Implementation and testing of basic algorithms in PV systems with batteries on a common DC link

Katarina Ćeranić, Mila Gligorijević, Lazar Stojanović and Aleksandar Milić

***Abstract*—Photo-voltaic systems with batteries on a common DC link, i.e. the concept of the Point of Common Coupling (PCC), is increasingly in use. In such systems, it is necessary to achieve the basic system functionalities, such as bidirectional battery operation, efficient Maximum Power Point Tracking (MPPT) regimes on the PV panels, as well as constant voltage on the common DC link for the consumer needs. In this paper, the basic algorithms for battery and panel operation in the MPPT mode are provided. The analysis was first verified in software packages and later by implementing algorithms on the developed low-power prototype of the system, where the basic functionalities were presented. Additionally, the robustness of the algorithms to power transients and disturbances which are common in the PCC systems was tested.**

***Index Terms*—DC link, Point of Common Coupling, battery, MPPT, battery charging strategy.**

I. Introduction

One of the leading causes of global warming is production of the electrical energy. Commonly used energy sources are non-renewable, such as coal, oil and natural gas, where their usage directly results in the pollution of air, water and land. In the past few decades, the use of renewable energy sources, especially wind and solar power, has become more common [1][2]. Further, a stand-alone PV system whose application context is specific to the countryside or isolated locations for self-feeding, is seen as a substitute for the utility grid connection [3]. In such applications, photo-voltaic systems (PV) almost always imply the use of batteries in their continuous operation. Namely, this application enables the consumer to be independent from the electrical grid, as well as, to simultaneously act as a consumer and a producer of electrical energy. Thus, there is a need for a scaled down energy storage system which interacts with the clean energy source.

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The main disadvantage of PV panel employment is the fluctuating output power induced by the variable solar irradiance. This introduces difficulty into fully capitalizing on the panel production, hence creating a need for a control algorithm which would track the maximum power point – MPPT algorithm [4], such as Perturb and Observe (P&O), Incremental Conductance (IC), Current Sweep (CS) technique [5][6], or Open Circuit Voltage (OCV) technique [7][8], along with the Particle Swarm Optimisation (PSO) based algorithms [9]. The main goal of these algorithms is circumventing the practical issues which arise with the PV panel implementation - variable irradiance or damaged cells. Comparison of these algorithms has shown that each has its advantages and disadvantages – where P&O and IC implementation is straightforward, their robustness to disturbance is not a strong point. These two algorithms are also incapable of locating the global maximum on the P-V curve, which usually occurs when the PV string has multiple bypass diodes i.e. multiple power peaks. PSO, in particular, has found its implementation in large string operations, where multiple bypass diodes are unavoidable. However, more advanced algorithms, PSO and CS, are much more complex with their benefits being insignificantly greater than those of P&O and IC in terms of microcontroller implementation. The main shortcoming of the VOC technique is the fact that it requires the power delivery to be halted every time the open circuit voltage of the PV string is needed for further calculation.

Although the development of MPPT algorithms as well as controlled battery charging and discharging algorithms have progressed, there are applications where basic algorithms, reliably implemented, can achieve acceptable results. There, fast high-performance processors are redundant and, thus, avoided, which immediately reduces the overall cost of the product. For this reason, this paper deals with the implementation and testing of basic algorithms in the system presented in Fig. 1, which contains PV panels and a battery connected to a common point. The paper is organized as follows – in Section II an overview of the analyzed system is presented, section III provides basic analysis of the implemented control algorithms. Further, the results of the comparison of the applied algorithms obtained in the simulations and in the experimental setup are presented in Sections IV and V, respectively. Finally, a brief conclusion of the comparison is given.

II. SYSTEM OVERVIEW

The system, on which the control has been implemented, falls in line with the streamlined topology – it is composed of a buck converter as the input stage and a four-switch synchronous buck-boost converter connected to the battery [10]. The point of common coupling (PCC) for these two converters is the DC link, which is also the connection point for the consumer. The prototype parameters are provided in Tables I and II, and the entire power stage schematic is shown in Fig. 1.

TABLE I
SYSTEM PARAMETERS

	L[μH]	C[μF]	$R_{DSon}[\Omega]$
Buck	11.3	22	0.01
Buck-Boost	4.7	100	0.008
DC Link	/	450	/

TABLE II
PV PANEL PARAMETERS

V_{OC}[V]	I_{SC}[A]	V_{MPP}[V]	I_{MPP}[A]
21.9	1.84	17.6	1.7

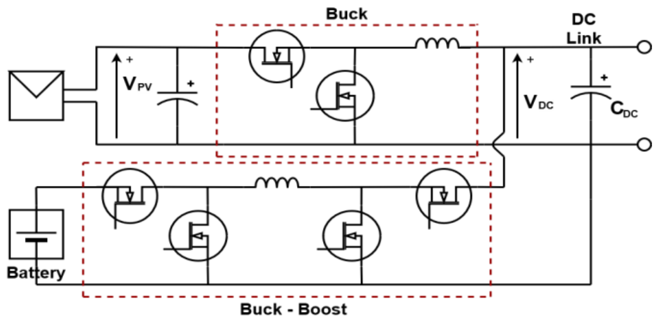

Fig 1. System overview

The hardware design which is increasingly represented in the industry comprises of an input stage communicating with the PV panels and a battery power stage where the common point is the DC link. The DC link voltage is kept consistently within the desired margins, either by generating the power from the PV panels or by discharging the battery [11]. Li-ion battery cells have become the mainstream portable power source due to their exceptional characteristics, such as high specific power density, high cell voltage, low self-discharging rate, high charging current and long life cycle [12]. Hereof, the developed prototype, which will be discussed in more detail in Section V, uses two identical Li-ion batteries connected in series and PV panels whose characteristics are shown in Fig. 2.

In general applications pertaining to higher power derivation, the input step would have been a boost converter, due to its continuous input current [13]. This paper is considering low-voltage low-power applications, so a buck converter as the input stage was chosen, despite the discontinuous input current, which ought to render the MPPT mode inoperable. The desired MPPT operation regime is feasible if a capacitor is connected in parallel to the panels, as it enables the continuous power necessary for the MPPT algorithms. Thus, the input buck converter lowers the panel voltage to the DC link voltage and the MPPT algorithm governs the duty cycles of the input buck. The battery buck-boost keeps the DC link voltage constant and charges or discharges the battery in accordance with the system state [10].

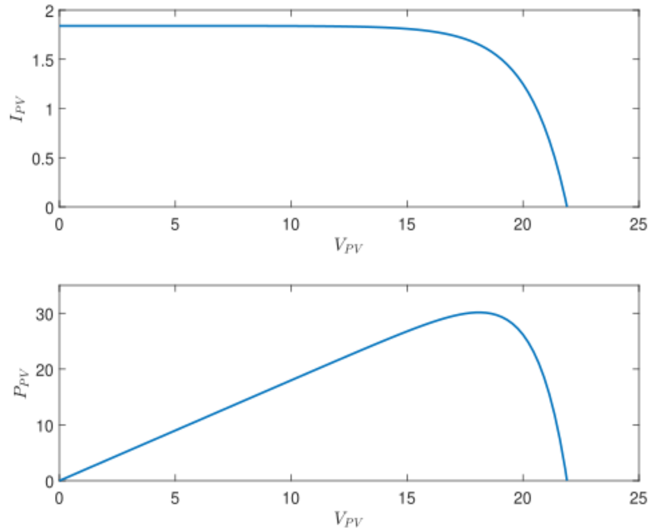

Fig. 2. Current to Voltage and Power to Voltage Characteristics

Various converters which allow the battery management i.e. bidirectional power flow have been devised. Some of them are: buck-boost, SEPIC, Cuk, synchronous four-switch buck-boost and multi-level bidirectional converters [14]. The chosen converter here is the synchronous four-switch buck-boost due to its ease of implementation.

III. ANALYSIS OF CONTROL ALGORITHMS

A. MPPT algorithms analysis

In this Section, the two employed MPPT algorithms are the "hill climbing" algorithms P&O and IC – shown in Fig. 4 and Fig. 5. P-V characteristics of the panels, which are used in both algorithm designs, are shown in Fig. 2. These two algorithms have been chosen for their ease of implementation and low computational power they expend. P&O and IC both slide the operating point along the P-V characteristic of the panels so that the string produces the maximum power available at any given point in time [15]. When using P&O, the controller incrementally adjusts the harvested power by measuring the panel voltage and panel current, and then either takes a step forward or backward along the P-V curve depending on the needs of the system, as shown in Fig. 3. The main issue with this method is that even when the input power is stable, the derived power oscillates in the vicinity of the MPP.

IC does not produce output power oscillations. It relies on the slope of the P-V curve and, as such, upon reaching the MPP, remains there due to zero inclination. The controller maintains these working states until the irradiation changes.

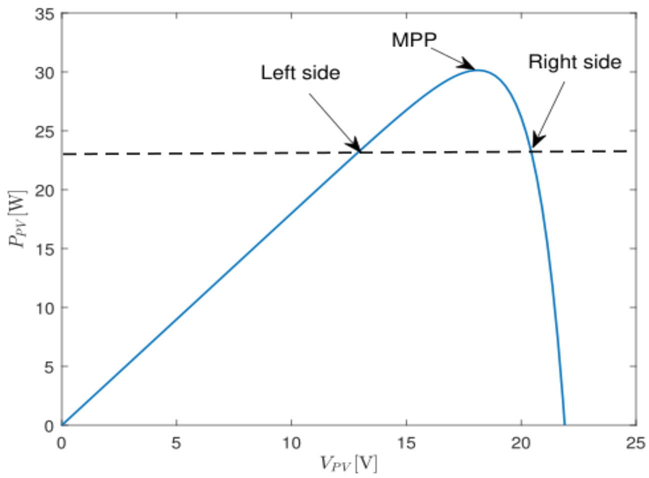

Fig 3. P-V operating point positions

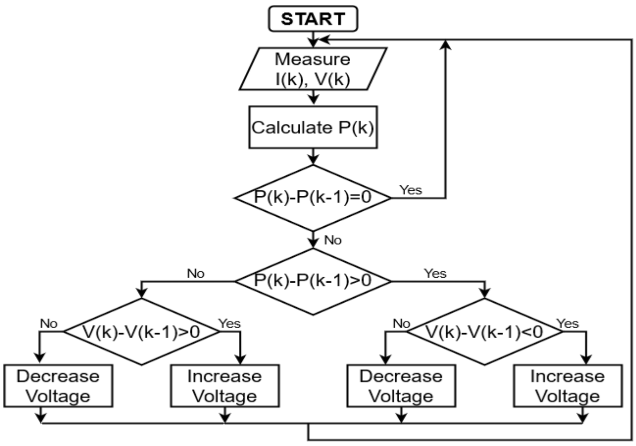

Fig 4. Perturb and Observe Algorithm

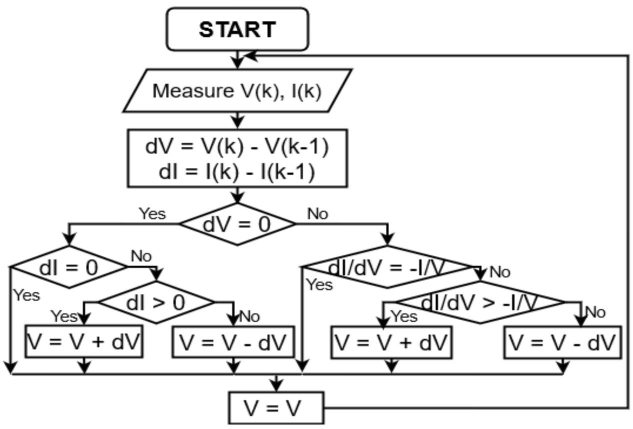

Fig 5. Incremental Conductance Algorithm

B. Battery charging

Another topic of importance is the battery charging strategy. In order to charge, the battery needs to be connected to a power supply. This triggers an oxido-reduction reaction – oxidation occurs on the positive electrode, the one releasing electrons, while reduction manifests on the negative, attracting the released electrons and charging the battery. Discharge happens when the battery is connected to a load – the process of discharging is directly opposite to charging [16]. The battery charging process is done by a combination of Constant Current (CC), typically no greater than 1C or 2C, and Constant Voltage (CV) operating modes, as show in Fig. 6 [12].

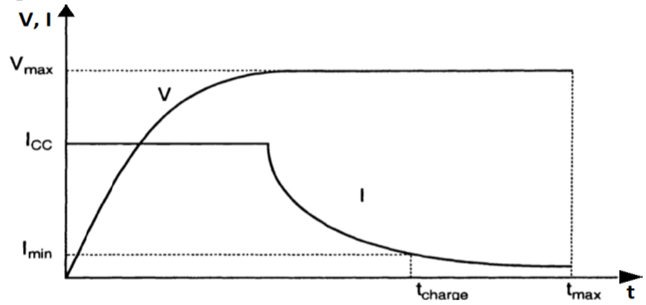

Fig 6. CC-CV Battery Charging

In practice, the values of voltage and charging current are dictated so as to preserve the cell lifespans – high values of maximum voltage and their application for extended periods of time should be avoided [17][18]. Since the prototype operates with the above-mentioned batteries, which are Li-ion based, the best charging method is Constant Current – Constant Voltage (CC-CV). Constant Current (CC) entails charging with a constant current value. This is maintained until the battery reaches the designated voltage value. So as to not overcharge the battery, the voltage value at which CC is stopped has to be less than 100% - usually the cut-off voltage is around 80-90%. In the developed prototype, the charge rate is limited to 1C. This process is then followed by Constant Voltage (CV) charging mode – it charges the battery to full capacity while the current exponentially reduces.

C. CC-CV and the stability of operating points

The CC-CV method charges a battery with a constant current until the battery voltage increases to the constant voltage limit. Then the voltage is kept at said limit while the charging current gradually decreases. In the CC-CV charging method, the CV regime typically lasts longer, prolonging the total charging time [19]. By employing the optimal constant values of current and voltage for the used battery, one is able to achieve the most efficient battery charging process.

Another important operational mode pertains to the situation where the load power consumption is low and the battery is already full. Therefore, it is necessary to move from the MPP in order to not overcharge the battery or jeopardize the DC link voltage. Assuming that the eventual load and the battery combined are able to consume less power than what the panel can generate, in these cases, it is necessary to move the operating point to the part of the curve where less power is generated. This is done by controlling the input power via the input buck converter and is the main idea behind the CC-CV algorithm implemented in this paper.

Bearing in mind the topology of the panel converter, the peak in power production is going to firstly be reflected in the DC link voltage V_{DC} – which is going to start increasing. Each power demand corresponds to two operating points – one to the left of the MPP, and another one to the right, refer to Fig. 3. The criteria for the operating mode choice is the system stability, which is ascertained through a system model. Assuming that the converter is in equilibrium, the operating point is tested to small perturbation. In (1) and (2) U_{CDC} represents the DC link capacitor energy. P_{PV} is the panel power and P_0 is the sum of all losses, load and battery consumption. The equation (3) is valid due to the nature of the converter – here, D refers to the duty cycle.

$$\frac{dU_{C_{DC}}}{dt} = P_{PV} - P_0 \tag{1}$$

$$U_{C_{DC}} = \frac{C_{DC} \cdot V_{DC}^{\;2}}{2} \tag{2}$$

$$V_{PV} = \frac{V_{DC}}{D} \tag{3}$$

Combining equations (3) and (2) and inserting that into (1) results in the following model:

$$\dot{V}_{PV} = \frac{1}{C_{DC} \cdot D^2 \cdot V_{PV}} \cdot (P_{PV} - P_0) \tag{4}$$

$$V_{PV} = f(V_{PV}) \tag{5}$$

To apply indirect Lyapunov method [20], the model (4) has to be linearized first:

$$\frac{\partial \dot{V}_{PV}}{\partial V_{PV}} = \frac{1}{C_{DC} \cdot D^2} \cdot \left(\frac{\partial P_{PV}}{\partial V_{PV}} \cdot \frac{1}{V_{PV}} - \frac{P_{PV} - P_0}{V_{PV}^{\;2}} \right) \tag{6}$$

In order for the equilibrium point $P_{PV}=P_0$ to be stable:

$$\frac{1}{C_{DC} \cdot D^2} \cdot \frac{\partial P_{PV}}{\partial V_{PV}} \cdot \frac{1}{V_{PV}} < 0. \tag{7}$$

Since $C_{DC}>0$, $V_{PV}>0$, (7) is equal to:

$$\frac{\partial P_{PV}}{\partial V_{PV}} < 0 \tag{8}$$

This is true only for the part of the P-V curve that is on the right side of the MPP, as seen in Fig. 3. A detailed overview of the employed CC-CV algorithm is provided in Fig. 7.

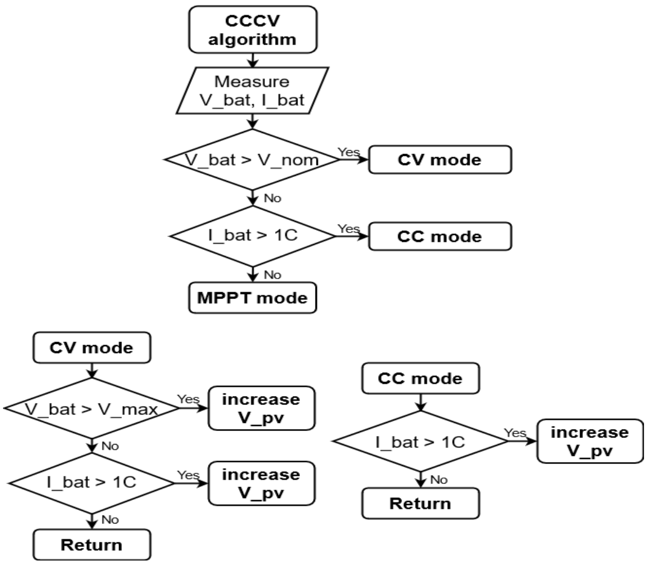

Fig. 7. CC-CV algorithm

IV. Simulation results

For the purpose of this paper, the analyzed system presented in Fig. 1 was simulated in a MATLAB - Simulink software package. In the simulations, it was adopted that the maximum output power of the system is 80 W, which corresponds to the developed prototype of the system. This is going to be discussed in more detail in the next chapter. The simulation conditions include irradiance which changes throughout the duration of the simulation and a load that can be optionally connected or disconnected. The MPPT algorithm adapting to variable irradiance is shown in Fig. 8. During the test, it was adopted that there is a consumer of constant power on the common DC link, which is at constant voltage. For this reason, from the presented results, one can identify a change in battery current depending on the power delivered from the panels. That is, depending on the generated power, the battery switches from the discharge mode into charging mode and vice versa. Also, it can be concluded that the implemented algorithm has a fast response with no switching upon varying the input irradiance.

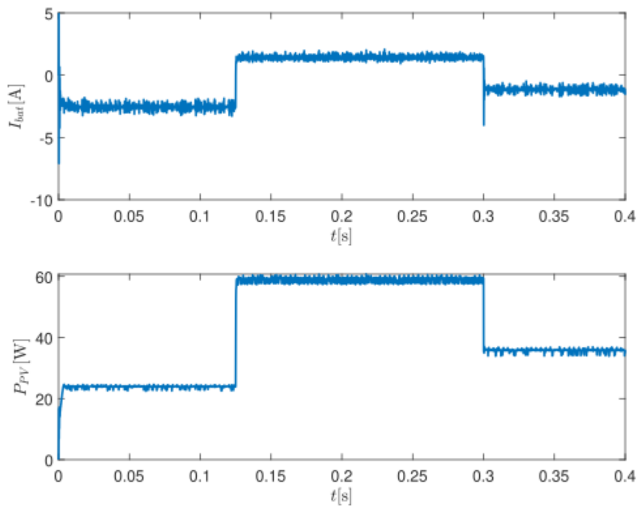

Fig. 8. MPPT mode with variable irradiance

Further, Fig. 9 depicts the battery charging current and the power derived from the panels when the load is suddenly disconnected during the CC charging mode. The current peaks, at the moment of disconnection, however, the controller quickly limits it to the maximum allowed value. The derived panel power is appropriately lowered, showcasing the controller's ability to adapt to disturbances. However, oscillations can be observed in the generated power of the panel, which in this mode, is delivered directly to the battery.

Similarly, the controller adjusts to the load disconnection during CV mode - Fig 10. The battery voltage is swiftly returned to the designated voltage value and the power is correspondingly reduced which is achieved by changing the active pulse width when controlling the switches on the panel converter. Similar oscillations can be observed in the output power of the panel as in the previous test.

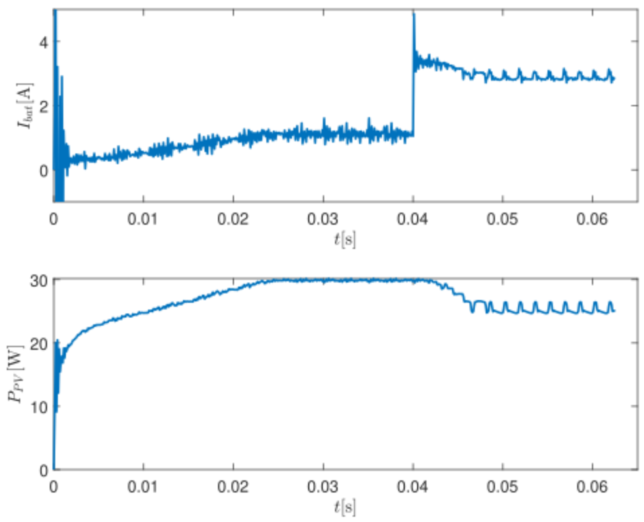

Fig. 9. CC mode with sudden load disconnection

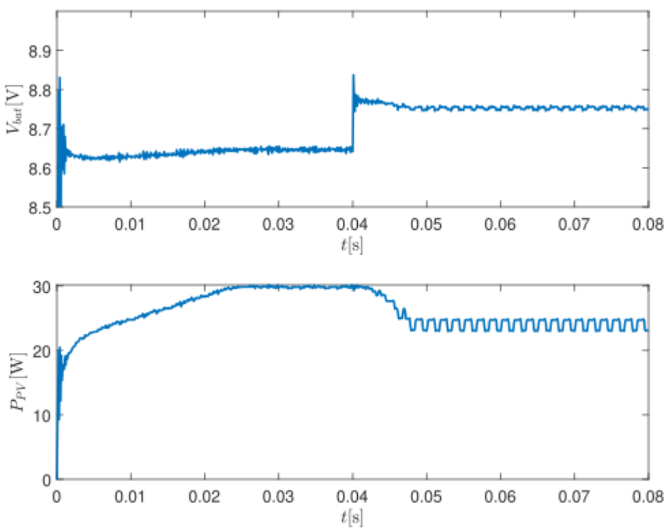

Fig. 10. CV mode with sudden load disconnection

V. EXPERIMENTAL RESULTS

For the required testing of the presented algorithms in actual working conditions, a prototype of the analyzed system was developed in the Digital Drive Laboratory, University of Belgrade. The experimental setup and the prototype can be seen in Fig. 11 and Fig. 12, respectively. The setup consists of two PV panels mounted on the wall. Four halogen lights supplied through two autotransformers simulate variable irradiation. The setup also includes the prototype, an oscilloscope and current probe monitoring the battery current. A resistive load is connected to the DC link. The presented algorithms were implemented on a low-power STM32l4r5qi processor with a code execution time of 10 µs.

Regarding the MPPT stage, tests of the two presented algorithms were performed. The results are presented in Fig. 13, where the MPPT rise time can be observed to be around 180 ms, as well as the power oscillation when the MPP is located. Theoretically, IC is supposed to be more stable once in the MPP, however, in this application, IC operates less effectively due to the induced noise on the prototype.

Fig. 11. Testing experimental setup

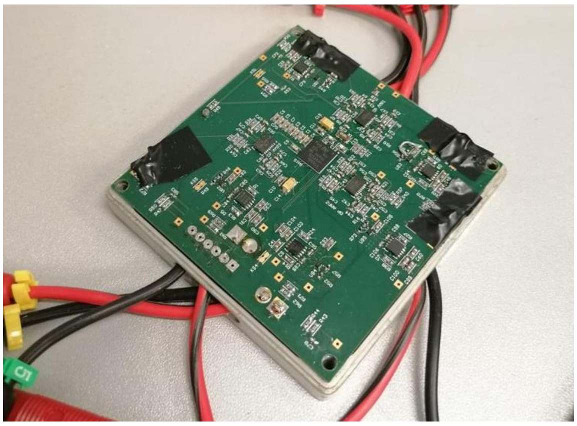

Fig. 12. Developed prototype

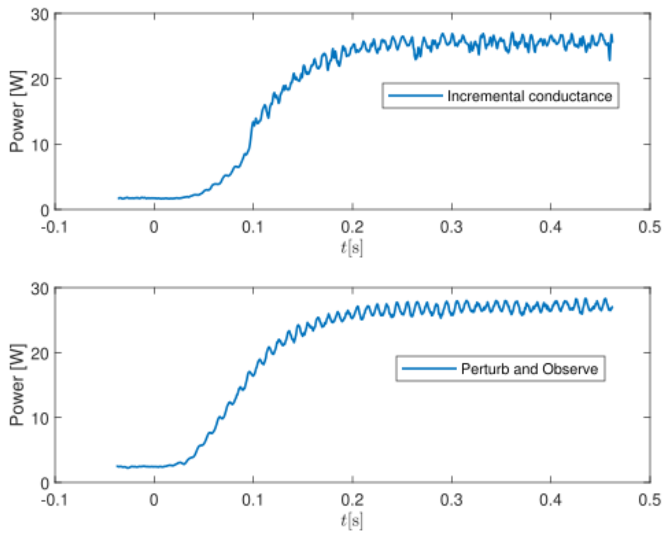

Fig. 13. MPPT methods comparison

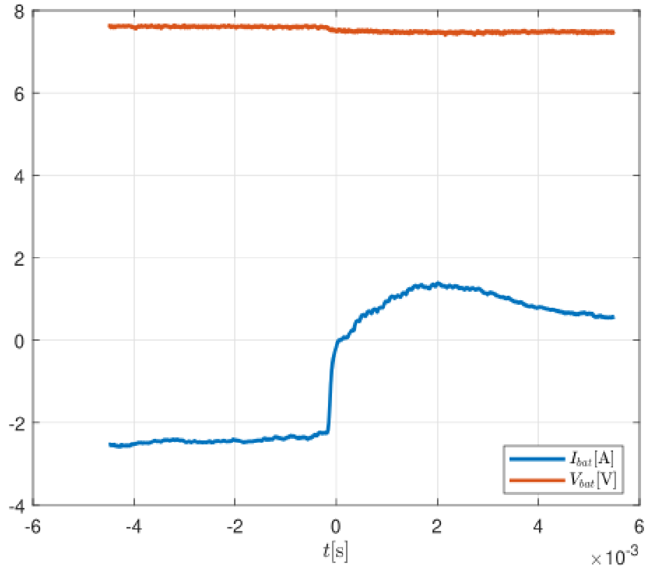

Fig. 14. Transition from charge to discharge

As for the battery, Fig. 14 shows the transition between charging and discharging modes as well as the DC link voltage. From the presented results, it can be concluded that the DC link voltage does not experience too many disturbances during this transient. This is achieved by an external voltage control loop of the converter on a battery that maintains the DC link voltage at a constant value of 7.8 V. An internal current control loop maintains the battery charging and discharging current. The switching frequency of 300 kHz has resulted in the low values of the charge and discharge current ripple. Also, it can be seen that both battery modes are successfully achieved – charging when the current takes a positive value and discharging when the current becomes negative. Insufficient input power is simulated by lowering the irradiance, which results in triggering the change from charge to discharge.

VI. Conclusion

This paper presents a simple design of an algorithm for controlling a low-power PV system supported by batteries. The logistics of the algorithms that are often encountered in practice are presented as they have been implemented on the developed prototype of the system. The simulation results were expanded upon by the experimental results. Furthermore, the three basic system requirements were met, bidirectional battery operation, panel operation in the MPPT mode as well as constant DC link voltage for the needs of powering an arbitrary consumer. The presented algorithms are quickly and easily implemented on low-power and low-cost processors. Of course, the presented solution has an extensive space for improvement when considering system performance, algorithm execution speed as well as robustness to disturbances.

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