Y. Beck, N. Sober

Experimental Verification and Comparative Study of Various MPPT Algorithms

Choosing and implementing a Maximum Power Point Tracking (MPPT) algorithm in a photovoltaic (PV) system, along with choosing the power converter, constitutes the fundamental basic capabilities of a photovoltaic system. MPPT techniques are implemented in photovoltaic systems to achieve full utilization of PV array output power. Today there is a wide variety of MPPT algorithms, each one has its advantages and disadvantages. This paper presents theoretical, as well as experimental comparison results, in several aspects regarding four MPPT methods based on the basic two MPPT algorithms (Perturb and Observe, Incremental Conductance), implemented on a single DC/DC converter, under the same experimental conditions. The theoretical and experimental comparison is performed for characteristics of ripple around the MPP and the convergence time. The experimental results are provided and supported by theoretical analysis and show that gradient based methods have better convergence time as well as ripple values in comparison to fixed step methods.

Key words: algorithms, maximum power point tracking, photovoltaic, renewable energy

Eksperimentalna provjera i komparativna analiza različitih MPPT algoritama. Odabir i implementacija algoritma za traženje točke maksimalne snage (MPPT) zajedno s odabirom pretvarača snage određuje osnovna svojstva fotonaponskog sustava. MPPT algoritmi omogućuju iskorištavanje cjelokupne izlazne snage fotonaposnkog sustava. Danas postoji veliki broj različitih MPTT algoritama, od kojih svaki ima svoje prednosti i mane. Ovaj rad predstavlja usporedbu teorijskih i eksperimentalnih rezultata četiriju MPPT metoda baziranih na dva MPPT algoritma (Perturbacije i promatranja, te Postepene vodljivosti), implementiranih na jednom DC/DC pretvaraču, pod istim eksperimentalnim uvjetima. Teorijska i eksperimentalna usporedba je provedena s obzirom na karakteristiku valovitosti oko točke maksimalne snage i vrijeme konvergencije. Eksperimentalni rezultati zajedno s teorijskom analizom pokazuju da gradijentne metode imaju bolje vrijeme konvergencije i vrijednosti valovitosti u odnosu na metode s fiksnim korakom.

Ključne riječi: algoritmi, traženje točke najveće snage, fotonaponski, obnovljiva energija

1 INTRODUCTION

Harnessing solar energy using photovoltaic cells is one of the methods for producing non-conventional, clean and renewable energy. Using photovoltaic (PV) cells allows reducing the dependence on traditional, non-renewable energy sources. The energy is sustainable and maximized when the PV array is installed properly and the automatic system utilizes the cell output energy to the maximum electrical energy which can be provided by the cells. This system is the maximum power point tracker (MPPT) system.

Photovoltaic array, under specific irradiance and temperature conditions, exhibits a current-voltage characteristic with a unique point, called the maximum power point (MPP) where the array produces the maximum output power [1]. Photovoltaic systems characteristics changes along with these environmental changes and mainly de-pends on irradiance levels [2, 3] and ambient temperatures [1, 4, 5]. Nowadays, the major holdback for wider use of PV arrays is mainly due to the low efficiency of the PV cells and not necessarily their cost. While converting solar irradiation energy to electrical energy commercial PV arrays efficiency is about 13 to 15 percent. Furthermore, the power provided by a PV array depends, as mentioned above, on the operating voltage and it's a nonlinear function. This nonlinear Power/Voltage curve, as shown in Fig. 1, has a maximum point corresponding to a specific voltage, solar irradiation, temperature, and the aging of the PV array.

Thus, a control system that keeps the maximum efficiency, by tracking the MPP available under specific atmosphere condition, is needed.

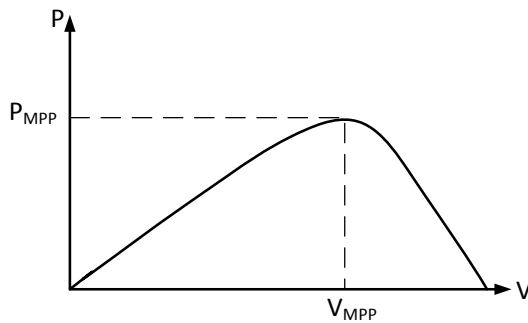The algorithms role in an MPPT system is crucial in

Fig. 1. P-V Curve of a photovoltaic cell

order to obtain these goals along with to address the MPPT challenges either in steady state or in changing atmosphere conditions.

Various MPPT techniques have been explored in the literature; many of them are summarized in T. Esram, and P.L Chapman work [6], and there are many others, such as in [7-15].

Nevertheless, the two most common implemented algorithms, in which the four proposed algorithms in this paper are based on, are Perturb and Observe(P&O) [6, 16], and Incremental Conductance (IncCond) [6, 17, 18], which are widely used, and therefore were chosen to be the base algorithms of the four compared algorithms discussed in this paper.

This paper presents an experimental verification and comparative results derived from implementing four MPPT algorithms: 1) P&O [6, 16], 2) Three points weight comparison method for improving P&O [16, 19], 3) Incremental Conductance [6, 17, 18], and 4) Variable step size Incremental Conductance [17, 18]. All the above-mentioned algorithms were implemented on a single Full Bridge Phase Shift (FBPS) PWM DC to a DC converter. The experiments were performed under the same atmospheric conditions (Temperature and irradiance level), and connected to the same photovoltaic arrays for enabling an objective comparison. Integrating four algorithms, with different step size (i.e. voltage drop over the converter components), on the same DC to DC converter with its components' specification limitations, was a great challenge which was overcome by proper design of the converter, together with proper integration of the algorithms to the converter components' specification limitations.

This research presents actual experimental measurements of the adaptive step algorithm, as well as coping with partial shaded effect on the same converter. It was performed with a complete and operational photovoltaic system under two environmental conditions, uniform and partial irradiance of the PV array. The results compare the algorithms under two different characteristics: 1) Convergence time; and 2) Ripple around MPP.

2 CHALLENGES

The MPPT system's role is to maintain the best output power efficiency, where MPPT algorithms' biggest challenge is to automatically find the ideal operating point, which is the MPP indicated by the P-V curve. It is well known that, under uniform PV array's irradiance, the main goal of the system is to locate and maintain the MPP.

Furthermore, challenges such as "convergence time", which is the time that takes the algorithm to get to the MPP and the 'ripple around the MPP", are two challenges that depend on each other. This dependency is caused due to the method of convergence, which implies large or relatively small duty cycle step size in the converters PWM control.

On one hand, relatively large step size will cause a fast convergence time but will also cause a large ripple around the MPP and on the other hand, relatively small step size will cause oscillation around the MPP to decrease but also a long time of convergence.

After all said, MPPT algorithms tries to cope with these challenges in different ways, some algorithms are better suitable for complying with one challenge and some algorithms are more suitable for other challenges.

3 ALGORITHMS REVIEW

3.1 Perturb and Observe

Due to its simplicity, the Perturb and Observe (P&O) algorithm is considered to be the most commonly used algorithm in practice [4-6, 16, 19]. The P&O algorithm's flow chart is presented in Fig. 2.

Periodically, the P&O algorithm makes a decision that leads to increment or decrement of the solar array voltage (by changing the duty cycle). In Each period, the P&O MPP tracker, is perturbing the converter's duty cycle and observing the consequent result (the change in output power) at the subsequent period. According to Fig. 1, while the operation point is located on the left side of the MPP, incrementing (decrementing) the voltage increases (decreases) the PV array's output power. On the other side, while the operation point is located right to the MPP, incrementing (decrementing) the voltage decreases (increases) the PV array's output power.

Therefore, in case a periodically perturbation leads to increase (decrease) the PV array output power, then the following perturbation proceeds in the same (opposite) direction [5, 6].

In Fig. 2, "Set Duty Cycle" denotes the perturbation of the solar array voltage. Duty+ and Duty- represent the subsequent perturbation in the same or opposite direction, respectively.

As noted, the simplicity of this algorithm makes it very popular among present applications. However, the algorithm has some drawbacks. Its main drawback is derived from the fact that decisions are being taken either to proceed in the same direction, or to the opposite direction on the subsequent perturbation. Therefore, in the steady state case (when the MPP has been reached), the algorithm continues with the decisions making (two options – same/opposite direction), which causes oscillations around the MPP. This behavior leads to loss of output energy and incapability to cope with rapidly changing atmospheric conditions (in such case the P&O diverges the operation point from the MPP) [6]. The oscillations created in the P&O algorithms are well detailed in [4, 5]. Two more drawbacks of the algorithm are its fix step size and its lack of capability to cope with low irradiation [5]. There are several solutions addressing the oscillation generated by the P&O algorithm. Using a different MPPT algorithm (such as Incremental conductance) to prevent the oscillations can be a solution. However, besides choosing another algorithm, to ensure that the MPP is tracked using the P&O, even under sudden change in irradiance, a creation of "waiting" function while arriving at the MPP [5] can be used, or the three-point weight comparison method can be implemented [16, 19].
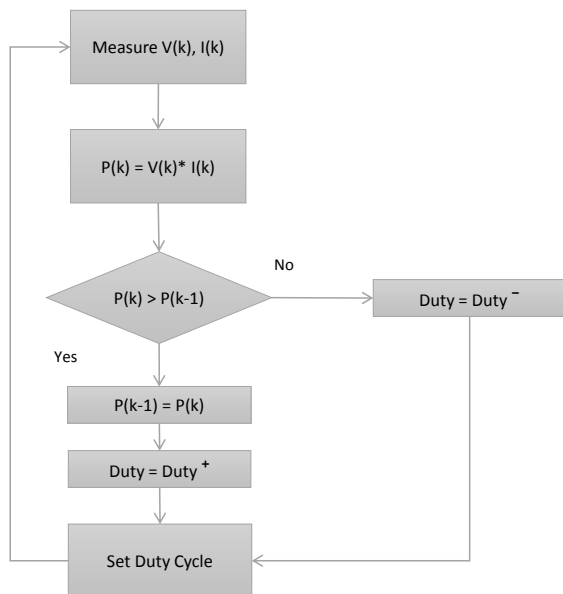

Fig. 2. P&O flow chart

3.2   B. Three-Points Weight Comparison Method for Improving P&O

As opposed to the standard P&O algorithm, this method is based on perturbation of three consecutive points to observe their power change. The standard P&O algo-

rithm oscillates around the MPP, resulting in a loss of PV energy, especially in cases of rapidly changing solar irradiation. Therefore, The Three-Points Weight Comparison (TPWC) method is proposed to cope with a rapidly operation point movement when varying irradiation changes occur. The TPWC algorithm periodically perturbs three consecutive points. Each period includes first observation at the current operation point (A), i.e. output power observation, perturbation, i.e. increasing the duty cycle by a fix step size to observe the output power at the following operation point (B), and a third perturbation, i.e. decreasing the duty cycle by two fix steps sizes to observe the output power at the pervious (relatively to point A) operation point (C) [16, 19].
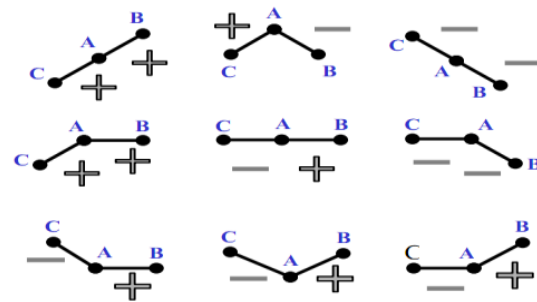

Fig. 3.   The nine possible cases of the three operation points [16, 19].

As exhibited, each two operation points can either get positive or negative weighting status, according to their compared power value. Of the three observation points, two positively (negatively) weighted operation points leads to increase (decrease) of the duty cycle. In the last two cases, when one operation point status is negative and one is positive, the MPP has been reached or solar irradiation is rapidly changing, therefore no change to duty cycle is required and it remains as it was before (the duty cycle of operation point A) [16]. The TPWC algorithm is presented in Fig. 4.

3.3   Incremental Conductance

The Incremental Conductance (IncCond) algorithm is based on the PV array characterization curve's slope [6, 17, 18]. Fig. 5 presents three possibilities of the slope.

Restating, the IncCond is based on the differentiation between PV array power to its voltage. This algorithm is based on the fact that the PV curve's slope is zero at the MPP, negative right to the MPP, and positive left to the MPP, as follows:

$$\left. \begin{array}{ll} dP/dV = 0 & at\,MPP \\ dP/dV > 0 & left\,to\,MPP \\ dP/dV < 0 & right\,to\,MPP \end{array} \right\} \qquad (1)$$
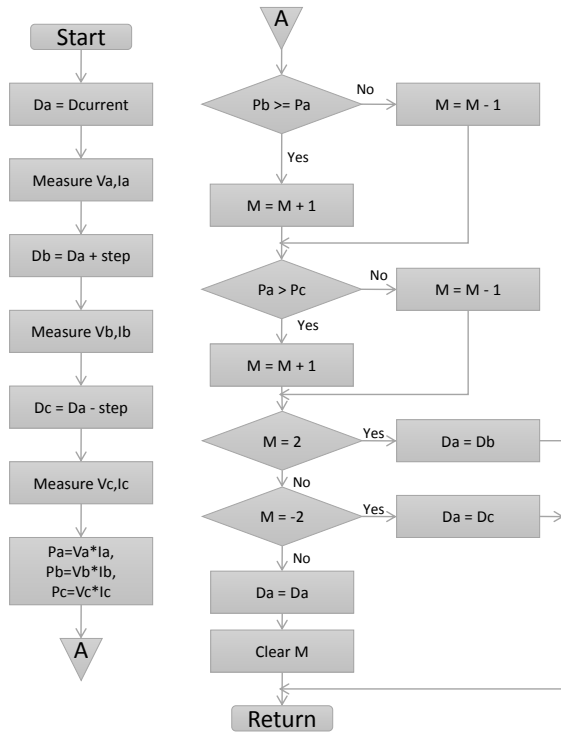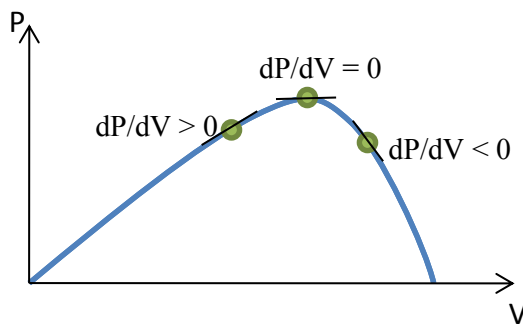
Fig. 4. TPWC algorithm

Fig. 5. IncCond slope possibilities

The P-V curve is derived from the following equation:

$$\frac{dP}{dV} = \frac{d(I \cdot V)}{dV} = I + V\frac{dI}{dV} \approx I + V\frac{\Delta I}{\Delta V} \quad (2)$$

Rephrasing the conditions to the left and right to the MPP:

$$\left. \begin{array}{ll} \Delta I/\Delta V = -I/V & at\, MPP \\ \Delta I/\Delta V > -I/V & left\, to\, MPP \\ \Delta I/\Delta V < -I/V & right\, to\, MPP \end{array} \right\} \quad (3)$$

Thus, when the operation point located to the left (right) of the MPP and the condition $\Delta I/\Delta V > -I/V$ ($\Delta I/\Delta V < -I/V$) exists; Increase (decrease) in PV's voltage

is necessary to achieve MPP. In case the operation point is located at the MPP, the condition $\Delta I/\Delta V = -I/V$ exists and increment/decrement to the PV's voltage is not required. The changes to the PV's voltage are being implemented by increasing (decreasing) the DC-DC converter's duty cycle. Accordingly, the algorithm can track the MPP by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$). Fig. 6 presents the algorithm flow chart.

In common with the P&O algorithm, in case of low irradiance, the IncCond might make the wrong decision as the PV's curve is flat [5] and the slope is zero ($dP/dV=0$ or $\Delta I/\Delta V = -I/V$), even if the MPP has not been reached. As opposed to the P&O algorithm, the IncCond provides a better mechanism to cope with solar irradiance change. In such case, when the operation point located at the MPP and sudden irradiance change occurs, the IncCond will chose to advance towards the MPP.
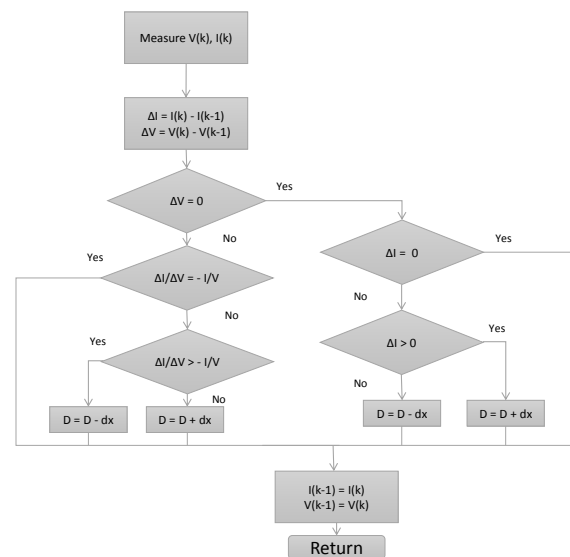

Fig. 6. IncCond Algorithm

Taking into account the fix step size that is a trade-off between the convergence time to the tracking accuracy around the MPP, it is crucial to choose the right step size that would give us an optimum between these two parameters. However, the fact that the step size is fixed contributes to the inflexibility of the algorithm, therefore being a drawback of the fix step size algorithms, generally and particularly the IncCond.

3.4 Variable Step Size Incremental Conductance

In order to cope with the dilemma of choosing the optimum step size, an improvement algorithm, Variable Step Size Incremental Conductance (VSIncCond), is proposed

[17, 18]. This algorithm provides a solution to the trade-off between convergence time and MPP tracking accuracy, by changing the step size automatically according to the PV array curve. In the case where the operation point is located far from the MPP, the algorithm increases the step size in order to shorten the convergence time, respectively. In the case where the operation points are located around the MPP, the algorithm decreases the step size in order to increase the MPP tracking accuracy. This behavior is being implemented based on the fact that the PV curve's slope is high, far from the MPP, and low around the MPP. Therefore, the slope value at the present operation point location, together with a factor, constitutes a multiplier variable which decides the next step size to be used. In order understand better the slop value's influence; Fig. 7 is presented [17].
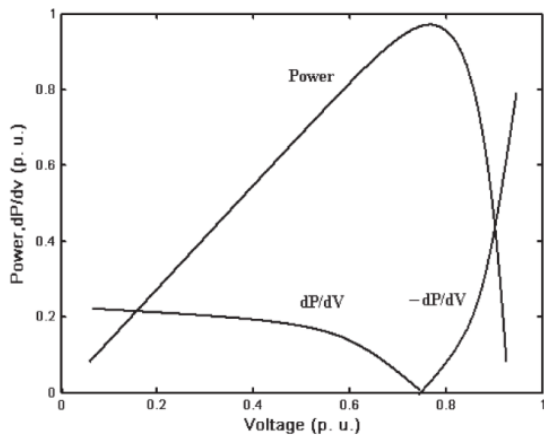

Fig. 7. Variation of the PV curve versus its slope

It is clearly seen from Fig. 7 that the slope decreases as the operation point gets closer to the MPP area, and increases as the operation point gets far from the MPP area. Thus, the step size calculated per each step is calculated according to (4).

$$\Delta D = \Delta D_{\max} \cdot N \cdot \left| \frac{dP}{dV} \right| \qquad (4)$$

where ΔD denotes to the step size, ΔD_{max} denotes to the maximum step size per DC-DC convertor, $|dP/dV|$ denotes to the slope value at the present operation points, where coefficient N is the scaling factor. To better understand the scaling factor calculation, the reader is referred to [17]. As it is well known and presented in Fig. 8, the *VSIncCond* is addressed in the case of $\Delta V=0$. In such cases, it is impossible to calculate the *dP/dV* slope. Therefore, in such a case the step size will be calculated according to the differentiation in power due to the differentiation of current

(*dP/dI*). Thus equation (5) is proposed.

$$\Delta D = \Delta D_{\max} \cdot N \cdot \left| \frac{dP}{dI} \right| \qquad (5)$$

Taking into account the step size change, it is clearly seen that the VSIncCond better addresses rapidly irradiance changes by adjusting the step size accordingly. Likewise, it preserves the IncCond's advantage on the P&O by tracking the MPP without oscillating around it by decisions inherent in the algorithm, existing in the P&O decisions.

This algorithm, together with the previous three algorithms, provides good solutions to challenges issued by uniform irradiance. Fig. 8 presents the algorithm flow chart.
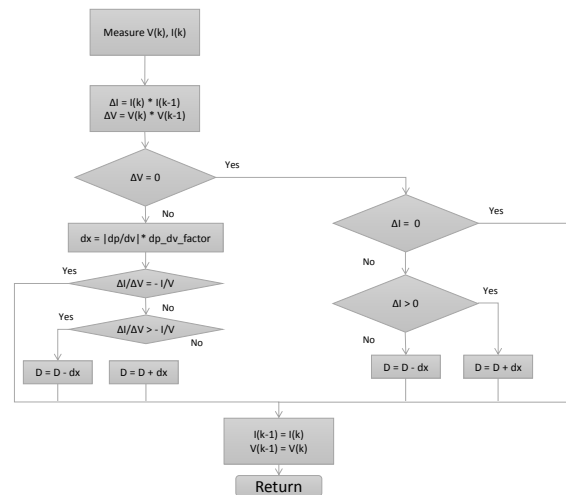

Fig. 8. VSIncCond algorithm

4   THEORETICAL ANALYSIS

4.1   General

For comparison between the implemented four algorithms, the following theoretical section is proposed to fully support the experimental results which are presented in the experimental section ahead.

The two characteristics on which the algorithms are tested are: a) ripple around the MPP; and b) convergence time.

All proposed algorithms are feasible and therefore the application will require the specific characteristics from the system. Therefore, this section is vital. MPPT algorithm efficiency, η_{MPPT}, plays an important role in the power efficiency of a system. This efficiency can be written as:

$$\eta_{MPPT} = \frac{\int_0^t P_{actual}(t)dt}{\int_0^t P_{\max}(t)dt} \qquad (6)$$

where $P_{actual}(t)$ is the time dependent actual power produced from the photovoltaic array under the MPPT algorithm's control, and $P_{max}(t)$ is the time dependent true actual maximum available power at a given temperature and irradiance. Therefore, the voltage ripple effects this efficiency in the steady state operation mode of the system around the MPP. The convergence time affects this efficiency in the dynamic state when a change occurs (temperature, irradiance). It is evident that both above mentioned characteristics influence the utilization and efficiency of the photovoltaic system.

4.2 Voltage ripple around MPP analysis

The algorithms as reviewed above have either variable step size or fixed step size. The ripple around the MPP, $\Delta V_{MPP(ripple)}$ will be equal to the step size of the converters voltage, $\Delta V_{stepsize}$ namely:

$$\Delta V_{MPP(ripple)} \approx \Delta V_{step\ size} \tag{7}$$

If A is the amplitude of the voltage step in the case of a fixed step algorithm,

$$\Delta V_{Fixed\ step} = A, \tag{8}$$

and from (4), in the case of a variable step algorithm, the voltage step will be:

$$\Delta V_{variable\ step} = \nabla P \cdot A \tag{9}$$

When the algorithm approaches the MPP,

$$\nabla P|_{MPP} \to 0 \tag{10}$$

Therefore:

$$\Delta V_{variable\ step} \to 0 << A \tag{11}$$

Therefore, the voltage ripple in the case of a variable step algorithm is much smaller than in the case of a fixed step algorithm, as expected and will be shown in the experimental results.

4.3 Convergence time analysis

MPPT system convergence time is the duration in which the MPPT system reaches its maximum power point (MPP). This parameter is mostly important when rapid changes occur in the atmospheric conditions, thus the importance of this parameter depends on the application that the MPPT system serves. For example, in mobile applications, when atmospheric conditions may vary in a way that the MPP occasionally changes, perhaps it will be better to converge to the new MPP faster in order to obtain higher efficiency of the system.

The photovoltaic cell can be represented by the well–known voltage-current characteristic equation:

$$I(V) = I_{ph} - I_0(e^{qV/n \cdot k \cdot T} - 1) \approx I_{ph} - I_0 e^{qV/n \cdot k \cdot T} \tag{12}$$

The equation for the power will be derived by multiplying the current by the voltage and $P(V)$ function, as shown in Fig. 1 and can be written as:

$$P(V) = I_{ph} \cdot V - V \cdot I_0 e^{qV/n \cdot k \cdot T} \tag{13}$$

For this discussion, it is sufficient to look at (13), as P is a function of V and all the remaining variables are constants. For convenience, (13) can be rewritten as:

$$f(x) = \alpha x - \beta x e^{\gamma x} \tag{14}$$

where x represents V, $f(x)$ represents the power function, and α, β and γ are the constants.

The convergence problem can be considered as: $\min_x f(x)$.

The first and second derivatives of $f(x)$ are:

$$f'(x) = \alpha - \beta(1 + \gamma x)e^{\gamma x} \tag{15}$$

and

$$f''(x) = -\beta(2\gamma + \gamma^2 x)e^{\gamma x}. \tag{16}$$

Since the second derivative is negative, we can thus conclude that f is concave over $[0,\infty)$. Also, $f'(0) = \alpha - \beta$, and we know that $\alpha > \beta$ (since the reverse saturation current is much smaller from the photon current of the cell). Under these assumptions, the function has a unique maximum point on the interval $[0,\infty)$.

The maximum upper bound of the maximum point is denoted by x*. Then:

$$f'(x^*) = \alpha - \beta(1 + \gamma x^*)e^{\gamma x^*} = 0 \tag{17}$$

Consequently (by using the inequality ex≥x+1)

$$\alpha - \beta e^{2\gamma x^*} \leq \alpha - (1 + \gamma x^*)e^{\gamma x^*} = 0 \tag{18}$$

Therefore,

$$x^* \geq \frac{1}{2\gamma} \ln \frac{\alpha}{\beta} \tag{19}$$

Overall,

$$x^* \in \left[\frac{1}{2\gamma} \ln \frac{\alpha}{\beta}, \frac{1}{\gamma} \ln \frac{\alpha}{\beta}\right] \tag{20}$$

Furthermore, the fixed and variable step methods can be addressed as a grid search over the interval as in (20), in which the step sizes will be of length ε and take the

minimal value among the grid points. This approach requires $O\left(\frac{1}{\gamma}\left(\ln\frac{\alpha}{\beta}\right)\frac{1}{\varepsilon}\right)$. The second approach is to look at the gradient method. In this approach, since this function is strongly concave, it follows that the number of operations required to obtain an ε- optimal solution is $O\left(\ln\frac{1}{\varepsilon}\right)$. Since the dependency in ε in the gradient method is via the expression $\ln\frac{1}{\varepsilon}$ rather than $\frac{1}{\varepsilon}$, it follows that the gradient method is more efficient in convergence.

5 EXPERIMENTAL RESULTS

5.1 The experimental setup

The MPPT algorithms were analyzed independently on an independent MPPT system, one that is not connected to the central power grid and operates only on solar energy.

The system includes an energy DC/DC power converter that was connected to the output of the PV array. The selected power converter was a Full Bridge Phase Shift (FBPS) PWM DC/DC converter.

MPPT algorithms were implemented on a Texas Instruments microcontroller TMS320C2000. The total setup also included the photovoltaic modules which are capable of producing 200Watts peak each and a 20Ω load. A basic block diagram for the test setup is shown in Fig. 9.

As noted before, the experimental results compare the two characteristics: (a) convergence time, (b) voltage ripple around the MPP. These characteristics were tested for the four proposed algorithms. For comparing (a) and (b), the experiment was performed under uniform irradiance where the PV array was located on the roof and observed full sun radiation of 0.895-0.965 Sun. Atmospheric conditions, temperature and irradiance level were taken and observed while performing the experiments and the temperature was approximately 500.
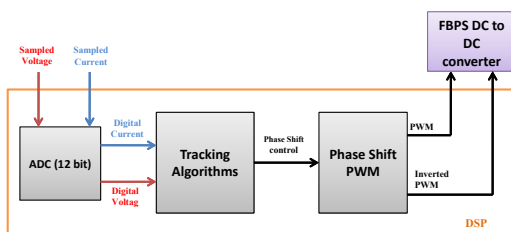
Fig. 9. Basic Block Diagram of the Test Setup

5.2 Convergence Time results

The algorithm was implemented with an upgraded method for fast total convergence time which included an initialization procedure. This basic procedure objective is to initiate the system to a specific duty cycle value before the algorithm decision making starts (See Fig.10).
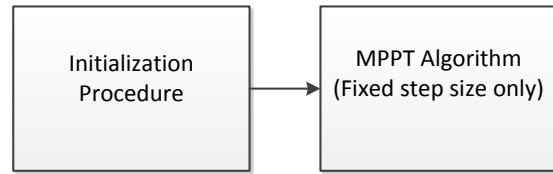
Fig. 10. Initialization procedure and MPPT algorithm block diagram

This initialization procedure added value is in the trade-off between the duty cycle step size and convergence time duration that was discussed in the "challenges overview" section, thus it is relevant only for algorithms that change the duty cycle using a fixed step size. The initialization procedure enables the opportunity to implement two different step sizes for changing the duty cycle, one will be utilized in the initialization procedure and one will be utilized in the MPPT algorithm itself. Furthermore, it decreases real time processing due to its relatively simplified implementation compared to the algorithm decision making process implementation. This procedure is well shown in all of the tested algorithms. The duty cycle in this procedure was chosen to be 50%. Thus, the MPPT system will initiate this procedure first, until reaching 50% duty cycle (using a fixed duty cycle step size to protect the HW in the power converter) and then algorithm decisions will take place. This initial procedure happens only at first system uptime and from that point forward only the algorithm itself takes place. Figure 11 exhibits the voltage and current characteristic that was taken from the output of the MPPT system. Furthermore, Fig. 11 demonstrates the initialization procedure, when the initial point in this figure indicates the system first activation. Duration time of the initialization procedure is about 15 seconds, a duration that is taken into account in advance and is acceptable due to its added value when considering the total system convergence time to the MPP, as explained earlier.

Figure 12 exhibits the convergence time differences between the four proposed algorithms. The total convergence time was measured from the initialization procedure to the point when MPP was reached. For Fig. 12(d), that represents the convergence time of the variable step size IncCond algorithm, the initialization procedure is absent due the fact that its operation method is based on the variable step size from the beginning and not on fixed step size method as the others.

As shown in Table I, with regard to the convergence time characteristic, variable step size IncCond has the obvious advantage with total convergence time of 24.16 seconds. Furthermore, analysis of the different algorithms leads to the conclusion – P&O and IncCond are utilizing two fixed steps' sizes, one for the initialization pro-
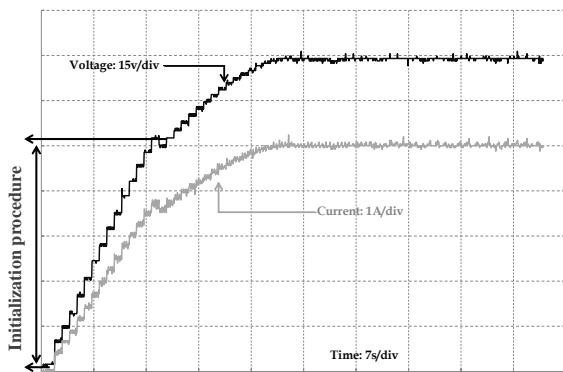
Fig. 11. Initialization procedure for reaching 50% duty cycle

Table 1. Algorithms total convergence time summery table

Algorithm	Total convergence time [sec]
P&O	31.36
TPWC improvement for P&O	31.24
IncCond	31.96
Variable step size IncCond	24.16

cedure and one for the MPP search procedure. While all algorithms are based on one iteration per decision in their search procedure, TPWC, (apart from using two fixed steps sizes), the search procedures decisions are based on two iterations as it first sample power location ahead, then previous power location and only in the second iteration it can decide on the step that must be taken, this is clear indication for longer time. In this paper, it is clear that the TPWC is the longest convergence time method. The most efficient convergence time method in this paper is the VSIncCond (also shown in Table 2, above) as it utilizes from its first moment to the moment it locates the MPP a variable step size which changes according to the PV curve gradient. Even though the Two Stages VSIncCond is based on VSIncCond, it takes more time to converge to the MPP, as it does in its algorithm procedure, which takes longer. It is a tradeoff that must be taken while coping with partial shading. It is important to indicate that all time measurements were taken from the MPPT system in which the DSP time base period (TBPD) were set to a specific value. This TBPD value can be changed. Thus, if system TBPD were to be changed, all time measurements will be changed accordingly, however, the differences between the algorithms convergence time will be sustained.

5.3   Ripple around the MPP

As discussed earlier, there is a dependency between the MPPT convergence time to the oscillations that are taking place around the maximum point. This dependency is due

to the fact that these two characteristics will be influenced by the duty cycle step size value.

It can be derived from this paper's experimental results that the ripple around the MPP is influenced by: 1) duty cycle step size – a) fixed step size or b) variable step size; and 2) the basic algorithm decision making method. In other words, the algorithm includes "no change" decision or not, for example, in the P&O algorithm, decisions are being taken either to proceed in the same direction or to the opposite direction on the subsequent perturbation. Therefore, in steady state case (when the MPP has been reached) the algorithm continues with these decisions which cause the oscillations around the MPP, as explained in more details in the algorithm review section. Thus P&O uses fixed duty cycle step size and lack of "no change" decision, as can be shown in Fig. 13.

As opposed to the P&O algorithm, all other algorithm basic operations include a decision to make no change in the duty cycle when MPP has been reached, thus the ripple around the MPP will be smaller than in P&O. Furthermore, referring to, there is a clear advantage to the variable step size IncCond algorithm, due to the fact that the duty cycle step size varies according to the PV curve slope, i.e. includes variable step size as elaborated in the algorithm review section and can be shown in Fig. 14.

Fixed step and lack of "no change" are manifested in the "pulse" magnitude and in the constant period of the pulse respectively. The "pulse" constant period indicates that there is always a decision to change the duty cycle and lacks a decision to not change the duty cycle. Variable step and "no change" are manifested in the curve shown in Fig. 14, the variable step can be explained as the magnitude of the curve is changing in non-constant values which is the exact purpose of the variable IncCond algorithm; and "no change" can be explained as the curve has no constant period that is visible to the observer. That is to say that the decisions are being taken in the same period, but the fact that the "no change" decision is part of the procedure, we get the effect of better flatness around the MPP (and it has no constant period). This effect is common to all the algorithms besides P&O due to the fact that it is caused by the "no change" decision that is integrated in each algorithm.

6   CONCLUSIONS

This paper presents the theory as well the comparative experimental results of four MPPT algorithms which were implemented on the same converter for maintaining constant experimental conditions. The paper shows first analytically that gradient based methods have better convergence time as well as ripple values than fixed step convergence.

Regarding Convergence time the results, as can be seen in section 5B, clearly prove the advantage of Variable step
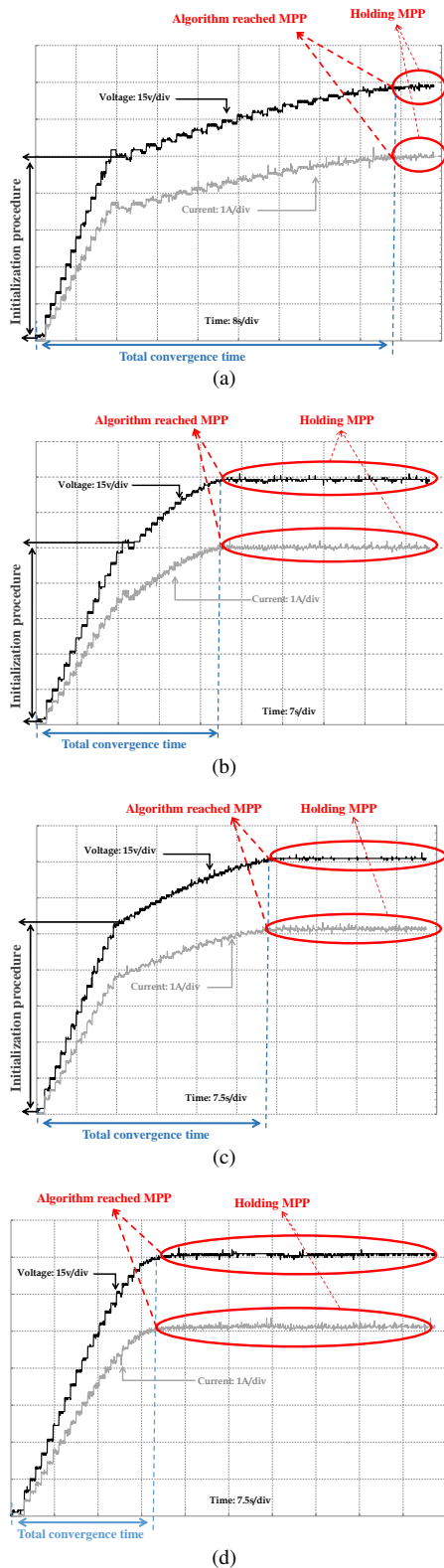
(a)

(b)

(c)

(d)

Fig. 12. (a) P&O (b)TPWC improvement for P&O; (c) IncCond (d) Variable step size IncCond
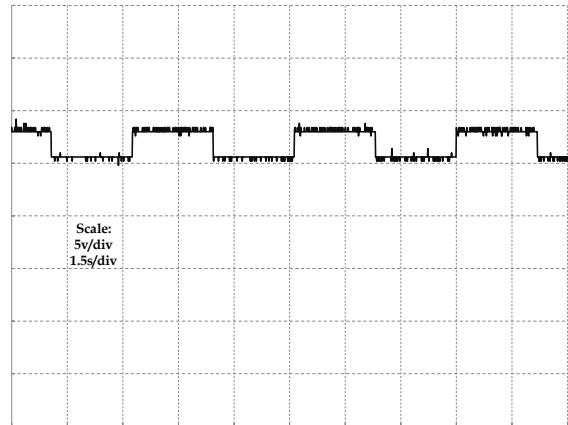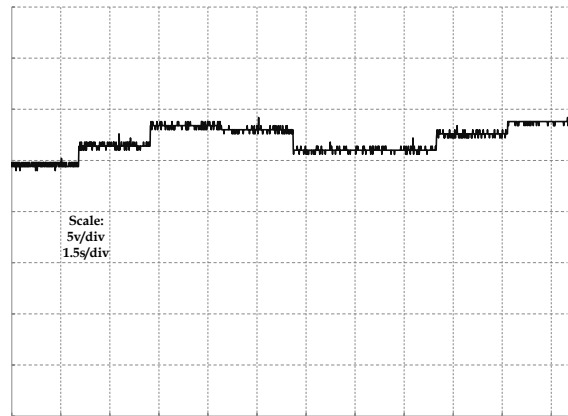

Fig. 13. P&O ripple around MPP

Fig. 14. Variable step size IncCond ripple around MPP

size IncCond, due to the algorithm's operation method, which selects the step size each time based on the PV curve slope. In contrast, the "Three points weight comparison method" algorithm has the worst convergence time, due to the fact that the decision procedure in this algorithm is very long, as well as using the "fixed step size" when decisions are finally made. These facts make it the slowest algorithm in general, and especially when referring to the convergence time parameter.

Regarding the characteristics of ripple around MPP, this characteristic is influenced by two parameters, fluctuations generated due to the algorithm decision procedure itself, and fluctuations caused due to the use of the fixed step size and not a variable step size. It is concluded that the P&O algorithm has a significant disadvantage compared to other algorithms. This disadvantage is mainly due to the incapability of making a "no change" decision when the MPP has been reached. Hence, it leads to significant fluctuations around the maximum power point, although irradiation changes do not exist. Moreover, the P&O dis-

advantage is also affected by the ripple magnitude, which is determined by the fixed step size that the P&O algorithm is set to. On the other hand, according to the experimental results, it is proven that the best performance algorithm, concerning the ripple around the MPP, is the "variable step size IncCond", due to its capability of choosing a different step size according to the PV curve's slope, together with the ability to make a "no change" decision when the MPP has been reached.

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Y. Beck was born in Tel Aviv, Israel, on November 30, 1969. He received the B.Sc degree in electronics and electrical engineering from Tel Aviv University in 1996, the M.Sc. degree in 2001, and the Ph.D. degree on the subject of ground currents due to lightning strokes in 2007 both from Tel Aviv University as well. Since 1998, he has been with the Interdisciplinary Department, the Faculty of Engineering, Tel Aviv University. In 2008 joined HIT-Holon Institute of Technology, Holon, Israel, as a Lecturer and from 2010 is acting as the head of Energy and Power Systems department at the faculty of engineering. His research interests include Smart Grid technologies, lightning discharge phenomena; lightning protection systems; power electronics, and photovoltaic systems.

N. Sober was born in Tel-Aviv, Israel, on December 3, 1981. He joined Israel Defense Force in 2001 to play technical role as part of the technologic core of IDF. In 2005, he joined InspiAir, an Israeli startup, which developed wireless communication system in WiFi (802.11 g/b) standards. In 2007, he joined Airspan Networks, a leading company in Wireless Broadband specialized in developing products based on WiMax(802.16) and LTE standards. In 2012, he joined SanDisk Inc., a leading company in the flash industry developing flash devices. He received the B.Sc degree in electronics and electrical engineering from HIT-Holon Institute of Technology in 2011, ad was a part of a research team on Developing Maximum Power Point Tracker ("MPPT") system based on most common MPPT algorithms.

AUTHORS' ADDRESSES

Dr. Yuval Beck
Nadav Sober
Faculty of Engineering,
Holon Institute of Technology,
52 Golumb st. , Holon 5810201, Israel