, t_e]$, where b is the beginning and e is the ending of the day, with a maximum value