Control Engineering Practice 21 (2013) 971–980

Contents lists available at SciVerse ScienceDirect

Control Engineering Practice

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

Lyapunov-based switched extremum seeking for photovoltaic power maximization

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ARTICLE INFO

Article history:
Received 6 June 2012
Accepted 10 February 2013
Available online 19 April 2013

Keywords:
Adaptive control
Nonlinear control
Lyapunov methods
Photovoltaic systems
Renewable energy

ABSTRACT

This paper presents a practical variation of extremum seeking (ES) that guarantees asymptotic convergence through a Lyapunov-based switching scheme (Lyap-ES). Traditional ES methods enter a limit cycle around the optimum. Lyap-ES converges to the optimum by exponentially decaying the perturbation signal once the system enters a neighborhood around the extremum. As a case study, we consider maximum power point tracking (MPPT) for photovoltaics. Simulation results demonstrate how Lyap-ES is self-optimizing in the presence of varying environmental conditions and produces greater energy conversion efficiencies than traditional MPPT methods. Experimentally measured environmental data is applied to investigate performance under realistic operating scenarios.

1. Introduction

1.1. Problem statement

Extremum seeking (ES) deals with regulating an unknown system to its optimal set-point. To this end, a periodic perturbation signal is typically used to probe the space. Once the optimal set-point has been identified, most methods enter a limit cycle around this point as opposed to converging to it exactly. Hence, one of the main challenges with ES is eliminating the limit cycle and converging to the optimal set-point asymptotically. This paper investigates a novel Lyapunov-based switched extremum seeking (Lyap-ES) approach that supplies asymptotic convergence to the optimal set-point. The proposed concept is demonstrated on a well-studied yet important problem: maximum power point tracking (MPPT) in photovoltaic (PV) systems.

1.2. Literature review

Two bodies of literature form the foundation of this work: MPPT in PVs and extremum seeking control.

1.2.1. MPPT in PVs

The MPPT literature is extremely broad, and contains techniques that range in complexity, hardware, performance, and popularity, among other characteristics. The survey paper by Esram and Chapman (2007) provides a comprehensive comparative analysis of over 90 publications on MPPT techniques. The most popular technique, perturb & observe (P&O), perturbs the input voltage to determine the direction of the maximum power point (MPP), and moves the operating point accordingly. However, the controller eventually enters a periodic orbit about the MPP. This approach does not require *a priori* knowledge of the PV system and is simple to implement. However, P&O can diverge from the MPP under certain variations in the environmental conditions (Femia, Petrone, Spagnuolo, & Vitelli, 2005; Kwon, Kwon, & Nam, 2008). Recently, an exponentially decaying adaptive version of P&O has been developed (Buyukdegirmenci, Bazzi, & Krein, 2010), which has conceptual similarities to our proposed method. An alternative method, incremental conductance (IncCond), seeks to correct this issue by leveraging the fact that the slope of PV array power output is zero at the MPP. As a result, this algorithm estimates the slope of the power curve by incrementing the terminal voltage until the estimated slope oscillates about zero (Hussein, Muta, Hoshino, & Osakada, 1995). A drawback of P&O and IncCond methods is that both stabilize to limit cycles. Ideally, one desires a peak seeking scheme that is asymptotically convergent and self-optimizing with respect to shifts in the MPP. This motivates a control-theoretic approach to MPPT. A recent paper examined an adaptive backstepping approach, for which convergence to the MPP is theoretically proven under a persistency of excitation condition (El Fadil & Giri, 2011). This paper examines an alternative non-model-based approach, extremum seeking.

Extremum seeking control and its application to photovoltaic systems represent an important and relevant subset of MPPT literature. Specifically, Leyva et al. (2006) and Bratcu, Munteanu,

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http://dx.doi.org/10.1016/j.conengprac.2013.02.009

Bacha, and Raison (2008) utilize extremum seeking for PVs by injecting an exogenous periodic signal. A separate research group developed ripple correlation control (RCC), which utilizes the signal ripple that inherently exists in systems with switching power electronics as the perturbation signal (Esram, Kimball, Krein, Chapman, & Midya, 2006). The stability and optimality of this approach has been established in Logue and Krein (2001). RCC has the critical advantage of utilizing existing signal ripples, instead of injecting artificial perturbations. As such, RCC is only applicable to systems which inherently contain ripple characteristics. Recently, Brunton, Rowley, Kulkarni, and Clarkson (2010) utilized the 120 Hz inverter ripple in a PV system within the context of an extremum seeking control theoretic approach to MPPT. Consequently this work established an important link between extremum seeking control and ripple-based MPPT (Bazzi & Krein, 2011).

1.2.2. Extremum seeking control theory

Prior to the nonlinear and adaptive control theory developments in the 1970s and 1980s, extremum seeking was proposed as a method for identifying the optimum of an equilibrium map. Since then, researchers have extended extremum seeking to the general class of nonlinear dynamical plants (see e.g. DeHaan & Guay, 2005; Krstic & Wang, 2000) and applied the algorithm to a wide variety of applications (e.g. air flow control in fuel cells Chang & Moura, 2009, wind turbine energy capture, Creaby, Li, & Seem, 2008, ABS control, and bioreactors, Ariyur & Krstić, 2003). During this period there have been several innovations that have improved the practicability of ES. For example, convergence speed can be enhanced by adding dynamic compensators (Krstić, 2000) or applying alternative periodic perturbation signals (Tan, Nešić, & Mareels, 2008). A Newton-based algorithm can also be developed by estimating the Hessian of the unknown nonlinear map (Nešić, Tan, Moase, & Manzie, 2010).

1.3. Contributions

This study focuses on a general problem—asymptotic convergence to the extremum of a static nonlinear unknown function. As such, this paper extends the aforementioned research and builds on the authors' previous work (Moura & Chang, 2010) to add the following two new contributions to the ES control and MPPT bodies of literature. First, we introduce a switching method for ensuring asymptotic convergence to the optimal operating point, based on Lyapunov stability theory. Second, we demonstrate this algorithm in simulation for MPPT problems in PV systems—a novel and control theoretic alternative to traditional MPPT methods.

1.4. Paper outline

This paper is organized as follows: Section 2 describes the extremum seeking control design and our novel Lyapunov-based switching strategy. Section 3 discusses a case study of the proposed ES method on MPPT for PV systems. Finally, Section 4 presents the main conclusions.

2. Extremum seeking control

In this section we introduce and expand upon a simple yet widely studied extremum seeking (ES) scheme (Ariyur & Krstić, 2003; Krstic & Wang, 2000) for static nonlinear maps, shown in Fig. 1. Since the case study on photovoltaic systems involves a static plant model (albeit parameterized by time-varying disturbances), the scope of our analysis is limited to static plants. One may also consider the more general singular perturbation analysis for dynamic plant models presented in Krstic and Wang (2000).

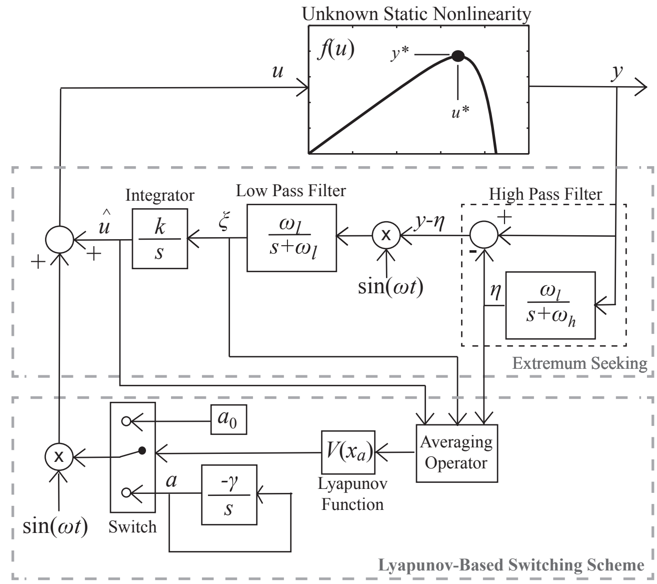

Fig. 1. Block diagram of switched extremum seeking control system.

Before embarking on a detailed discussion of this method, we give an intuitive explanation of how extremum seeking works, which can also be found in Krstic and Wang (2000) and Ariyur and Krstić (2003), but is presented here for completeness. Next, we design the Lyapunov-based switching extremum seeking control to eliminate limit cycles.

2.1. An intuitive explanation

The control scheme applies a period perturbation $a_0 \sin(\omega t)$ to the control signal $\hat{u}$, whose value estimates the optimal control input u^*. This control input passes through the unknown static nonlinearity $f(\hat{u} + a_0 \sin(\omega t))$ to produce a periodic output signal y. The high-pass filter $s/(s+\omega_h)$ then eliminates the DC components of y, and will be in or out of phase with the perturbation signal $a_0 \sin(\omega t)$ if $\hat{u}$ is less than or greater than u^*, respectively. This property is important because when the signal $y-\eta$ is multiplied by the perturbation signal $\sin(\omega t)$, the resulting signal has a DC component greater than or less than zero if $\hat{u}$ is less than or greater than u^*, respectively. This DC component is extracted by the low-pass filter $\omega_l/(s+\omega_l)$ and represents the sensitivity $(a_0^2/2)(\partial f/\partial u)(\hat{u})$. We may use a gradient update law $\dot{\hat{u}} = k(a_0^2/2)(\partial f/\partial u)(\hat{u})$ or a quasi-Newton method (Ghaffari, Krstić, & Nesic, 2011) to force $\hat{u}$ to converge to u^*. Next we rigorously develop the ES algorithm.

2.2. Averaging stability analysis

Extremum seeking systems generally enter a limit cycle around the optimum, as opposed to converging to it asymptotically. To eliminate this drawback we propose a switching control scheme. This scheme decays the periodic perturbation's amplitude once the system has converged within the interior of a ball around the optimum. The switch criterion is determined using Lyapunov stability methods. Allowing the perturbation to decay exponentially is not new (Buyuk et al., 2010; DeHaan & Guay, 2005); however, it is the first application in a switched scheme, to the authors' knowledge.

In the following derivations, the Lyapunov function is ideally calculated with respect to a coordinate system centered at the extremum. However, the extremum is unknown *a priori*. In the