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# Searching of the extreme points on photovoltaic patterns using a new Asymptotic Perturbed Extremum Seeking Control scheme

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ABSTRACT

The features of new Asymptotic Perturbed Extremum Seeking Control (aPESC) scheme have been analyzed in this paper. The proposed aPESC scheme is able to find the extreme points on multimodal patterns generated by a photovoltaic (PV) array under Partial Shading Conditions (PSCs). Besides the Global Maximum Point (GMP), other Local Maximum Point (LMP) close to the GMP could be useful to be known in specific engineering applications in order to use a global (optimal) or local (suboptimal) optimization solution. The tuned parameters (the dither gain $k_2$ and the loop gain $k_1$) of two adaptive control loops of the aPESCH1 scheme proposed here (instead of one for the classical aPESC schemes) will be designed to locate and track accurately the GMP and LMPs on different multimodal PV patterns.

The constraining rules related to scanning limits and closed loop stability will set the designed range for the tuned parameters. A general procedure to design the dither gain $k_2$ to locate the GMP will be shown. The LMPs will be found by fine-tuning of gain $k_2$. The loop gain $k_1$ will be designed considering the stability's limit of the closed loop containing the PV system dynamic and aPESCH1 scheme. The performance obtained was highlighted using different PV patterns and a PV system implemented in MATLAB/Simulink software®.



## 1. Introduction

Knowledge of multiple extremes (named below as Local Maximum Points - LMPs) of the multimodal function defined for complex control problems may be useful in some optimization tasks due to constraints imposed to the process' variables [1,2]. In such cases, the Global Maximum Point (GMP) could not be realizable and a LMP (a suboptimal solution) must be found in the searching zone delimited by the given constraints [3]. Furthermore, the multimodal function may be dynamically defined for some applications [4], so it is important to know some LMPs in the searching zone delimited by the dynamic constraints [5]. The static and dynamic multimodal patterns will be used here to evaluate the performance of the Asymptotic Perturbed Extremum Seeking Control (aPESC) scheme proposed, named below as aPESCH1 scheme because computes the first harmonic (H1) of output process based on Band Pass Filter (BPF).

Optimization has multiple applications in different areas of science [6,7], engineering [8,9], and economics [10,11]. The optimization's goal is to find an optimal solution in the searching zone where the objective function has been defined [12]. This solution must be quickly obtained with reduced cost and good performance related to finding accuracy that defines the stopping criteria [13]. In practice, it is desirable to find GMP and LMPs of a given objective function in order to choose the best solution due to the physical and economic constraints imposed [14]. This best solution may be selected from the available solutions [15]. It is preferable to know all LMPs of a given objective function in order to switch the optimized system to an appropriate solution that is close to

*Abbreviations:* ACS, Ant Colony Systems; ANN, Artificial Neural Network; aPESC, asymptotic PESC; aPESCH1, asymptotic PESC based on BPF and MV blocks to compute the H1 magnitude; BPF, Band Pass Filter; DE, differential evolution; EA, Evolutionary Algorithms; ESC, Extremum Seeking Control; FC, Fuel Cell; FLC, Fuzzy Logic Controller; GA, genetic algorithm; $G_d$, , signal which modulate the dither; GMP, Global Maximum Point; GMPP, Global Maximum Power Point; GMPT, Global Maximum Point Tracking; aPESC2BPF, aPESC scheme based on two BPFs; HPF, High Pass Filter; H1, first Harmonic of a signal; LF, low frequency; LMP, Local Maximum Point; LPF, Low Pass Filter; MPP, Maximum Power Point; MPPT, Maximum Power Point Tracking; MV, Mean Value; PESC, Perturbed-based Extremum Seeking Control; PSC, Partially Shaded Condition; PSO, particle swarm optimization; PV, photovoltaic; $R_S$, searching resolution; $T_{acc}$, , tracking accuracy; $T_{eff}$, , tracking efficiency.

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one previously used, reducing the transitory regime and the control effort [16]. As an example, the search and tracking of the GMP of a PV array may be considered herein. The GMP can be found based on different firmware-algorithm [17,18]. The GMP must be tracked in a large search range of power due to Partially Shaded Conditions (PSCs), which means a current- or voltage-mode control of power interface [18]. A constrain related to the variation of the control variable (for example, with no more that 20% to reduce the transitory regime) is recommended to be used [19]. Consequently, a LMP with level close to GMP (in range of the 5% tracking resolution) will be used a suboptimal solution, instead of the GMP that is far from the previous optimal solution located. Note that the tracking efficiency will increase as well due to reduced time to locate the LMP (which means high tracking speed). The performance indicators that are usually used to evaluate the GMP tracking algorithms applied in PV applications are the searching resolution, the tracking accuracy, the tracking efficiency, and the tracking speed. These performance indicators may be used on multimodal optimization as well [14].

Multimodal optimization means to find the multiple suboptimal solutions (the LMPs) and not only one optimum (the GMP) [14,20]. In fact the algorithms developed for multimodal optimization have been usually borrowed for the PV applications and for other problems [20,21]. For example, the Evolutionary Algorithms (EA) have been proposed for multimodal optimization from 1975 [22,23], being developed based on several natural processes and animal-behaviors such as the genetic algorithms (GA) [24,25], the adaptive learning algorithm [26], the differential evolution (DE) algorithms [27], the simulated annealing [28], gradient search algorithm [29], the particle swarm optimization (PSO) algorithm [30], and hybrid algorithms [31]. The algorithms mentioned above are usually used as firmware-based GMP tracking (GMPT) algorithms in the first stage, when the GMP is located based on Evolutionary Algorithms such as GAs [32], DE [33], PSO [34], ant colony optimization (ACO) algorithm [35], Fuzzy Logic Controller (FLC) [36], Artificial Neural Network (ANN) [37,38], and chaotic search [39]).

This paper reports a new method to find the Global Maximum Point (GMP) and other Local Maximum Points (LMPs), and how to set appropriately the tuning parameters $k_1$ and $k_2$. So, this paper represents the first attempt to use the ESC algorithm for multimodal optimization.

If the both tuned parameters (the dither gain $k_2$ and the loop gain $k_1$) will be designed based on the scanning rule of the constrained (searching) range and the stability rule of the closed loop, then any extreme points can be located accurately. In this study the dither gain ($k_2$) will be fine-tuned on the scanning range defined for each LMP. The loop gain ($k_1$) will be set to a value that assures the stability of the closed loop. The methodology of design will be presented and exemplified through many case studies, including a PV system under variable irradiance. The performance of the proposed aPESCH1 method will be analyzed in next sections and summarized in Conclusion. Consequently, the paper is structured as following. The previous research work in field of aPESC methods will be shortly mentioned in Section 2. The aPESC scheme proposed will be briefly investigated in Section 3. The searching model for the local extrema will be developed in Section 4. The main rules to design a stable GMP control based on aPESC scheme will be shown in Section 5 using the roots locus and the small signal model of the searching process. The methodology to design the tuning parameters for locating the GMP and LMPs will be given and the exceptions will be mentioned as well. The performance indicators related to the optimization problem will be defined in Section 6. In Section 7, the promising performance of the aPESCH1 scheme will be highlighted by estimating the main performance indicators (the searching resolution, tracking accuracy, tracking efficiency, and tracking speed). Last Section concludes the paper.

## 2. Previous research work

The Extremum Seeking Control (ESC) scheme is proposed here for finding multiple (local or global) extrema of a function (a steady state map or a dynamic map) in a single variable, but the algorithm could easily be extended to multiple variables using different frequencies for the dither on each variable or dithers in quadrature for two variables [40,41]. The objective function considered here is of continuous scalar type, which can be defined by a black-box model, but the multi-input function may be considering as well. The aPESCH1 scheme has two loops: (1) the scanning loop which will locate the LMP by sweeping the multimodal pattern based on an asymptotic dither modulated by the first harmonic ($H_1$) of the output signal and controlled by the dither gain ($k_2$); (2) the locating loop will accurately find the LMP (or the GMP) and will track it based on the classical PESC loop tuned by the loop gain ($k_1$). So, the main contribution of the paper is the proposal of an ESC with two loops: one loop is responsible for restricting the search space (i.e. defining constraints within a local maximum that has to be found) and the second loop is the usual loop of the ESC scheme, which cannot find in any condition the GMP. Note that the aPESCH1 algorithm proposed here finds and tracks the GMP within the constrained search space in any condition if the GMP is higher than the highest value of LMPs with the value named below as the searching resolution. This feature has been extensively analyzed in [42] based on different aPESC scheme, so the GMP Tracking (GMPT) based on new aPESCH1 scheme will be shown here for good benchmarks proposed in the literature [43,44] to assess the performance of proposed method in convergence to a global or local optimum with high resolution. The conditions under which the global extremum can be reached based on the proposed aPESC scheme will be defined in Section 4, and the convergence proof could be given in the same manner as for any basic aPESC scheme, with some difference shown in [45]. Note that this proposal [45] is close to one of the aPESC variant analyzed in [41], but the authors did not explore in [45] the feature of this aPESC scheme for global search. So, this proof will be not repeated here due to length of paper, but other mathematical aspects related to stability of the aPESCH1 scheme are shown and validated using more cases studies.

The aPESC algorithm requires a priori knowledge of the range where the LMPs are usually located within the constrained search space on the steady state map or the dynamic map, but this design aspect can be solved based on preliminary tests (see the case studies below). If the nonlinear map has a few and dense multiple optimal points with differences between the LMPs lower than the searching resolution, then the aPESC algorithm may fail in finding the GMP. The searching resolution is set by the tracking accuracy which depends by the dither's frequency and amplitude [46,47], but note that this is higher than 99.9% in all studies' cases shown here due to the asymptotic decrease of the dither's amplitude for the aPESCH1 scheme. Thus the searching point will converge to the vicinity of GMP if the tuning parameters are in the GMP range designed for this action, but also may converge to the vicinity of a LMP by fine tuning of the parameters $k_1$ and $k_2$ outside of the GMP design range. All LMPs located near to the starting point until the GMP, but not over the GMP, will be found by tuning the values of the parameters $k_1$ and $k_2$. The LMPs located on the map in the opposite part of the starting point related to GMP can be found if the starting point will be chosen in that opposite part of the map.

The GMPT performance and efficiency of the aPESCH1 algorithm will be briefly compared here with other GMPT algorithms,