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Energy harvesting from the *PV* Hybrid Power Source

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ABSTRACT

In this paper it is proposed a Maximum Power Point (*MPP*) tracking technique for the photovoltaic (*PV*) system based on an advanced Extremum Seeking (*aES*) control that improves both basic performances of the *ES* control schemes: guaranteed convergence and proved internal robustness. Beside these features that are necessary in case of unmodeled dynamics, other features such as higher search speed and improved accuracy of the *MPP* tracking process are demonstrated. Thus, different irradiance sequences are used to test the performances of the *MPP* tracking process, where each of them could represent a worse scenario than in reality. Analysis in the frequency domain reveals the main relationships between the *aES* control parameters (the values of closed loop gain and dither amplitude) and the performance indicators (the search speed and tracking accuracy). If the dither amplitude is set to be proportional with the magnitude of the first harmonic of the *PV* power processed in the *ES* control loop, then the *aES* control will exhibit a negligible power ripple after the *MPP* was caught. Therefore, the proposed *aES* control outperforms all *ES* control schemes in overall power efficiency.

1. Introduction

Solar energy has no territorial restrictions, so it will be widely used because it is an emerging green energy resource that has a price which continues to drop each year. As the investments on *PV* (photovoltaic) panel systems are still expensive, the goal to harvest the maximum energy from a *PV* system is one of main challenges for the designers. Thus, every *PV* system must operate efficiently using an appropriate energy harvesting technique based on an *MPP* (Maximum Power Point) tracking control technique. Since the operating point of the *PV* system mainly depends on the level and dynamics of the load power, irradiance and temperature, the *PV* Hybrid Power Source (HPS) must have, in addition, at least an Energy Storage System (*ESS*) to assure the balance of the power flow on the *DC* (direct current) bus [1]. An *MPP* tracking control that could harvest all the energy available from the *PV* panel would improve the overall system efficiency. Many *MPP* tracking techniques have been proposed during the last decades, which can be categorized as direct and indirect methods [2], or as below [3]:

- Methods based on a known algorithm for the *MPP* tracking. For example: perturbation and observation (P&O) algorithm, incremental conductance algorithm, hill climbing, current sweep, three-point weight comparisons, and so on [4]. Also a mix of them could be used based on the measurements of the *PV* cell characteristics (power vs. current or voltage) [5]. The tracking algorithms can compute online the nearest operating point to the *MPP* based on perturbation with constant or variable step size on the current or voltage, which finally produces tracking oscillations around the *MPP*. Considering variable level for the insolation and temperature, two sensors are usually required to measure the *PV* panel voltage and current [6], but low cost sensorless variants can be implemented, too [7];
- Artificial Intelligence-based *MPP* tracking algorithms. Fuzzy logic control, artificial neural network and evolutionary algorithms are used to optimize the operation of the above-mentioned methods related to the search speed [8], level of tracking oscillations [9] and *PV* HPS robustness under variable irradiation on cloudy weather [10]. The annual amount of errors was measured as being of about 6.6% in classical P&O method, but appropriate solutions to reduce these errors based on artificial intelligence can be developed, reducing this value below 2% [11].
- Computational methods. The main advantages of the *MPP* tracking control methods based on computational models are their intrinsic robustness [12] and high search speed [13], but

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note that the tracking accuracy is still dependent on the model used for the solar cell [14].

Also, the energy efficiency of the whole *PV* system depends on the grid-connected power converter used [15] or on the number of sun tracking axes [16].

In this paper it is proposed a real-time optimization method based on the *ES* control scheme to increase both search speed and tracking accuracy indicators related to the performance of finding the *MPP* under different operating conditions of the *PV* panels. It can be noted that all of the above-mentioned *MPP* tracking methods use fixed or variable small iteration steps determined by the accuracy and tracking speed requirements, which are two performance indicators that typically require opposite values in the admissible control range. Thus, if the step size is decreased to obtain a higher accuracy in finding the *MPP*, then the searching speed will be lower and vice versa. The *aES* (advanced Extremum Seeking) control is proposed to overcome the above limitations, by using an adaptive gain for the dither amplitude based on the first harmonic (H_1) of the *PV* power. This real-time optimization approach is a type of direct input adaptation technique, which turns the optimization problem into a feedback control problem that implements optimality via tracking of the controlled variables. Other two approaches can be distinguished on real-time optimization according to the adapted quantities [17,18]: (1) model-parameter adaptation that updates the parameters of the process model [17], while (2) the modifier adaptation modifies the constraints and gradients of the optimization problem [18]. Note that both techniques repeat iteratively the optimization phase [19].

The first approach contains hybrid methods such as self-optimizing control and necessary conditions of optimality tracking [20], and different *ES* control techniques [21] (starting with self-oscillating *ES* algorithm [22] and *ES* regulators [23], and continuing with the others listed below). In the hybrid approach it can be noted that the self-optimizing control loop rejects the modeled disturbances on a fast time scale and the necessary conditions of optimality tracking loop corrects the unmodeled disturbances on a slower time scale [24].

As it is known, the *ES* control is a well-known method of adaptive closed loop control used for searching of unknown extremum on a static input–output characteristic. The interest in *ES* control schemes in academia and industry was revived in the last decade [24,25], as soon as the stability-proofs are first shown in Ref. [26], and then extended in Ref. [27]. Thus, the *ES* control has been successfully used in various technical applications [28], including the *PV* systems [29]. The tracking accuracy reported in literature is of 99.99% and this is also noted in the *PV* inverters data sheet [30]. Note that the tracking accuracy is defined as 100 P_{PV}/P_{MPP}, where P_{MPP} is the power of *PV* panel operating at the *MPP* and P_{PV} is the average power harvested from the *PV* panel using an *MPP* tracking scheme [31].

The boost converters are widely used as power interface between the *PV* panel and common *DC* bus [32]. The voltage on *DC* bus is the input voltage for the inverter system, eventually grid connected [15].

If a *PV* array uses a grid-connected inverter, then the switching action of power devices must generate an almost sinusoidal voltage at the inverter output, which is synchronized with the grid voltage and must have the same magnitude for both first harmonics of mentioned voltages. As a consequence, two types of ripple appear on the *PV* array power: (1) a low frequency (*LF*) ripple having harmonics at multiples of the grid frequency, and (2) a high frequency (*HF*) ripple having harmonics at multiples of the switching frequency.

Ripple correlation control can use both types of ripple that normally overlap on the *PV* power signal, P_{PV} [33]. Most of the ripple correlation control schemes utilize the natural inverter ripple to either perform P&O method [34] or *ES* control [35].

In Ref. [36] it is shown that the proposal to use an extended Kalman-Filter for gradient estimation may offer faster search speed than the classical *ES* control, but here an *aES* control scheme that can effectively improve the search speed and accuracy simultaneously is proposed. Further information about the classical *ES* control schemes is shown in Section 3.

The goal of this paper is to show that the proposed method can be used to accurately determine the *MPP* and to demonstrate that this method has improved performances related to energy harvesting from the *PV* panel. In addition to the performances inherited from the basic *ES* control schemes, a guaranteed convergence and an internal robustness, further performances are shown under variable weather conditions [10,37]. Due to the difficulties of real-world experimental set-up, the experiments on the effects of fluctuating irradiance level for the solar cells have been made only by numerical simulation.

The paper is organized as follows. Section 2 briefly presents the solar cell model used in simulation. Section 3 deals with *ES* control schemes. After a review of classical *ES* control schemes, the proposed *aES* control scheme with an adaptive closed loop gain is explained. A brief review of the main results obtained on stability and convergence of the *ES* control schemes is shown, too. An interesting analysis of the *ES* control schemes in the frequency domain is presented in Section 4. The performances obtained for the *ES* control schemes on *PV* module under constant irradiance are shown in Section 5. The comparative results on *PV* module under constant irradiance are shown in Section 6 using the two *ES* control schemes: the *aES* and modified *ES* (*mES*) control schemes. The latter was introduced in Ref. [28]. The performances of the *aES* control scheme are clearly highlighted in Section 7 based on *PV* module under variable irradiance. A *PV*/*ESS* HPS is designed based on *aES* control scheme and then tested under a dynamic load and variable weather conditions to prove an improving of the performance indicators compared to the basic *ES* control schemes. The last section concludes the paper.

2. Solar cell model

Because temperature variations are typically much more gradual than irradiance changes, for the remainder of the analysis performed in this paper it is assumed that the temperature is constant, $T = T_R = 298$ K. Neglecting the parallel resistance, R_p, the solar cell is modeled as below (for example, see Refs. [3,12]):

$$I_{PV(cell)} = K_{IG(cell)} \cdot G - I_{0R} \cdot \left[\exp\left(\frac{V_{PV(cell)} + R_s I_{PV(cell)}}{n V_T} \right) - 1 \right]$$

where $V_{PV(cell)}$ represents the solar cell voltage, $I_{PV(cell)}$ represents the solar cell current, R_s is the series resistance of the solar cell, $K_{IG(cell)} = I_{sc(cell)}/G_R$ the irradiation to short-circuit current gain, $I_{L(cell)} = I_{sc(cell)}\ G/G_R$ the light-generated current, G the level of instantaneous irradiation, and other parameters are mentioned in Table 1. The values of V_{oc}, I_{sc}, R_s, and other parameters are obtained from the data sheets of the *PV* panel used, while the values of V_{MPP} and I_{MPP} are measured (see Section 5.1).

3. *MPP ES* control techniques

The higher order *ES* (*hoES*) control schemes are shown in Fig. 1. The classical *ES* control, also named as first order *ES* control scheme, is based on the scalar scheme shown in Fig. 1, but without augmentation related to the use of the filter blocks, the high-pass (*HPF*) and low-pass filters (*LPF*) [31]. A modified *ES* (*mES*) use a