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Global Extremum Seeking Control of the power generated by a Photovoltaic Array under Partially Shaded Conditions

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ABSTRACT

This paper analyses the performance of new Extremum Seeking Control scheme which has two adaptive control loops: (1) the searching loop locates the Global Maximum Power Point by sweeping the Photovoltaic pattern based on an asymptotic dither; (2) the tracking loop finds and tracks accurately the Global Maximum Power Point based on similar loop used in Perturbed-based Extremum Seeking Control schemes proposed in the literature. The advantages of the Asymptotic Perturbed-based Extremum Seeking Control scheme in comparison with other Extremum Seeking Control proposals are evaluated as (1) cost and complexity of implementation, and (2) performance obtained based on four indicators: the searching resolution, tracking accuracy, tracking efficiency, and tracking speed. Four solutions are implemented in MATLAB/Simulink software® to evaluate the most efficient method to obtain the asymptotic dither based on the first harmonic of the output signal from controlled process, the Photovoltaic Array under Partially Shaded Conditions. The chosen variant from the four schemes was further analyzed as performance, robustness to Partially Shaded Conditions, fast changes of the irradiation, and environmental noise. Different patterns for the irradiance profile were used to test this control scheme in tracking of the Global Maximum Power Point generated by different Photovoltaic arrays. Two normalization gains are used to adapt the proposed control scheme to different Photovoltaic arrays. The other two gains (the dither's gain and the loop's gain) are designed for best performance in sweeping and tracking of Global Maximum Power Point. The performance obtained is similar or superior to the other algorithms used for tracking the Global Maximum Power Point.

1. Introduction

The target for 2030 of power generation from Photovoltaic (PV) array in total power generation was set in range of 7–17% for different countries [1]. The main obstacles to increase this ratio are the installation cost and energy efficiency [2]. It is worth to mention that the installation cost has decreased yearly due to the advances in PV physics and the latest technology in panel fabrication assures an energy efficiency of maximum 19% [1,2]. Consequently, all PV energy available must be harvested from the PV array operating under Partially Shaded Conditions (PSCs) or high dynamic variations of the irradiance profile [3]. Thus, a Global Maximum Power Point Tracking (GMPPT) algorithm must to be used instead of MPPT algorithm. The objective of a GMPPT algorithm is to track the Global Maximum Power Point (GMPP) not the Local MPPs (LMPPs) of the PV pattern usually generated during of a sunny-cloudy day [4]. It is know that the MPPT algorithms remain blocked in one of the LMPP [5], but the GMPPT algorithms

Abbreviations: ACS, Ant Colony Systems; ANN, Artificial Neural Network; aPESC, Asymptotic PESC; aPESCs, Asymptotic PESC based on scalar ESC scheme; aPESCH1, Asymptotic PESC based on FFT to compute the H1 magnitude; aPESCLy, Asymptotic PESC based on Lyapunov switching function; BPF, Band Pass Filter; DE, Differential Evolution; EA, Evolutionary Algorithms; ESC, Extremum Seeking Control; FFT, Fast Fourier Transform; FLC, Fuzzy Logic Controller; GA, Genetic Algorithm; G_d, signal which modulate the dither; GMPP, Global Maximum Power Point; GMPPT, Global Maximum Power Point Tracking; GaPESC, Global aPESC scheme based on one BPF; GaPESCbpf, Global aPESC scheme based on two BPFs; GaPESCd, Global aPESC scheme based on derivative operator; GaPESCH1, Global aPESC scheme based on FFT to compute the H1 magnitude; HC, Hill Climbing; HPF, High Pass Filter; H1, first Harmonic of a signal; IC, Incremental Conductance; LMPP, Local Maximum Power Point; LPF, Low Pass Filter; MPP, Maximum Power Point; MPPT, Maximum Power Point Tracking; MV, Mean Value; PHC, Percent of the Hit Count; PESC, Perturbed-based Extremum Seeking Control; PESCs, Scalar PESC; P&O, Perturb and Observe; PSC, Partially Shaded Condition; PSO, Particle Swarm Optimization; PV, Photovoltaic; RCC, Ripple Correlation Control.

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will operate in two phases to locate GMMP and then to accurately find the GMPP (but with less than 100% Percent of the Hit Count (PHC) as it is shown in [6]). Thus, in last decade this challenging subject was in attention of the researchers and over one hundred GMPPT algorithms were proposed [3,6]. The GMPPT algorithms were classified in firmware-based and hardware architecture-based algorithms [6] and their performance is extensively compared in reviews mentioned above based on the following performance indicators: the searching resolution, tracking accuracy, tracking efficiency, and tracking speed.

The firmware-based GMPPT algorithms operate in two stages.

The GMPP is located in the first stage using a search based on different algorithms [6]. For example, the Fuzzy Logic Controller (FLC) proposed in [7] for tracking the MPP could be easily developed based on extended rules' base for locating the GMPP as well. The Artificial Neural Networks (ANNs) can be also used for locating the GMPP [8]. The genetic k-means algorithm based on ANN with radial basis function network is used for GMPP prediction [9]. The Evolutionary Algorithms (EAs) based on Differential Evolution (DE) method can be used for locating the GMPP as well [10]. The performance of Genetic Algorithms (GAs) is compared with classical MPPT methods in [11]. The optimization algorithms inspired from nature such as Ant Colony Systems (ACSs) and Particle Swarm Optimization (PSO) algorithms are successfully applied for locating the GMPP [12]). The best performance related to PHC value which was recently reported in the literature has been obtained for Particle Swarm Optimization (PSO) algorithm [13]. The best performance related to locating speed was reported for a chaotic search of the GMPP [14].

The GMPP is tracked accurately in the second stage using a popular MPPT algorithm [15].

The Perturb and Observe (P&O) algorithm use a perturbed step to track the MPP [16]. The perturbed step decreases for improved variants based on the P&O in order to reduce the power ripple and increase the tracking accuracy [17]. The performance obtained for the Incremental Conductance (IC) algorithm and P&O algorithm under dynamic weather conditions is shown in [18]. An advanced MPPT algorithm based on basic IC method is proposed in [19] to improve the tracking speed. Development of a microcontroller-based MPPT algorithm using the Hill Climbing (HC) method is presented in [20]. An advanced MPPT algorithm based on basic HC method is proposed in [21] to solve the trade-off between accuracy and speed.

Note that more than fifty MPPT algorithms are identified in reviews and all have demonstrated good performance under low variation of the irradiance profile (for example see [22]). Some of them were used also in the second stage to accurately track the GMPP [23]. The discrete-time implementation of the Ripple Correlation Control (RCC) is shown in [24]. The scan of the current or the voltage is used to track the MPP [25], but different way than here, where the Extremum Seeking Control (ESC) algorithm is involved [26]. Precise MPP estimation using P–V curve geometry is shown in [27], but the dynamic of the irradiance profile and the environmental noise are not considered in robustness evaluation. Experimental tests of open-loop MPPT techniques are presented in [28] for direct method proposed. The performance of fractional methods based on Short Circuit Current is highlighted in [29]. A comparative study on of Open Circuit Voltage method [30] in comparison with the dP/dV feedback control method is performed in [31]. Reduced tracking speed is obtained based on the dP/dI feedback control [32] in comparison with dP/dV feedback control. The MPPT implementations based on slide control methods are shown in [33]. The ESC-based MPPT algorithms are applied for stand-alone [34] or grid-connected [35] PV applications.

The main disadvantages of these algorithms are related to oscillations around the MPP and their blocking in one of the LMPPs (rather than finding of the GMPP) [6]. The generated PV power increases with about 45% if a MPPT algorithm is used on a PV array during a sunny day, but the PV systems with MPPT controller became ineffective if the shading coefficient is over to 30% [1]. The use of GMPPT algorithm instead of a MPPT algorithm can solve this issue of a PV array under PSCs.

Consequently, the GMPP algorithms are tested and compared in order to identify the best and efficient solutions to be implemented. For example, in [6] it is shown that the GMPP algorithm proposed in [36] may fail under weather conditions that are different to assumptions considered in [36]. Note that these PV patterns were generated by different PV array under PSCs, and these cannot cover all operating situations. Thus, a great effort is made for standardization of PV patterns for testing the MPPT algorithm, such as the EN 50530 that is used for dynamic standard tests. Innovative PV patterns for dynamic testing of the GMPPT algorithm are proposed here.

The dividing rectangle (DIRECT) GMPPT algorithm proposed in [37] to find the peak values is based on mathematical rules to locate the LMPPs and has the higher tracking speed from the GMPPT algorithms analyzed in [6]. The higher tracking accuracy is obtained for the PSO-based GMPPT algorithm proposed in [38], but is worth to mention that the use of complex firmware-based GMPPT algorithms increases the complexity of the digital controller as well. Consequently, efficient and simple implementations of the GMPP controller should to be found based on other types of scanning of the PV pattern, such as proposed here. Recently, an interesting scanning method is proposed in [39] based on scanning of the voltage. The maximum PV power, P_{mpp}, is obtained by using a sweeping [22] or peak [39] strategy to identify the GMPP. Note that the experimental tracking time reported (about 4 s [22]) is a bit higher for a very dynamic irradiance profile that can be obtained in tropical conditions.

The method proposed here is an attempt based on the previous research of the author [40]: the Asymptotic Perturbed-based Extremum Seeking Control (aPESC) scheme that uses the first harmonic (H1) of the PV power to asymptotically modulate the dither. This proposal avoids the constraints or disadvantages posed by the GMPPT algorithms in two stages, which are critically discussed in reviews [3,6,10]. This proposal also improves the performance obtained with the PESC schemes [41]. The aPESC schemes are proposed for tracking the GMPP [42]. The aPESC variants are tested in [43] and here are topologically compared in Section 2.

As it is known, besides the criteria of the cost and control circuit complexity of a real-time energy management system [44], the performance indicators mentioned above are mainly used to compare the GMPPT algorithms. It is worth to mention that not all GMPPT algorithms proposed in the literature are fully evaluated based on performance indicators mentioned above, but the reviews [3–6] give to the reader a complete comparison of the most well know and efficient GMPPT algorithms. It can be noted that even these algorithms cannot fulfill all the criteria. Each algorithm excels in not more than two performance indicators. For example, the better tracking accuracy during the stationary regime is reported for the PSO-based GMPPT algorithm [12,38], being of about 99.96% (as average value), but these methods require a longer tracking time in comparison with other type of GMPPT algorithms and the complexity of the controller is relatively high. Consequently, the PSO-based GMPPT algorithms are unsuitable for use in tropical areas that exhibit rapid PSCs and, in addition, the cost of implementation is the biggest.

Also, the effectiveness of the ANN&FLC-based GMPPT algorithms is not guaranteed in any criteria because these algorithms are based on the training stage that use a set of PV patterns [7–9], including some PSCs (such passing clouds), which are difficult to be modeled [3]. Furthermore, the complexity of the controller is relatively high for these types of GMPPT algorithms.