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Global Maximum Power Point Tracking (GMPPT) of Photovoltaic array using the Extremum Seeking Control (ESC): A review and a new GMPPT ESC scheme

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ABSTRACT

The objective of this paper is to present a survey of the Perturbed-based Extremum Seeking Control (PESC) methods and their applications in Photovoltaic (PV) arrays under Partially Shaded Conditions (PSCs). A new PESC scheme is also proposed to seek and track the Global Maximum Power Point (GMPP) of the PV power. This scheme has better performance than other GMPP methods and it may revive the specialists' interest in applying this PESC scheme in PV applications and others multimodal problems from industry. Different PV and nonlinear multimodal patterns were used to test the proposed control scheme. The results obtained have shown very good performance related to search speed and tracking accuracy of the GMPP under different PSCs simulated.

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1. Introduction

The output voltage and current of the Photovoltaic (PV) cells vary according to changes in weather and environmental parameters such as the irradiance and temperature. Therefore, these parameters will modify the output PV characteristics, resulting PV patterns with a unique Maximum Power Point (MPP) or multiple peaks (local extremes). Because the temperature variation is typically much more gradual than the irradiance changes, the PV patterns used in simulation are generally obtained using different irradiance levels for PV panels connected in series and/or parallel into a PV array. Instead of a Local MPP (LMPP), the global MPP (GMPP) must be always searched in order to extract the maximum PV power available.

During the last decades the researchers have proposed several MPP tracking (MPPT) algorithms that demonstrate good performance (search speed and tracking accuracy) under constant irradiance level. These algorithms will be referred here as the conventional MPPT algorithms (together with their variants). Besides the most popular conventional MPPT algorithms, which are the Perturb and Observe (P&O) [1,2], Incremental Conductance (IC) [3,4], and the Hill Climbing (HC) [5,6], a lot of other conventional MPPT algorithms are proposed in the literature, such as the Ripple Correlation Control (RCC) [7,8], sweep current or voltage methods [9], load current and load voltage minimization [10,11], Fractional Short Circuit Current [12], Fractional Open Circuit Voltage [13], dP/dV or dP/dI feedback control [14], model predictive control [15], and so on [16–25]. Note that more than fifty conventional MPPT algorithms are identified in recent reviews [16–25]. Most of the reviews are focused on conventional MPPT methods [16–21].

The reviews [22–25] addressed the GMPPT issue, and a critical evaluation of the Extremum Seeking Control (ESC) methods is very briefly made only in review [25]. It is obvious that the ESC methods are not popular as the conventional MPPT methods and hence these have been omitted for brevity in most reviews. For example, in review [25] is noted that the experimental data cannot be provided for real condition of PV panel operation, but few laboratory experiments were recently reported in the literature and these experiments will be discussed here.

The PV array operates under variable insolation conditions in both real and laboratory cases, but the PV patterns are clearly different. A real PV pattern is difficult to be emulated due to different PSCs that may occur. For example, the PV panels installed on buildings (on the rooftop and facades, or even as eaves) may be shaded at any moments by clouds, by neighboring buildings during a sunny day, or by coating with dust. It is obvious that first and third case can also affect the PV panels installed into a big PV array (such as a PV farm). So, the PSCs occur in such conditions and the PV patterns will have multiple LMPPs, besides the GMMP, generating a mismatch between the generated power and harvested power at the GMPP (which it is potentially available using a GMPPT algorithm). Note that the conventional MPPT algorithms remain stuck in one of multiple LMPPs of the PV pattern. Reported results show an increase with about 5% in generated power if a GMPPT algorithm is used instead of a conventional MPPT algorithm [26]. So, the GMPPT algorithms were intensively studied in the last decade in order to find design rules, highlight new research directions, report their limits in real operating conditions, and compare the performance obtained. The GMPPT algorithms proposed in current literature can be classified in two main classes [25]: firmware-based and hardware architecture-based algorithms.

The hardware-based algorithms are clearly related to the power converter topology and PV system design [27,28]. The types of common PV system architectures are of centralized (using a central inverter [29]), hybrid (using a series and/or parallel connection of strings of PV panels integrated into a PV array, where each string uses a DC–DC converter [28]), and decentralized (using a microinverter for each panel [27]). Thus, a lot of optimization solutions are proposed in the literature and more than forty hardware-based algorithms are identified in recent reviews [24,25].

In the last years the soft computing techniques are intensively studied due to its natural adaptability to multimodal functions, such as PV patterns generated for large PV arrays under PSCs. Furthermore, new cheap controllers are now available to process the signals involved in soft computing techniques to quickly solve different optimization problems. Thus, a lot of soft computing techniques are proposed in the literature and more than forty soft computing techniques are identified in recent reviews [23,25]. The soft computing techniques may search the GMPP based on the chaotic search [30], Fuzzy Logic Controller (FLC) [31,32], Artificial Neural Network (ANN) [33] and Evolutionary Algorithms (EAs), where EAs include genetic algorithms (GAs) [34], differential evolution (DE) [35], particle swarm optimization (PSO) [36], ant colony systems (ACSs) [37]. An excellent review of soft computing techniques is made in [25], where new GMPPT techniques were classified and compared. In this study is mentioned that the GMPP search can be also made based on different ESC methods [38,39]. Here, it is proposed a new perturbed-based ESC (PESC) scheme that uses an additional feed-forward control of the dither gain based on the first derivative of the PV power. The proposed PESC scheme locates and tracks the GMPP in one stage, so the search speed is higher that the two-stage searching methods. For example, a 2 kW step on the PV pattern is tracked in less than one second using the advanced ESC scheme proposed in [38], which use the Fourier Transformation to modify the dither gain with the amplitude of the first harmonic (H_{f1}) of the PV power. A filtering approach is proposed here to approximate the H_{f1} amplitude. Thus, the dither gain will depend by the changes in the process. Furthermore, the tracking accuracy during steady-state regime is higher than 99.9% based on this technique, being comparable or higher than all reported results in the literature for PV applications [23–25] and other ESC-based industrial applications [40,41]. To the best of the author's knowledge, the PESC scheme proposed here is new in existing literature.

Consequently, the objectives of this paper are the following: (1) to present a survey on the ESC methods and ESC-based optimization applications focused on the PV systems; (2) to classify and compare the PESC schemes from the topological point of view; (3) to identify the PESC-based MPPT methods that are appropriate to track the GMPP in second stage (after the GMPP is located in first stage based on a soft computing searching techniques); (4) to evaluate the performance of the PESC-based GMPPT method proposed here to search the GMPP in one stage.

Consequently, the paper is structured as following. In Section 2 of this study the PESC schemes from diverse references were collected, classified, compared, and summarized. The equivalences of these PESC schemes are noted here from the topological point of view and averaged control loop obtained, besides the values of the performance indicators and applications identified in the literature. The PV applications of the PESC-based GMPPT methods are review, too. The proposed PESC scheme is intuitively introduced and then it is analyzed in Section 3. The dynamic performance analysis is performed based on the averaged control loop method. The power characteristics of a PV array under PSCs are shown in Section 4. Some PV patterns are select to be used in simulations performed in this study. The results obtained (see Section 5) highlight the performance of the proposed PESC scheme to track the GMPP. Last Section concludes the paper.

2. Optimization-based extremum seeking control

The ESC method is an adaptive close-loop control method used to search the extremes (maximums or minimums) of a nonlinear