Testbench for Evaluations of Maximum Power Point Tracking Algorithms for Solar Energy Harvesting

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***Abstract*—In this paper, a simple testbench is presented for quick evaluation and comparison of maximum power point tracking (MPPT) algorithms. As a large variety of MPPT algorithms appeared and spread in the last two decades, it is necessary to provide quick and relevant means of fair comparison. Thus a testbench and its MATLAB/Simulink implementation are proposed and described. In this testbench two MPPT algorithms are compared: the widespread Perturb and Observe and one based on fuzzy logic. The testbench evaluates their convergence rate, tracking capability and steady state error.**

I. INTRODUCTION

The cost effective exploration of photo-voltaic (PV) panels, especially in locations where the daily average solar irradiation or the temperatures are low, calls for the use of supplementary control methods, like maximum power point tracking (MPPT). The power vs. voltage characteristic of PV panel presents a maximum in its curve, called maximum power point (MPP), and the tracking of MPP is achieved using various methods [1]: the classical ones are based on direct or indirect tracking (power vs. voltage curve fitting, Perturb and Observe) [2], but there are other control flavors such as fuzzy logic based control [3].

The exponential growth of publications in this domain [2] forces researchers to evaluate results as quickly as possible and many times meaningful and fair comparison of MPPT algorithms is difficult to obtain. Thus a systematic approach for MPPT algorithm evaluation is required. This paper describes a testbench structure implementable in various simulation environments for the evaluation of MPPTs.

The paper is organized as follows: the first section presents MPPT in the solar energy harvesting applications. Next, the design guidelines and the structure of a MPPT algorithm testbench are presented. The Matlab/Simulink implementation of the testbench is discussed in details. Two MPPT algorithms are also included in the Matlab/Simulink testbench: the classical Perturb and Observe (P&O) and a fuzzy logic based algorithm. The simulation results presented in section IV., are concerned with the convergence rate and steady state errors of the implemented algorithms and addresses their tracking capability. Finally, conclusions are drawn in the last section.

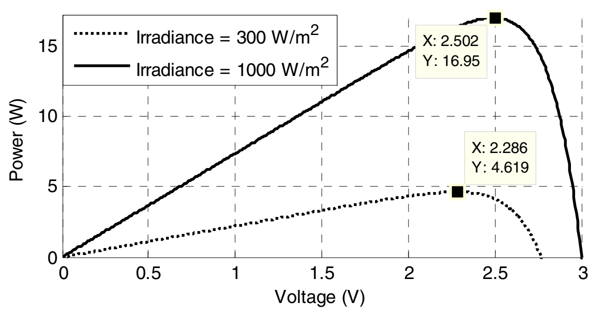

Figure 1. Power vs. voltage characteristic of a solar panel

II. ENERGY HARVESTING OF SOLAR PANELS

The photovoltaic power vs. voltage characteristics present a maxima, called maximum power point (MPP), which varies with respect to the solar irradiance. In Fig 1. a theoretical solar panel's power versus voltage characteristics is depicted under two illumination conditions. At 1000 W/m^2 irradiance the characteristic shows a MPP of 16.95W@2.5V, while under an illumination of 300W/m^2 the MPP is at 4.61W@2.28V. One can also conclude that with the increase of the illumination level the maximum power point also changes. The power vs. voltage characteristic of a real 2W solar panel was obtained in [4].

A common solar energy harvesting setup (see Fig. 2) consists of a solar panel connected through a DC/DC converter (or DC/AC converter, depending on the load profile) to an electrical load (resistive load, battery or the electric grid). In order to ensure the maximum amount of power delivered on the load, the voltage (or the current) on the PV cells controlled. This control is achieved by the MPPT algorithms. The common inputs of MPPT algorithms are the PV panel voltage and current, while the output is usually a pulse width modulated signal that controls a DC-DC converter. If a DC/AC converter is used to feed the harvested energy into the electrical grid, then synchronization is required.

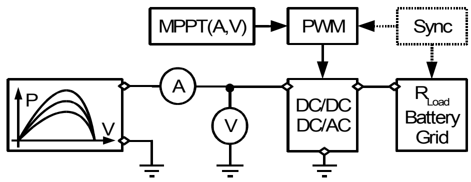

Figure 2. A common solar energy harvesting setup

III. MPPT ALGORITHM TESTBENCH

The fair comparison of MPPT algorithms can be achieved in an organized testbench, where each algorithm is placed in the same condition. The objective is to evaluate the algorithms in terms of their convergence rate and steady state error. In this section, the testbench design guidelines are stated, and then a possible implementation in Matlab/Simulink is presented.

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A. *Guidelines*

The design guidelines of the MPPT testbench are:

1. As the subject of the MPPT tracking is the PV panel, it is important to have a realistic PV panel model.

2. The testbench should verify the algorithms for both convergence and tracking capability. With other words, changing atmospheric conditions should be simulated.

3. The convergence should be evaluated in terms of iterations number. If one algorithm is operated at a higher frequency it may converge faster and the comparison will not be meaningful.

B. *Testbench structure*

The proposed testbench structure and its corresponding Simulink implementation (using Simscape toolbox) is presented in Fig. 3. Let us review the blocks in the model. The *Solver Configuration* block is required by the Simscape toolbox ("Backward Euler" solver type with 0.0001 sample time is used – note that this is the default configuration of the Simscape solver). The *Electrical Reference* is the ground of the electrical system and it is required by the Simscape solver. These two blocks are mandatory for a Simscape simulation. The *Irradiation, Solar panel, Ampere-meter,* and *DC/DC converter* subsystems model the electrical process of harvesting the solar energy and converting it to electricity. In this testbench, the controller takes a current measurement *I(k),* noted *I_k* in the Simulink model. The instantaneous power *P(k)* is computed as the product of *I(k)* and a control voltage *V(k+1),* noted as *V_k* in the model. Each control algorithm has a *V(k+1)* output. The *Multiport Switch* is used to select the output of the desired algorithm. The MPPT algorithms are implemented inside the *Perturb and Observe* and *Fuzzy* subsystems. The characteristics presented in Fig. 1 were obtained, by applying a ramp signal – generated in the *Ramp* subsystem – on the DC/DC controller. All these algorithms take as input the instantaneous power *P(k)* and the instantaneous voltage *V(k)* (this signal is connected to *V(k+1)*). The testbench saves the control voltage *V(k+1)* to the workspace.

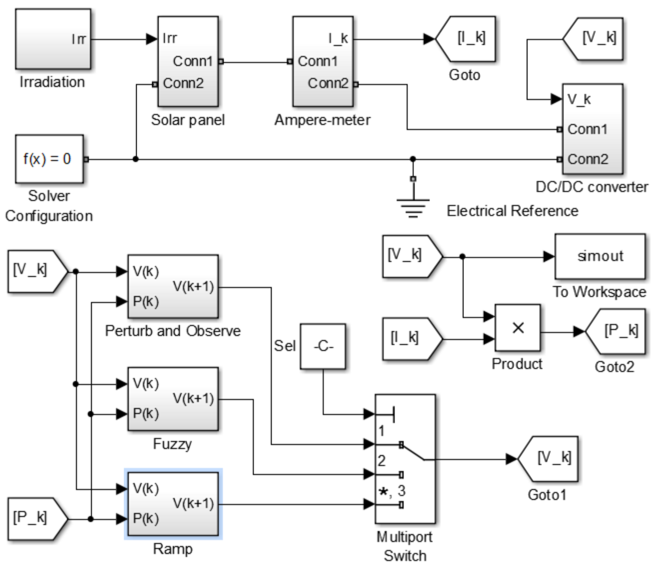

Figure 3. Testbench implementation in Matlab/Simulink

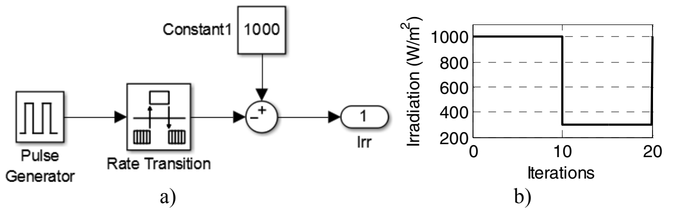

Figure 4. The simulation of changing athmosferic conditions a) the irradiation subsystem b) the resulting irradiation curve

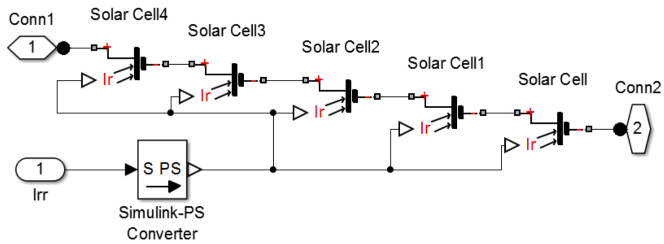

Figure 5. The MATLAB/Simulink model of a solar panel

The implementation details of the subsystems are presented in the followings.

1) *Irradiation subsystem*

This subsystem is used to emulate the changing conditions of the atmosphere. Let us suppose that at the startup of the MPPT algorithm the irradiance is 1000 W/m^2. After a while, the solar panel is shaded by a cloud and the irradiance decreases to 300 W/m^2. The *Irradiance* subsystem is depicted in Fig. 4a. It consists of a *Pulse Generator* that kicks in at the half of the simulation iterations with amplitude of 700 W/m^2, which is subtracted from a constant value of 1000W/m^2. A *Rate Transition* block had to be inserted, because the Simulink and Simscape components operate at different rates (sampling time). The resulting irradiation is depicted in Fig. 4b.

2) *The Solar panel subsystem*

The solar panel model used in the testbench is obtained by connecting serially a few solar cell models (see Fig. 5), where the solar cell model is included in the Simscape library. Each solar cell is set for a short circuit I_{sc} current of 7.34 A, an open circuit voltage of V_{oc} = 0.6 V, quality factor N = 1.5, series resistance R_s = 0.1 mΩ (typical values for an amorphous solar cell). The *Simulink-PS Converter* is required to convert the unitless Simulink input signal to a physical signal used by Simscape components.

3) *The Ampere-meter subsystem*

A current measurement block from the Simscape library is used to obtain the current sample *I(k)*. As this is a physical signal, it is converted to a unitless Simulink signal by the *PS-Simulink converter* (see Fig. 6a).

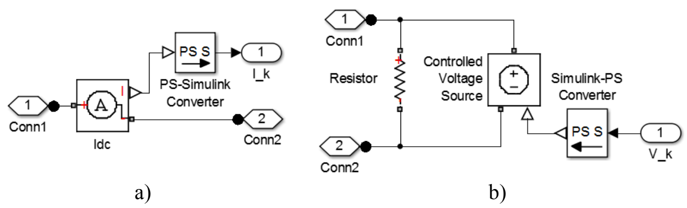

Figure 6. a) The Ampere-meter subsystem
b) The DC/DC converter subsystem

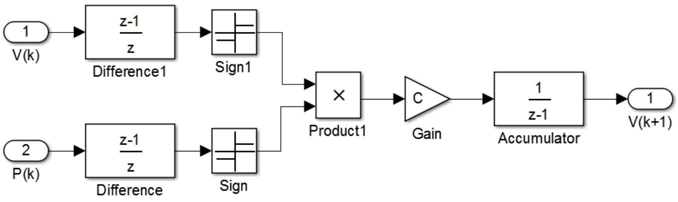

Figure 7. The implementation of the Perturb and Observe algorithm

4) DC/DC converter subsystem

The DC/DC converter model is depicted in Fig. 6b. It consists of two components: a 1 Ω *Resistor* and a *Controlled Voltage Source*, controlled by *V(k)* input signal.

5) Perturbe & Observe algorithm

This algorithm is the most frequent used, because its ease of comprehension, low implementation complexity and stable behavior. It is derived from its flow diagram (it can be found in many references, i.e. [1]); its Simulink implementation is depicted in Fig. 7. The scope of algorithm is to update the control voltage *V(k)* with ± C, an update constant. The sign of the constant C depends on the increase or decrease of the power and voltage. When both increased (both *P(k)-P(k-1)* and *V(k)-V(k-1)* positive) or both decreased (*P(k)-P(k-1)* and *V(k)-V(k-1)* negative) the sign is positive. When one increased the other decreased (i.e. *P(k)-P(k-1)* is positive and *V(k)-V(k-1)* is negative) the sign is negative. After all, the sign of the constant C can be computed as the product of the signs of the differences *P(k)-P(k-1)* and *V(k)-V(k-1)*. The *Difference* and *Difference1* are used to compute the *P(k)-P(k-1),* respectively *V(k)-V(k-1)*. The *Sign* and *Sign1* blocks compute the signs of differences. The product of the signs is scaled by the constant C and accumulated. The output of the *Accumulator* block is the updated control voltage *V(k+1)*.

6) Fuzzy control algorithm

The literature gives a few implementations of MPPT based on fuzzy logic. There are arguments in favor of this type of control: the computational costs of a fuzzy logic controller are comparable with other control algorithms, the design rules are easily formulated in a linguistic manner. The fuzzy controller is designed to minimize the error signal *E(k)* defined as:

$$E(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \tag{1}$$

Intuitively, the minimization of the *E(k)* signal means that the numerator is close to 0, in other words the algorithm found a maxima of the power vs. voltage characteristics. *E(k)* is negative and positive when the operation point is on the left, respectively the right side of the MPP. The direction in which the operation point is moving is given by the difference of the error signal *ΔE(k):*

$$\Delta E(k) = E(k) - E(k-1) \tag{2}$$

The implementation of the fuzzy logic based controller is depicted in Fig. 8. The inputs of the subsystem are the instantaneous power *P(k)* and voltage *V(k)*. The upper branch implements the operations necessary to obtain the error *E(k)* and the error difference *ΔE(k)*. These input signals are merged and limited in amplitude before being applied on the *Fuzzy Logic Controller*. The output of the controller shall be scaled and accumulated as in the case of the P&O algorithm.

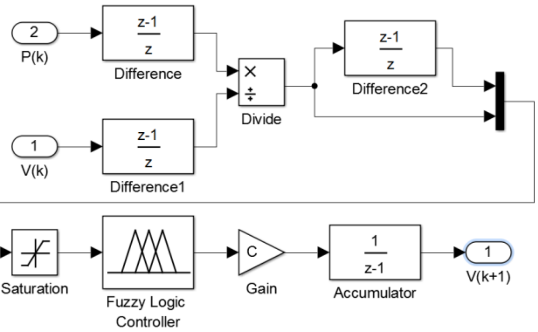

Figure 8. The implementation of the Fuzzy Logic Controller based MPPT

The ingredients to design a fuzzy logic controller are the membership functions and rule base. These design parameters are the ones found in [3]. The input membership functions were rescaled: as the PV power may vary between 0 to ~18 W, a suitable range for *E(k)* and *ΔE(k)* of [-4,4] was considered. If the PV power is normalized, then the membership functions could be defined on range [-1,1]. The resulting control surface is depicted in Fig. 9.

IV. SIMULATION RESULTS

A. Convergence of Perturb and Observe

An important design tradeoff of the P&O is the convergence rate versus steady state error which is controllable by the update constant C. The convergence of the control voltage *V(k)* and the theoretical MSE errors are depicted in Fig. 10 with 3 values of C: 0.1, 0.01 and 0.001. In the first half of the simulation an incident irradiance of $1000W/m^2$ is considered, and then a sudden change in the irradiation is simulated by reducing the irradiance to $300\ W/m^2$. If one uses the same PV panel as the one with the characteristics presented in Fig. 1, then the MPPs are at 16.95W@2.5V and 4.61W@2.28V. In all circumstances the algorithm converges to 2.5V and 2.28V. Note that the initial value of the control voltage *V(k)* is considered to be 2V. With C=0.1 the P&O converges fast, in tens of iterations it reaches the neighborhood of 2.5V and oscillates around this value. At the 50^{th} iteration the change in the irradiation occurs, and the tracking of the algorithm is verified. In a few iterations the P&O algorithm reaches 2.28V and oscillates around it. Using C=0.01 the P&O converges in 50-60 iterations, but the MSE is less

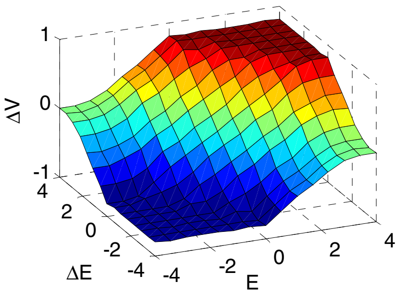

Figure 9. The control surface of the Fuzzy Logic Controller

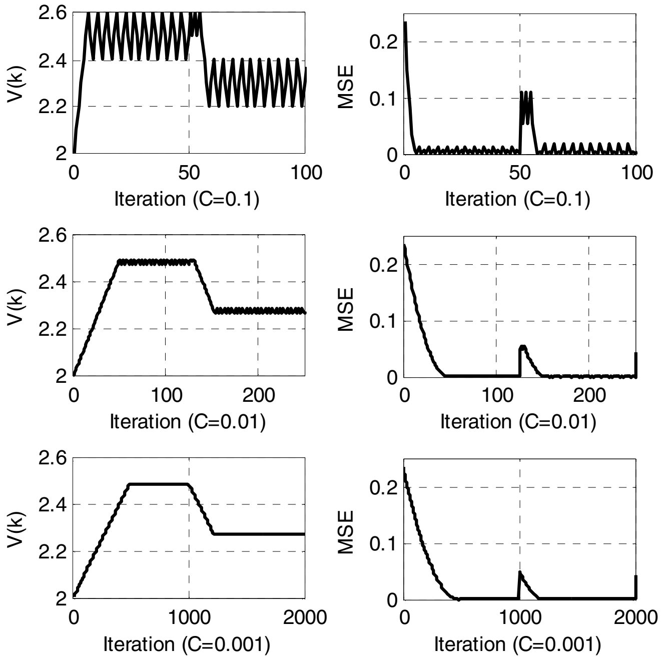

Figure 10. Control voltage and MSE error for Perturb and Observ MPPT

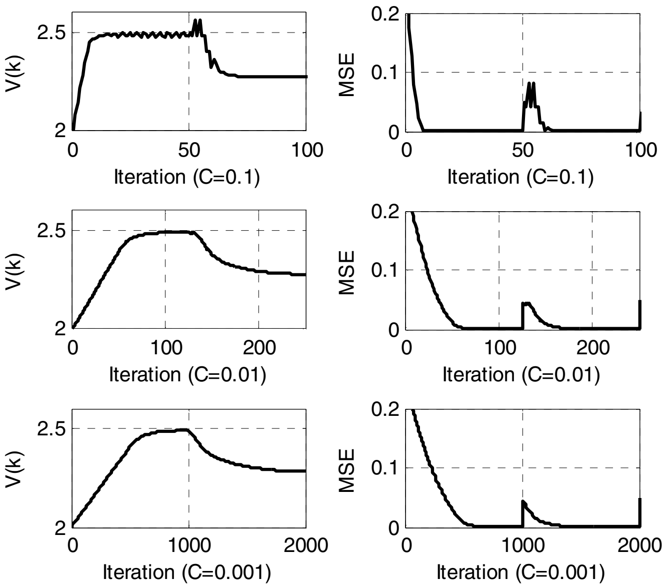

Figure 11. Control voltage and MSE error for Fuzzy Logic based MPPT

than it was for C=0.1. Finally, C=0.001 was used; in the steady state the error is very low in this case. The sampling period depends on the PV panel. It should be set high enough to avoid instability of the MPPT tracking and to reduce oscillations in the steady state when MPP was found [5].

B. Convergence of fuzzy logic based MPPT

The convergence of the fuzzy logic based MPPT algorithm with respect to the update constant C is studied. The output of the fuzzy controller shall compute a value in the limits of [-1,1]. This value is then scaled by the update constant C and accumulated. Let us consider 3 values of C: 0.1, 0.01 and 0.001 and conduct the same simulations as for the P&O algorithm.

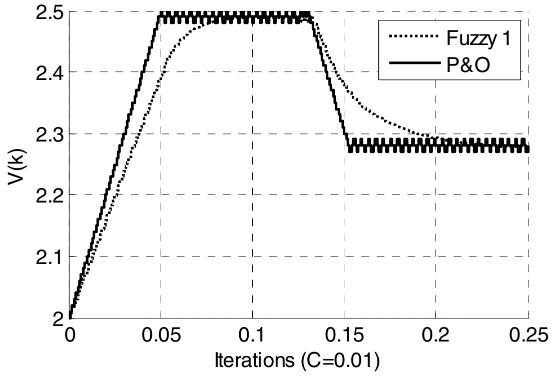

Figure 12. Convergence of P&O and Fuzzy Logic based MPPT

As can be seen in Fig. 11., the fuzzy MPPT converges in 10-20 iterations for C=0.1 – comparable to the convergence rate of the P&O – but the steady state error is less than in the case of P&O. Decreasing the size of C will result in lower convergence rate, but not much improvement in the steady state error.

Finally, the P&O and Fuzzy Logic Based MPPT are compared in Fig. 12. As the steady state error of the P&O algorithm was acceptable for C=0.01, this constant was considered in the comparison of the two algorithms. The convergence rates are comparable. But in terms of the steady state error the fuzzy controller is superior to the P&O.

V. CONCLUSIONS

This paper presents a testbench for maximum power point tracking algorithm deployed in solar energy harvesting. Using the testbench a fair comparison of diverse algorithms can be achieved. The testbench can be implemented in various design environments; we chose to implement it in Matlab/Simulink using Simscape library components. Two algorithms were implemented and compared in this paper, focusing on their convergence rate and steady state error. Also valuable confirmation of present knowledge is given, namely the behavior of fuzzy based MPPT control is found to be superior in terms of steady state error. Further work will comprise the practical implementation of the testbench. Furthermore, the computational complexity of MPPT algorithms could be included in the testbench as an evaluation criterion.

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