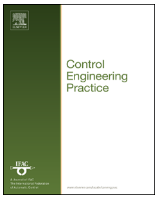
Control Engineering Practice 35 (2015) 83–91

Contents lists available at ScienceDirect

Control Engineering Practice

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



Multivariable maximum power point tracking for photovoltaic micro-converters using extremum seeking

Azad Ghaffari [a],*, Sridhar Seshagiri [b], Miroslav Krstić [c]

[a] *Joint Doctoral Program (Aerospace and Mechanical) Between San Diego State University and University of California, San Diego, La Jolla, CA 92093-0411, USA*
[b] *Department of Electrical and Computer Engineering, San Diego State University, San Diego, CA 92182-1309, USA*
[c] *Department of Mechanical and Aerospace Engineering, University of California, San Diego, La Jolla, CA 92093-0411, USA*

ARTICLE INFO

Article history:
Received 5 November 2013
Accepted 23 November 2014
Available online 17 December 2014

Keywords:
Photovoltaic systems
Maximum power point tracking
Extremum seeking
DC–DC micro-converters

ABSTRACT

It is well-known that *distributed architectures* such as micro-converters and micro-inverters for photovoltaic (PV) systems can recover between 10% and 30% of annual performance loss or more that is caused by partial shading and/or module mismatch. In this work, we present a novel multivariable gradient-based extremum-seeking (ES) design to extract maximum power from an arbitrary micro-converter configuration of PV modules, that includes cascade and parallel connections. Conventional maximum power point tracking (MPPT) schemes for micro-converters (where each PV module is coupled to its own DC/DC converter) employ a distributed control, with one peak seeking scheme per each PV module, thereby requiring one control loop and two sensors per module (one each for current and voltage). By contrast, the scheme that we present employs a single control loop with just two sensors, one for the overall array output current and the other one for the DC bus voltage. This multivariable design provides more flexibility in tuning the parameters of the controller, and also takes into account interactions between PV modules. The computational effort of our design is not higher than that of the conventional scheme, and simulation and experimental results show that our proposed design outperforms the conventional one. Thus, our proposed design offers two benefits: (i) the balance-of-system (BOS) cost reduction as a result of the lower number of sensors, and (ii) improved performance, both contributing towards reduced average cost/watt, and enhancing the economic viability of solar.

1. Introduction

Maximum power point tracking (MPPT) is a technique for maximizing the energy extracted from PV modules. Over the years, many MPPT methods have been developed and implemented (Bratcu, Munteanu, Bacha, Picault, & Raison, 2011; Brunton, Rowley, Kulkarni, & Clarkson, 2010; Dhople, Ehlmann, Davoudi, & Chapman, 2010; Esram & Chapman, 2007; Hohm & Ropp, 2003; Jain & Agarwal, 2007; Kadri, Gaubert, & Champenois, 2011; Lei, Li, Chen, & Seem, 2010; Leyva et al., 2006; Miyatake, Veerachary, Toriumi, Fuji, & Ko, 2011; Moura & Chang, 2010; Pai, Chao, Ko, & Lee, 2011; Patel & Agarwal, 2009; Petrone, Spagnuolo, & Vitelli, 2011; Ramos-Paja, Spagnuolo, Petrone, Vitelli, & Bastidas, 2010). These methods vary in complexity, convergence speed, cost, range of effectiveness, implementation hardware, and popularity. Comprehensive comparative analyses of currently available techniques can be found in Esram and Chapman (2007), Hohm and Ropp (2003), and Jain and Agarwal (2007).

Extremum-seeking (ES) is a non-model-based real-time optimization algorithm (Ariyur & Krstić, 2003; Krstić & Wang, 2000; Wang & Krstić, 2000; Wang, Yeung, & Krstić, 1999) for systems with unknown dynamics that has been applied to a wide range of technical applications, including MPPT in PV systems (Bratcu et al., 2011; Brunton et al., 2010; Lei et al., 2010; Leyva et al., 2006; Moura & Chang, 2010). It offers the advantages of fast convergence and guaranteed stability over a range of environmental conditions, and yet is simple to implement, and hence very cost effective in terms of processing/hardware requirements.

With the exception of Bratcu et al. (2011), all existing work on ES applies the technique to PV systems whose cells receive the same irradiance level, i.e., have unimodal power characteristics. Recent works (for example, Dhople et al., 2010) concentrate on designing MPPT methods to track multiple peaks (non-unimodal power) under rapidly changing irradiance conditions, and the

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* Corresponding author: Tel: +1 734 763 2227; fax: +1 734 647 3170.
E-mail addresses: aghaffari@ucsd.edu (A. Ghaffari), seshagir@engineering.sdsu.edu (S. Seshagiri), krstic@ucsd.edu (M. Krstić).

http://dx.doi.org/10.1016/j.conengprac.2014.11.007
0967-0661/

issues of partial shading and module mismatch. These studies have led to a growing interest in distributed architectures (also referred to as distributed power electronics), such as micro-converters (distributed DC/DC converters) and micro-inverters (distributed DC/AC converters) (Deline, Marion, Granata, & Gonzalez, 2011). While Bratcu et al. (2011) deals with ES design for micro-converters (one DC/DC converter for each module), it employs a scalar ES loop for each PV module. Two problems arise here. First, this scheme requires two sensors per module, current and voltage, which increases the levelized energy cost. Second, the coupling effect between PV modules is not addressed by this distributed control. Our current work shows that employing a multivariable MPPT algorithm instead of separate scalar ones solves these problems.

To the best of our knowledge, there are a limited number of multivariable MPPT schemes described in the literature, among which we refer the reader to Miyatake et al. (2011), Petrone et al. (2011), and Ramos-Paja et al. (2010). The last of these references (Ramos-Paja et al., 2010) uses a multivariable version of the popular Perturb and Observe (P&O) algorithm. Unlike scalar designs which require one current sensor for each module, the algorithm only requires a single current sensor on the DC bus. The operating point of the DC/DC converters are perturbed asynchronously, to minimize the possibility of converter interaction having a detrimental effect on the other modules. Closely related to Ramos-Paja et al. (2010) is the work in Petrone et al. (2011), where "extra variables" are employed in the classical P&O algorithm to overcome the limitation of scalar designs, which the authors say fail when the feasibility region is nonconvex. It is unclear how Petrone et al. (2011) compares with distributed architectures, with respect to power loss recovery in the case of module mismatch. Reference Miyatake et al. (2011) uses particle swarm optimization (PSO), which is an algorithm that employs multiple agents to "search" for the peak power. The paper does not describe the specific criteria used to select the number of agents and parameters of the PSO, or the conditions on the voltage and power boundary limits to stop the algorithm at Maximum Power Point (MPP). Also, in a PV system with a higher number of PV modules, the process of reinitialization and the tracking performance depend strongly on variable conditions like environmental factors, the nature of the PV modules, and the shading area. The authors claim that the required number of sensors are reduced to two, but to compute the pulse duration, the output voltage of each boost converter needs to be monitored by a separate sensor.

We present a multivariable gradient-based ES schemes with the following features:

- It is applied to micro-converter systems, and hence deals with the case of non-unimodal power characteristics, and deals specifically with the issue of module mismatch (for example, possibly different irradiance levels as a result of partially shaded conditions).
- The use of the non-model-based ES technique makes the design robust to partial knowledge of the system parameters and operating conditions.
- As opposed to scalar designs, our multivariable design only requires two sensors in all, for the overall PV system current, and the DC bus voltage. This is a significant reduction in hardware cost.
- Moreover, interactions between PV modules are inherently part of the multivariable design, and hence the transient performance is less-sensitive to environmental variable variations than a corresponding scalar design.
- The computational burden is of the same order as a scalar design, but with a slightly faster transient response than scalar ES designs, and significantly faster than non-ES based designs such as Miyatake et al. (2011).

In this expanded version of Ghaffari, Seshagiri, and Krstić (2012), we provide detailed guidelines for selection of the ES controller parameters, particularly the frequency distribution of the probing frequencies and bandpass frequencies of the lowpass filters. In addition, while the design was only validated by simulation in Ghaffari et al. (2012), here we present experimental results that demonstrate the effectiveness of the proposed algorithm against large step solar irradiance perturbations. Unlike several existing MPPT algorithms, ES requires no programming, and consists essentially of two filters, an oscillator, a multiplier, and an adder, all of which can be implemented using analog hardware (op-amps, resistors, capacitors). However, as is common in rapid prototyping, our implementation is done using the single-board dSPACE microcontroller.

The rest of this paper is organized as follows: the mathematical model of a PV module, along with a discussion of the DC/DC converter power electronics, is presented in Section 2. Section 3 introduces the scalar gradient-based ES scheme, presented for clarity for the case of a single module first, followed by how this is conventionally extended to the distributed micro-converter case. Our proposed multivariable gradient-based ES is presented and discussed in Section 4, along with some simulation and experimental results in Section 5, and a summary of our design and some concluding remarks in Section 6. A preliminary version of this paper was presented at the 2012 ACC (Ghaffari et al., 2012). The primary contribution of this work over Ghaffari et al. (2012) is the addition of experimental results to the simulation results that were presented therein.

2. Photovoltaic modules and power extraction

Our design and analysis are based on the standard PV module model described for example in Vachtsevanos and Kalaitzakis (1987), and shown schematically in Fig. 1. Each PV cell is modeled as an ideal current source of value I_{ph} in parallel with an ideal diode with voltage V_D. Electrical losses and contactor resistance are accounted for by the inclusion of the parallel and series resistances R_s and R_p respectively. The amount of generated current I_{ph} is dependent on the solar irradiance $\mathcal{S}$ and the temperature $\mathcal{T}$ through the following equation:

$$I_{ph} = \left(I^r_{ph} + k_i(\mathcal{T} - \mathcal{T}_r)\right)\left(\frac{\mathcal{S}}{1000}\right), \tag{1}$$

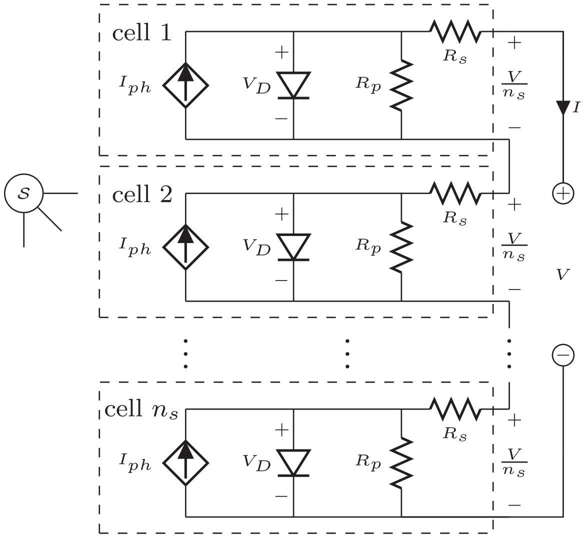

Fig. 1. Equivalent circuit of a PV module.