Low Power Battery Charger with Solar Panel Input -The M.P.P.T. Algorithms-

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Abstract— **This paper presents a comparative study of three maximum power point tracking (MPPT) algorithms to be used with solar panel input, both from theoretical and practical points of view. An improved perturb & observe (P&O), a sliding mode technique and a method based on power versus voltage variations (dP/dV) are presented. Optimization of the tracking algorithms targets both the tracking of fast changing illumination and the maximum power during constant illumination. All three algorithms have been verified on simulation. Two of them have been tested on a low power hardware platform that connects a low power, low voltage solar panel (20 W, 6 V) with a 12V lead-acid battery. Experimental results measured on two consecutive days with similar weather conditions but different MPPT algorithms are also presented.**

I. Introduction

Given the fact that the availability and performances of the solar panels, lead-acid batteries and power electronics increased dramatically in the last decade, there is a new trend in using solar power as primary source of energy for off-grid, low-power loads, [1], [2], [3], [4].

To utilize the solar panel at maximum available power, two requirements needs to be fulfilled: the photovoltaic (PV) panel needs to be positioned normally to the incident solar radiation and a DC/DC or DC/AC converter, controlled by a maximum power point algorithm, needs to be used between the solar panel and the storage element (or the load).

Implementing a pan and tilt mechanical system for a low power PV module does not justifies the installation and maintenance costs; more, the mechanical actuators would be powered from the solar panel itself, thus lowering the overall efficiency of the photovoltaic system.

Placing the PV panel(s) in a fixed position will lower the output power during some parts of the day, because of the inefficient angle between incident light ant the solar cells surface. In this situation, the only gain in power that can be obtained comes from the smart use of the DC/DC converter that connects the PV panel with the battery.

Since today electronics allows for DC/DC converters with efficiency as high as 98%, the MPPT algorithm used to control the converter plays the most important role in the efficiency of the PV system. The faster the maximum power point is reached, the smaller the power losses are in transitory solar illumination conditions. The smaller the oscillations around maximum power point, the better efficiency in stationary conditions.

There are numerous methods and algorithms that can be used to implement the MPPT. Some of them just approximate the optimum operating point according to the PV panel specifications, solar radiance, temperature etc, but others compute the real maximum power point.

In this paper we have considered three algorithms: an improved variant of perturb and observe (P&O), a true sliding mode algorithm and a modified incremental conductance. Methods are described in section II and the simulation results are presented in section IV. None of the presented methods uses real parameters of the panel itself, so that the presented algorithms can be used in a large area of applications.

In the algorithm development it is preferred the use of a re-programmable microcontroller to implement the MPPT algorithm, [5], [6]. Even in the production stage, the microcontrollers are still preferred due to low cost, low external components count, integrated analog-to-digital converter (ADC) and pulse width modulation (PWM) module, adequate processing power and possibility to implement complex functions (on the fly change of the algorithms, smart protection circuits, predictive behavior etc.).

Some of the PV panel manufacturers even mount a microinverter with MPPT function on the panel itself, allowing the extraction of the maximum power from each individual panel in the array, [7].

In terms of DC/DC converter structure, it is beneficial that the voltage of the PV panel to be either lower or higher than the storage battery bank voltage, to simplify the converter to a boost or buck circuit respectively.

Our experimental platform, presented in section III, follows these lines: a low cost 8 bit microcontroller with integrated 10 bit ADC and PWM module controls a boost converter connected between a 6V/20W solar panel and a 12V/55Ah lead-acid battery. Changing the MPPT algorithm means only to re-program the microcontroller.

Experimental results, measured for the improved P&O and dP/dV algorithms, are acquired with a custom data logger circuit, which saves the information in text format, on an SDCard. Later, the signals have been imported in Matlab and properly processed to be presented in section V. Section VI presents the conclusions of the work.

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II. PROPOSED CONTROL LOOPS

Three MPPT algorithms will be presented in this section from the theoretical point of view. All of them contain some improvements over the classical approach:

- improved P&O uses variable steps both for perturb and final change stages to both increase the response time of the control loop and decrease the power loss during perturb stages near the MPP;
- the sliding mode method considers the commutation surface dP/dt and computes at each step the optimal command for the DC/DC converter according to the sliding mode methodology;
- modified incremental conductance method uses a very simple equation that offers very good results in both transitory and stationary conditions.

Experimental results obtained with the improved P&O and modified incremental conductance algorithms are presented in Section IV. The sliding mode method will be implemented in a further research.

A. *Improved Perturb & Observe*

The advantage of this method consists in the intuitive control law: the PV current is altered by a small amount and the new power is compared to the old one. If the new power is higher, the operating point will be changed in direction of the perturbation, otherwise in the other direction, [8]. Three problems appear: the size of the perturbation, the reliability of the power comparison in the fast changing solar irradiation, and the intrinsic oscillations around the MPP. Fig.1. presents the structure of the improved control loop:

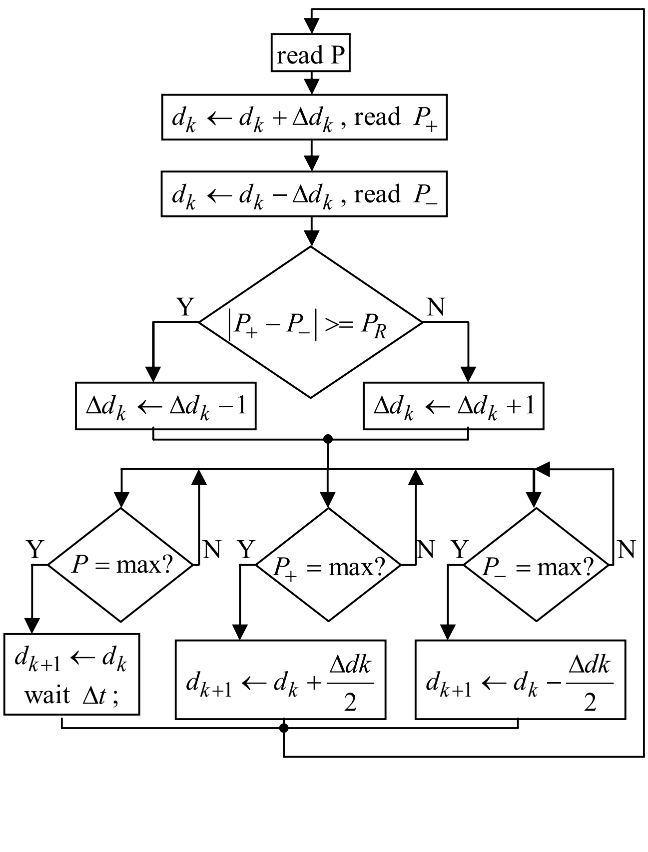

Figure 1. Structure of the improved perturb and observe control loop.

To minimize losses during the perturb stage, the perturbation must be as small as possible but high enough to lead to a reliable test of powers. To produce a valid test under all conditions, three powers should be measured in fast succession: one at current operating point, one at a lower and one at a higher current level. The algorithm will decide which power is higher and how the command signal needs to be changed. This solution also solves the problem of oscillations near MPP, because once arrived there, the actual power will be the highest one and the command will stay constant until the optimum power point changes due to external factors.

In the algorithm presented in Fig.1 we have noted: d_k =command output from the MPPT algorithm, at iteration step k; Δd_k =variation of command, d, to be used as perturbation; P, P_+, P_- =input powers; P_R =reference level of power variation in the perturb stage; Δt =delay between perturbations if the PV panel operate at the MPP.

The perturb test takes only 5ms, is made every 200ms once the PV panel is in the MPP and the output power from the PV panel is perturbed with only about 100mW around the current operating point.

B. *Sliding Mode Controller*

Sliding Mode Control (SMC) is a robust nonlinear control method that changes the dynamics of a nonlinear system by application of a discontinuous control signal that forces the system to slide along a surface [9], [10]. One application of sliding mode controllers is the control of electric drives operated by switching power converters. Because of the discontinuous operating mode of those converters, a discontinuous sliding mode controller is a natural implementation choice over continuous controllers that may need to be applied by means of pulse-width modulation.

The synthesis of sliding mode control implies, initially, the choice of a switching function s of adapted size, and in second place, the selection of a nonlinear control law to reach the sliding surface in a finished time.

We define the sliding surface as follows:

$$s = \frac{\partial P}{\partial t} = P[k] - P[k-1] \tag{1}$$

where *P[k]* is the output power of the photovoltaic panel a iteration step k and P[k-1] is output power at step $(k-1)$.

This sliding surface assures that the sliding motion is reached and regulates output voltage converter. In this control system, it is necessary to measure the output power of the photovoltaic panel and to change the duty cycle (d) of the DC/DC converter control signal. So, the output power is measured and compared to the previous output power, depending on the result of the comparison, the optimal duty cycle of sliding mode control is changed and the process is repeated until the maximum power is reached.

A practical form of the reaching law is [11]:

$$s[k+1] = (1-K)\cdot s[k] - Q\cdot sign(s[k]) \qquad (2)$$

$(1-K) > 0,\ Q > 0$

With the proportional rate term $-K\cdot s$, the state is forced to approach the switching manifolds faster when s is large. The reaching time is finite and is given by:

$$T = \frac{1}{K}\ln\frac{K|s|+Q}{Q} \qquad (3)$$

Having selected the reaching law equation, the control law can now be determined. Compute the time derivative of s along the reaching mode trajectory

$$s[k+1] - s[k] = V[k]\cdot I[k] - 2\cdot P[k-1] + P[k-2] \qquad (4)$$

Considering (2) and (4) and the relation between input voltage, output voltage and the duty cycle of the boost converter,

$$d = 1 - \frac{V_{PV}}{V_o} \qquad (5)$$

the output command of sliding-mode controller can be obtained:

$$d[k+1] = 1 - \frac{2\cdot P[k-1] - P[k-2] - K\cdot s[k] - Q\cdot sgn(s[k])}{V_o[k]\cdot I[k]} \qquad (6)$$

The *signum* function in the sliding surface can be replaced with the *saturation* function, to reduce the chattering phenomenon [9]. The saturation function would be defined as:

$$sat\left(\frac{s}{\tau}\right) = \begin{cases} \frac{s}{\tau}, & \left|\frac{s}{\tau}\right| \le 1 \\ \operatorname{sgn}\left(\frac{s}{\tau}\right), & \left|\frac{s}{\tau}\right| > 1 \end{cases} \qquad (7)$$

Where constant factor, τ, defines thickness of the boundary layer.

In conclusion, the sliding mode algorithm computes at each step the optimum value of the duty cycle, depending on actual input current, the output voltage and actual and two previous power levels.

C. Modified incremental conductance method

Another popular MPPT algorithm, based on the incremental conductance, computes the maximum power point by comparing the incremental conductance dI/dV with the array conductance (I/V). When the two values are equal, the PV panel operates at the MPP [12]. The controller maintains this operating point until external conditions changes. There are many variants of the method, some based on (dV/dI), (dP/dV), (dP/dI) etc. Although this method implies the use of derivates of the input and power signals, the intrinsic structure of a digital algorithm implemented in a microcontroller makes the computation of the derivative term a simple operation of subtraction between actual and previous measured values. An other advantage of software implementation of the method is that the divide by zero problem (dP/dV, with $dV = 0$) can be easily solved by testing the ΔV before calling the divide subroutine and managing the exception either by not performing the divide operation and keeping the previous value, either by replacing ΔV with a usable value.

We choose to adjust the operation of the DC/DC convertor according to dP/dV. Fig.2 presents the evolution of signals of interest as a function of duty-cycle (current is proportional to the duty cycle): dP/dV is negative if operating point is on the left of the MPP and positive on the right.

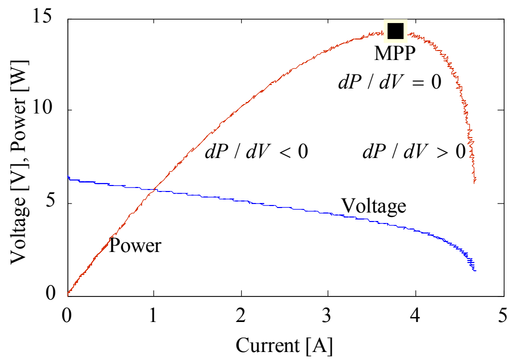

Figure 2. dP/dV as function of PV panel's current.

We choose a simple digital P.I. controller to maintain the dP/dV as close as possible to the zero. The control loop is presented in the following pseudocode, where α is a experimental constant:

$read\ V_k, I_k;\ compute\ P_k;$

$if\ V_k = V_{k-1}\ then\ dV \leftarrow 1\ else\ dV \leftarrow V_k - V_{k-1};$

$\frac{dP}{dV} \leftarrow \frac{P_k - P_{k-1}}{dV};$

$if\ \frac{dP}{dV} > \alpha\ then\ \Delta d \leftarrow sign\left(\frac{dP}{dV}\right)\cdot\alpha\ else\ \Delta d \leftarrow \frac{dP}{dV};$

$d_{k+1} \leftarrow d_k + \Delta d;$

$repeat;$

This way:

- duty cycle is automatically adjusted in the right direction at each sampling step,
- at MPP, $\Delta P = 0$ (due to quantization approximations of the analog to digital converter used to read the V_k and I_k signals) so $d_{k+1} \leftarrow d_k$ and the system does not oscillate around MPP.

The period of the control loop must be low enough to measure the variations of current and voltage, and high enough to track the rapid changes of the solar radiance. Values of 5…100ms are optimal for the chosen task and are easy to obtain with any low-cost microcontroller due to simplicity of the mathematical operations involved.

A variation of this algorithm can be found in some papers under the improper name "sliding mode" just because the nonlinear control equation is

$$d_{k+1} \leftarrow d_k + sign\left(\frac{dP}{dV}\right) \qquad (8)$$

III. THE HARDWARE PLATFORM

At low power levels, it is preferred that the whole system to be at low voltage, because of the better availability of the energy storage battery (12V, 24V lead-acid batteries are commonly used in cars). Most of the commonly low-power devices can be powered from a car cigarette lighter socket (12V), or a power adapter can be easily found. If needed, an inverter can be used to power the AC loads from the battery. The efficient use of the PV panel requires a DC/DC converter connected between the panel and the storage battery. This converter is controlled in such a manner that, when needed, the maximum power available at the PV panel is transferred to the battery or loads. It is preferred that the PV voltage to be either lower or higher than the storage battery bank voltage. This simplifies the structure of the DC/DC converter to either a boost or a buck converter.

In this paper we considered a low power PV panel of 20W/6V used to charge a 12V/55Ah lead-acid battery through a boost DC/DC converter, Fig.3. The electronic circuit was designed and built by the authors, to be used with this application.

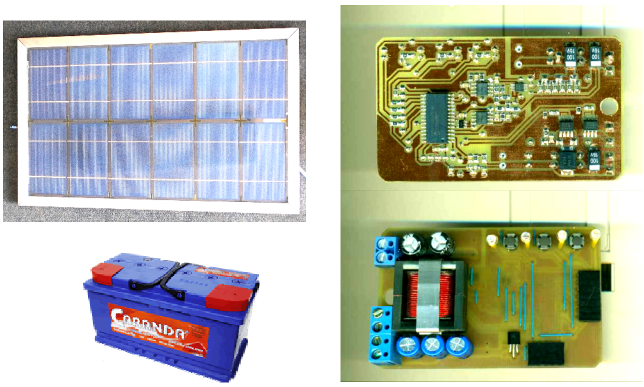

Figure 3. Hardware components, different dimmension scales.

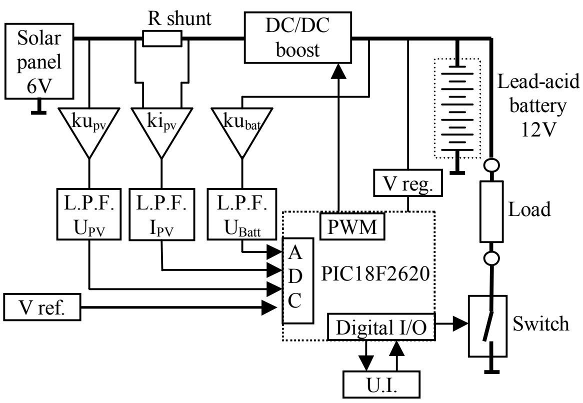

Figure 4. Structure of the experimental circuit.

Fig.4 presents the structure of the controller: the DC/DC boost converter is controlled with PWM signal generated by the microcontroller. The software control loop computes the PWM duty-cycle as a function of the input signals (voltage and current at the PV panel; battery voltage) and the MPPT algorithm.

A complete description of the electronic circuit is presented in [13].

The solar panel is built from 12 polycrystalline Si solar cells, each of 1.8W average power, 0.55V, 3.5A/cell at maximum power point. The power curve of the solar panel depends on solar irradiation, temperature, angle between solar panel and incident radiation, dust particles in air etc. For the given panel, placed in the middle of the Galati city, oriented S-W and tilted 60° to the horizontal, two power curves were recorded, at different solar radiation levels, Fig.5:

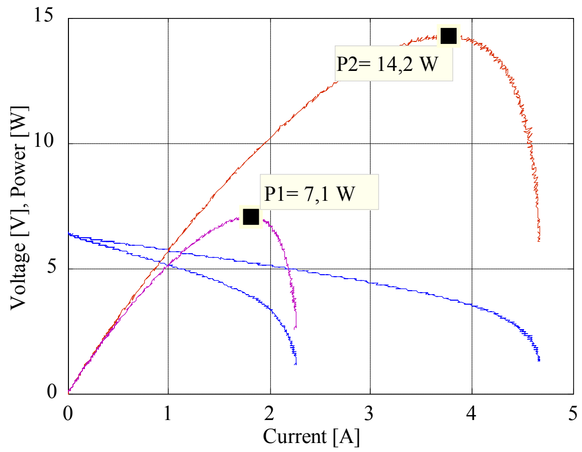

Figure 5. I/U curve of the PV module under two illumination values.

During all the measurements, the maximum power is lower than the maximum power specified by the producer (12*1.8W); the reason consist in the dust particles presents in the air in/over the city. The same panel, with the same electronics and MPPT algorithm performed much better in a remote area, far from city pollution.

From Fig.5, and considering the 12V battery used to store the energy, results the average value of the PWM duty-cycle used to control the DC/DC boost converter:

$$\tilde{d} = 1 - \frac{V_{PV\_MPP}}{Vo} \cong 0.6 \qquad (9)$$

The algorithm that runs in the microcontroller can read at any time all three input signals: PV panel's voltage, current and the battery voltage. Domains of these signals, as resulted from the 10 bit analog to digital converter in the microcontroller are:

Input voltage: [0; 7.2] V -> [0; 1023],
PV current: [0; 4.54] A -> [0; 1023],
Battery voltage: [0; 15.2] V -> [0; 1023],

These values were smartly chosen so that 1) will cover all the domain of the input signals, 2) multiplying the maximum values of the input voltage and current results 32.768, so that the instantaneous value of the PV power can be computed in the 8 bit microcontroller with only one multiply operation between two integer variables. This value can be displayed on the optional graphical display that can be connected to the microcontroller.

Duty cycle used to control the boost converter is represented on 10 bits, [0; 100] % -> [0…1023].

IV. THE SIMULATION RESULTS

To test the proposed control loops, a Simulink (SimPowerSystems) model of the system has been designed, Fig.6:

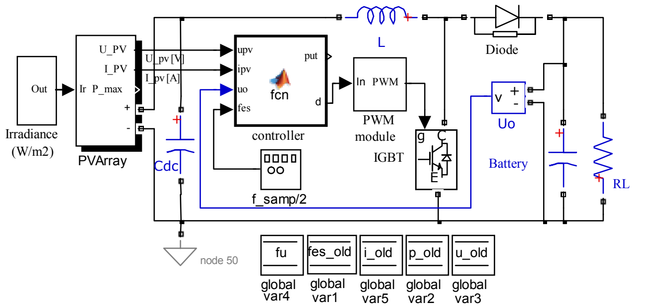

Figure 6. Structure of the Simulink model used to test the MPPT algorithms.

The PV panel model is based on the diode junction characteristics, and the panel's parameters mimics the ones of the real PV panel ($V_{OC} = 7.1V$; $I_{SC} = 4.1A$;); the voltage and current at the PV panel's level are measured in the "*PV Array*" block that also offers the theoretical maximum power that can be extracted (for comparison with the real one only); the input capacitor C_{dc} is used to smooth the current drawn from the PV module; battery is simulated with a 1F capacitor, to analyze the effect of the battery voltage variations over the control loop; inductor is 160 μH and the PWM module generates modulated signal with 20 kHz .

The control loop is software implemented, the same way it would be in the real microcontroller: a sampling signal activates the "*controller*" module that read the inputs and computes the output only at specified moments of time. All three algorithms are initialized with the duty cycle=50%.

A. Improved P&O simulation results

Signals in Fig.7 present the evolution of input voltage, current, power and duty-cycle. The periodic perturbation can be observed on all signals.

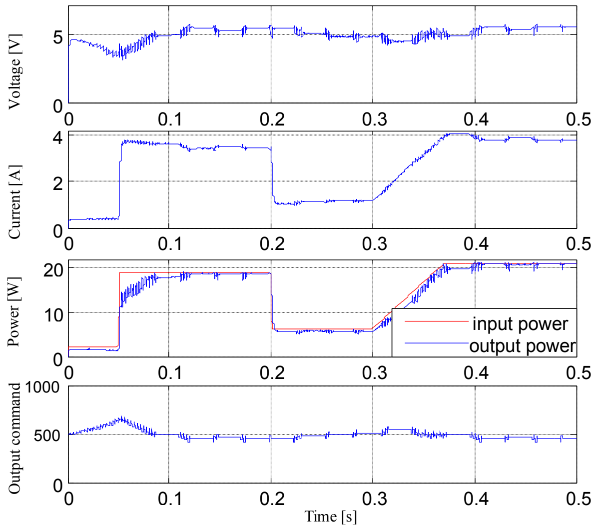

Figure 7. Simulation results for improved P&O.

As designed, the control loop waits for a constant amount of time with the actual duty-cycle only if the actual power is greater than both perturbed powers. This behavior speeds up dynamic response of the loop and lowers the losses during steady illumination condition.

The sampling period for the control loop is 1ms.

The overall efficiency of the circuit, computed as extracted energy / ideal maximum energy is 0.942.

B. Sliding mode controller

Fig.5 presents the evolution of the same signals, under the same illumination conditions, in the case of sliding mode controller. It can be observed the fast response at illumination changes, as well as the chatter of the command signal around optimal value. The three transitions noted in Fig.8 lead to the variation of the sliding surface as presented in Fig.9.

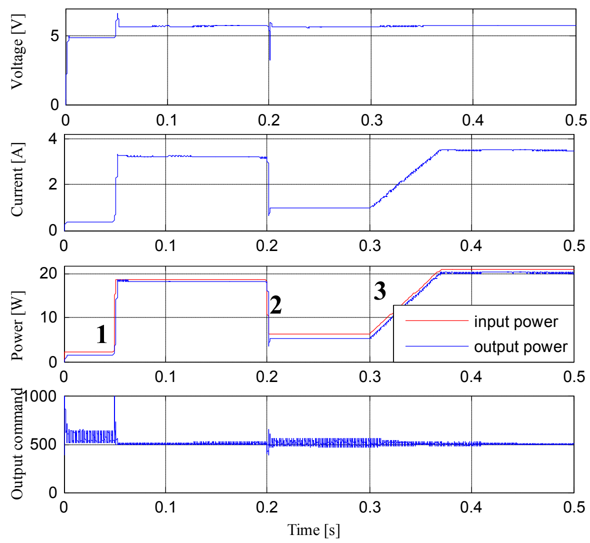

Figure 8. Simulation results for sliding mode controller.

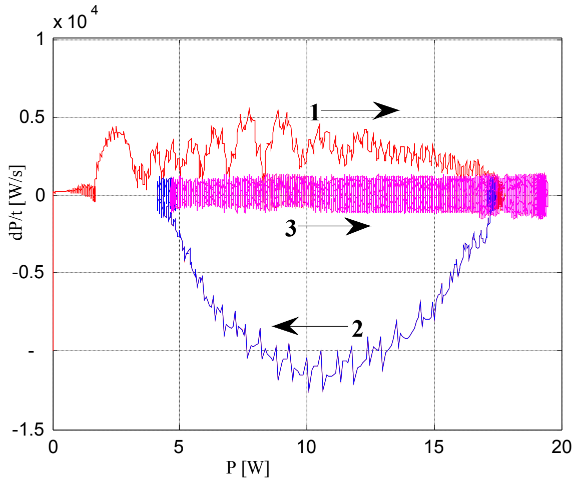

Figure 9. Transitions on the sliding surface.

The overall efficiency of the circuit, computed as extracted energy / ideal maximum energy is 0.951. The sampling period for the control loop must be close to 0.1ms.

C. *Modified incremental conductance method*

In the case of the modified incremental conductance control loop, signals presented in Fig.10 were obtained:

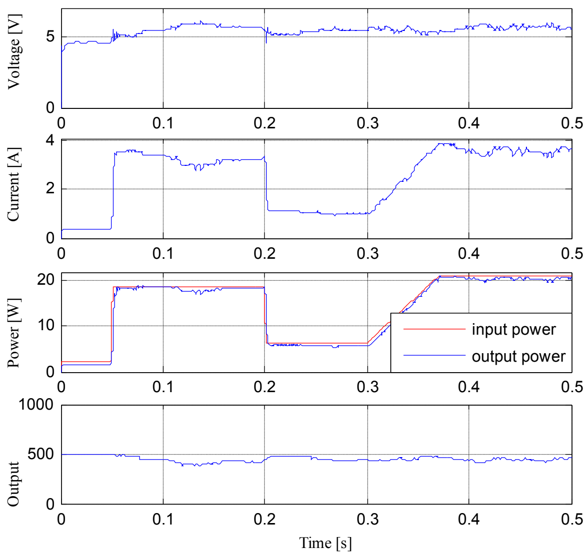

Figure 10. Simulation results for modified incremental conductance method.

Although the command variation seems erratically comparing with the other two cases, the efficiency is about the same: 0.947. The sampling period used for the controller was 2ms.

V. Experimental Results

From the three presented algorithms, the sliding mode one required both high speed mathematical computation and high sampling frequency of the input signals. It was concluded that implementation of this control law in the microcontroller already integrated on the hardware platform will be inefficient due to its low processing power.

A. *Improved P&O*

An electronic datalogger was used to record the signals presented in Fig.11:

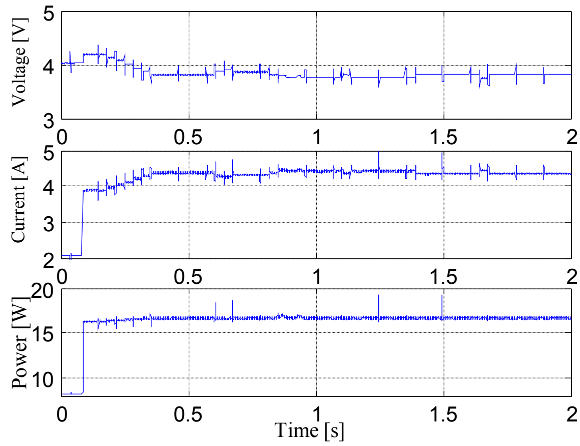

Figure 11. Experimental measurements for P&O response; step variation of illumination.

The same electronic datalogger was configured to acquire voltage and current signals at every 1 second, for eight hours, from 11^{00} to 19^{00}. The resulted file was used to create the plot in Fig 12:

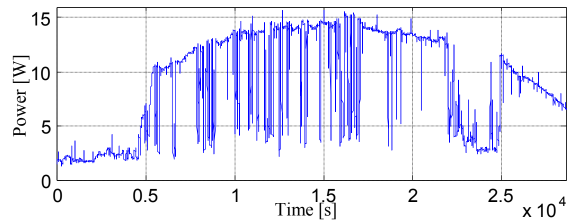

Figure 12. Generated power in the 11-19 hour interval (P&O)

A mean power value of 8.8W resulted on the considered time interval.

B. *Modified incremental conductance method*

In the case of incremental conductance MPPT algorithm, signals in Fig.13 were acquired for a step variation of the solar illumination:

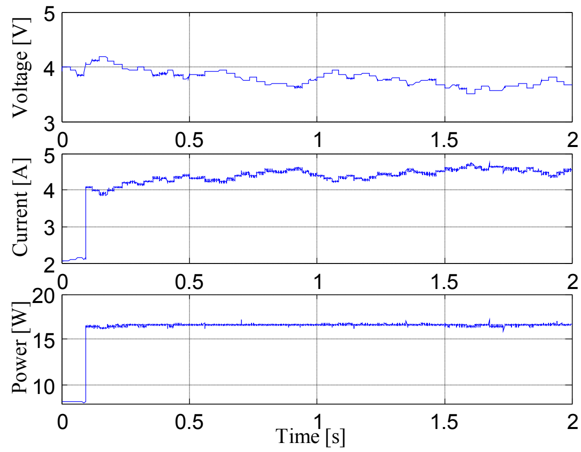

Figure 13. Experimental measurements for modified incremental conductance response; step variation of illumination.

It can be observed that the power stabilizes at the new value quicker than in the previously presented case.

More, even if the voltage and current changes erratically around optimum values, the power variation around MPP is insignificant, the same way that was observed in the simulation.

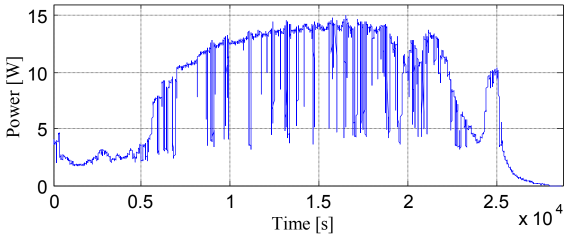

Figure 14. Generated power in the 11-19 hour interval (inc.cond)

The mean value of the input power measured the second day, Fig.14, was 7.89W because it rained for about one hour in the evening.

VI. Conclusion

This paper presented three “true” maximum power point tracking algorithms. That assures finding, reaching and tracking the operating point of the PV panel where the output power is at maximum, regardless of usual perturbations (temperature, incident irradiation etc.).

The presented methods are in fact variations of the classical approaches, but with proved improvements:

- the improved P&O is adapted to better follow the fast variations of the MPP (due to sudden shading/lighting of the PV panel) but it is also optimized to reduce the oscillations around MPP;
- the modified incremental conductance method is implemented in the form of a very simple numerical PI controller, with a minimum of mathematical operations. This allows for faster control loop execution and a better overall behavior of the MPPT circuit;
- the presented sliding mode technique follows the design methodology of the sliding mode controller and offers a control law that lead to the best simulation results.

Practical implementation of the sliding mode control law requires a microcontroller with higher processing power than the one already included in our experimental platform, mainly because of the small sampling time required for proper operation of the control loop, so only the improved P&O and modified incremental conductance approaches were implemented.

The experimental results proved that both control laws performed very well, according to the design and simulation way.

Due to the fact that optimum duty cycle varies only slightly with the MPP, a step variation of input illumination leads by default to a step variation of the output power close to the new MPP. The control loop will then finely adjust the command so that the operating point to change to the new real MPP. In the case of presented P&O, this adjustment last for about 0.2s, and in the case of modified incremental conductance it was under 0.1s.

Further improvements are always possible, for example by mixing various algorithms, using other DC/DC converter topology, using other category of processing unit (FPGA/CPLD/PSoC) etc.

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