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A New High Speed and Accurate FPGA-based Maximum Power Point Tracking Method for Photovoltaic Systems

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ABSTRACT

We introduce in this paper a new FPGA-based Maximum Power Tracker for photovoltaic systems. The developed approach targets to modify the perturb and observe in view of reaching rapid tracking and achieving excellent accuracy, while keeping the stability performance and the reduced complexity. To perform this improvement, an automatic and smart two steps switcher is integrated, in addition inputs FIR filters are incorporated**.** Therefore, a high sampling frequency is attained, and consequently the tracking speed is improved. MATLAB simulations and the Xilinx FPGA implementation results show that the improved approach reaches a performance very close to the recently published MPPT methods, with lesser complexity.

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1. INTRODUCTION

Due to the severity of the global energy crisis, environmental pollution and the depletion of fossil energy reserves in the next few decades, the global orientation towards the use of renewable energies has become a concrete thing. The sun is a source of energy without geographical boundaries inexhaustible, constantly and naturally regenerated; this is why it is called a "renewable and sustainable" source of energy. The photovoltaic effect is a physical phenomenon that occurs in a semiconductor based cell, which produces electricity when exposed to light. To produce more power, cells are assembled in series and in parallel to increase voltage and current and hence power [1]. The Photovoltaic (PV) procedure is therefore another alternative source for electrical power [2]. Unfortunately the yield of PV systems is still low (9-17%) especially at low levels insolation. The characteristics of current voltage (I-V) and power voltage (P-V) of a PV arrays vary both with irradiation and temperature. Each of these curves has a single point called maximum power point (MPP) at which the power is maximum; nevertheless the position of this point is not fixed because the meteorological conditions vary randomly.

To improve the efficiency of a PV system, maximum power point tracker (MPPT) is essential in order to extract a maximum power of the PV system rapidly and at all possible levels of insolation [3] [4]. This maximum can be located by mathematical models or algorithmic research techniques. Since 1968, date of the first publication on the control of the MPPT algorithm, the research continues to emerge [5]. Different types of algorithms that efficiently search for the Maximum Power Point (MPP) have been reported in the literature [6] [7]. All of them differ in their aspects such as the number of sensors required, complexity, speed of convergence, cost, and the efficiency of hardware implementation [8].

Several MPPTs algorithms have been suggested in the literature; the first type regroups the Hill climbing methods, perturb-and-observe and incremental conductance. These methods operate by creating a small perturbation of the voltage around its initial value and analyzing the behavior of the panel output power variation. If the power increases, the direction of disturbance is maintained otherwise it is reversed [9] [10]. The other type concerns the use of the look-up table of the electrical characteristics of the panels chosen for the calculation of the instantaneous power for all possible values of insolation and temperature [11]. The third type use Neural Network and Fuzzy Logic Control (PLC) [12].

The literature shows that the most popular and practical MPPT algorithms are: Perturb and Observe (P & O) and Incremental Conductance [13] [14] [15] but the P&O remains an unreliable method in the determination of the optimum operating point when rapid changes of sunlight occurs. The size of the disturbance affects the system performance; a small one slows the speed of reaching the maximum power while a large disturbance increases the oscillations around the maximum. To improve the performance of P & O some methods are proposed: Hossain and all [16] develop the incremental conductance algorithm for tracking the MPP of the PV while sudden environmental conditions occur; Lijun Qin and Xiao Lu [17] propose an adaptive P&O with variable step size perturbation to enhance the steady state and the dynamic performance; Qiang Mei [18] introduces a novel MPPT algorithm which adjusts automatically the step size to track the PV array MPP. Other authors propose methods using several algorithms for tacking the MPP in the event of sudden changes in irradiation [19].

In this paper we introduce a new FPGA-based Maximum Power Tracker for photovoltaic systems. The main target is to modify the perturb and observe in view of reaching rapid tracking and achieving excellent accuracy, while keeping the stability performance and the reduced complexity advantage.

2. PHOTOVOLTAIC SYSTEM

2.1. Photovoltaic Cell Model

The equivalent circuit of a photovoltaic cell is shown in Figure 1 [20].

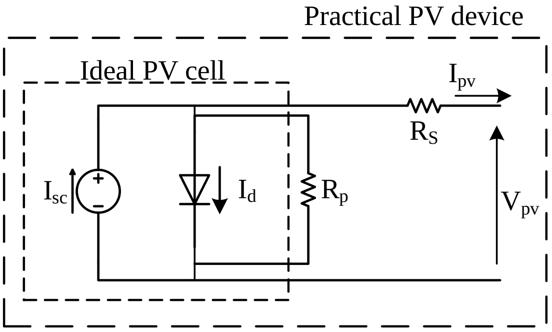


Figure 1. Circuit equivalent of a PV cell

To model the cell, the electrical quantities of the circuit shown in Figure 1 should be represented by an Equation; the current in the diode is given by the Equation 1:

$$I_D = I_0\left[exp\left\{\frac{V_D}{V_T}\right\} - 1\right] = I_0[exp\left\{\frac{(Vpv+Ipv*Rs)}{V_T}\right\} - 1] \quad (1)$$

I_0 is the saturation current of the reverse bias of the diode and V_D is the diode voltage which is given by the Equation 2.

$$V_D = (Vpv + Ipv * Rs) \quad (2)$$

V_T is a thermal voltage given by Equation 3.

$$V_T = \frac{kT}{q} \quad (3)$$

k is the Boltzmann constant which is equal to $1.3806503 \text{x} 10^{-23}$(J/K), T is the operating temperature of the cell in degree Kelvin, and q is the electron charge. The V_{pv} voltage is given by:

$$V_{pv} = (V_D - Ipv * Rs) \tag{4}$$

And I_p current is given by Equation 5:

$$I_p = \frac{V_D}{R_p} = \frac{Vpv}{R_p} + \frac{Rs}{R_p} I_{pv} \tag{5}$$

Finally, the expression of the current I_{pv} of a PV cell is given by the Equation 6:

$$I_{pv} = I_{sc} - I_D - I_p = I_{sc} - I_0 [exp \left\{ \frac{(Vpv + Ipv * Rs)}{V_T} \right\} - 1] - \frac{Vpv}{R_p} - \frac{Rs}{R_p} I_{pv} \tag{6}$$

2.2. Photovoltaic Panel Model

A photovoltaic cell doesn’t provide enough power to supply a load or a power grid. It is therefore necessary to assemble several cells in series or in parallel to get more power. A series connection increases the output voltage of the solar panel, while a parallel combination increases the current supplied to the load. Then it is necessary to introduce two new parameters $N_p$and Ns representing the number of cells in parallel and in series respectively. The total current I_{pv} delivered by the cells combination is given by the Equation 7 as follow:

$$I_{pv} = N_p I_{sc} - N_p I_0 [exp \left\{ \frac{(Vpv)}{N_s V_T} + \frac{(Ipv * Rs)}{N_p V_T} \right\} - 1] - \frac{Vpv}{R_p} - \frac{Rs}{R_p} I_{pv} \tag{7}$$

Where:
a. I_{sc}: the cell short -circuit current.
b. Rp: Resistance characterising recombination loss of carriers due to defects in the material.
c. Rs: Characterises the Joule effect losses in the semiconductor and losses through the gate and bad ohmic contact of the cell.

The amount of solar radiation affects the production of the charge carriers in the solar panel, thus affecting the cell current saturation (I_{OS}) which is given by the following Equation 8:

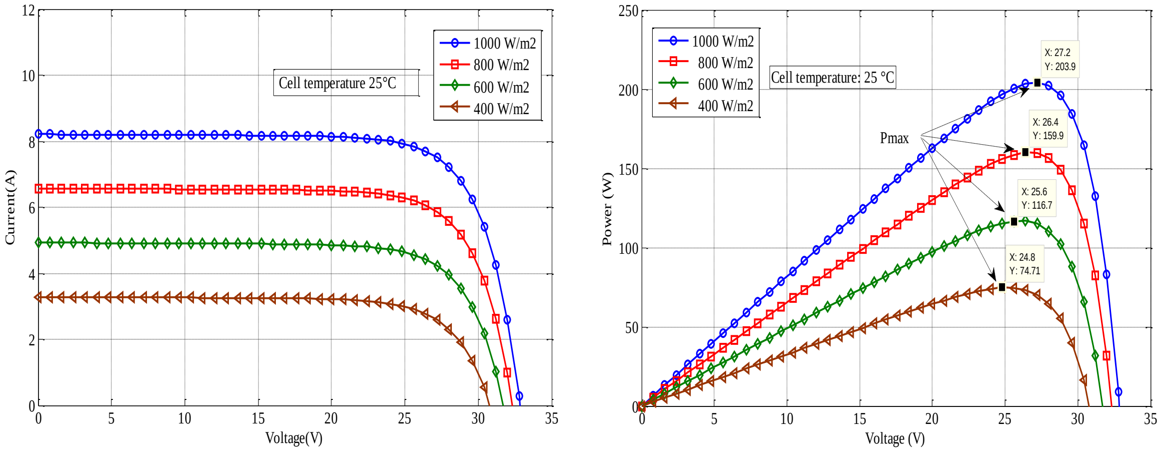
$$I_{os} = Irs[T/Tr]^3 \ \exp \left[q * \frac{E_{GO}}{\beta * K} \left\{ \frac{1}{Tr} - \frac{1}{T} \right\} \right] \tag{8}$$

Where:
a. Tr = temperature reference
b. K = 298.18
c. E_{G0} = 1.12 eV which is silicon band width
d. β = 1.740
e. Irs = reverse saturation current of the cell
f. Ios = cell saturation current.

2.3. P&O FPGA-Based PV power system

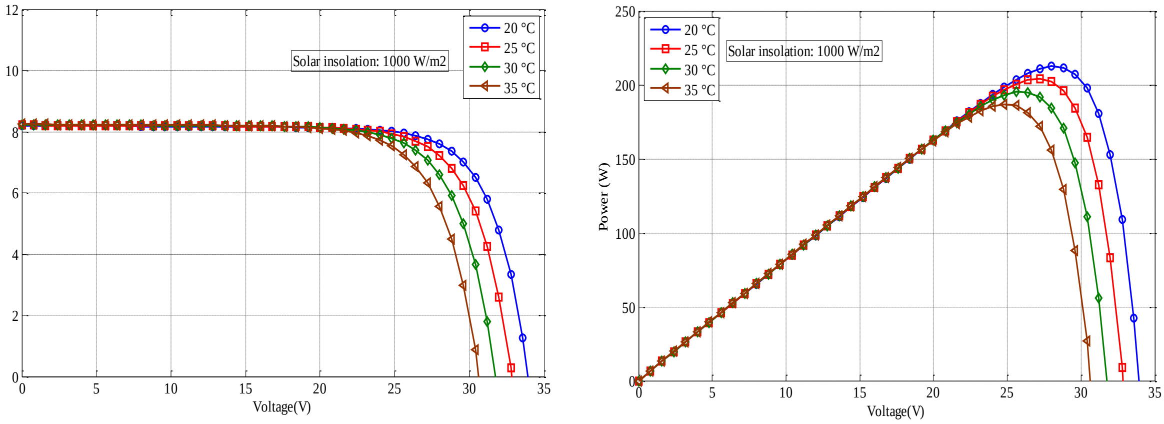
The presented system uses a Kyocera KC200GT panel, which Figure 2 and Figure 3 give the related characteristics under fixed solar irradiation and fixed cell temperature respectively. The system consists of photovoltaic power source (the panel), the DC-DC converter for adapting and shaping signals between the $I - V$ and the load resistor, two sensors for the voltage Vpv and the current Ipv and an FPGA-based system for tracking maximum power (MPPT) produced by the photovoltaic source which delivers a variable duty cycle pulse train to control the converter DC-DC loaded by the resistor R_L Figure 4.

The principle of P&O MPPT control is to disrupt the voltage V_{PV} of the panel periodically a small amplitude around its initial value and analyze the behavior of the P_{PV} power resulting variation. Thus, as illustrated in Figure 5 we deduce that if a positive increment of VPV voltage generates increased power PPV, this means that the operating point is in left of the MPP. However, if the power decreases, it means that the system has exceeded the MPP. A similar reasoning can be made when the voltage decreases. From these analyzes of the voltage change on the PPV. It is easy to locate the operating point relative to the PPM, and converge it to the maximum power through a control order.



(a) (b)

Figure 2. The current-voltage (a) and power-voltage, (b) Kyocera KC200GT characteristics under a fixed cell temperature (25°C)



(a) (b)

Figure 3. The current-voltage (a) and power-voltage, (b) Kyocera KC200GT characteristics under a fixed solar insolation (1000 W/m2)

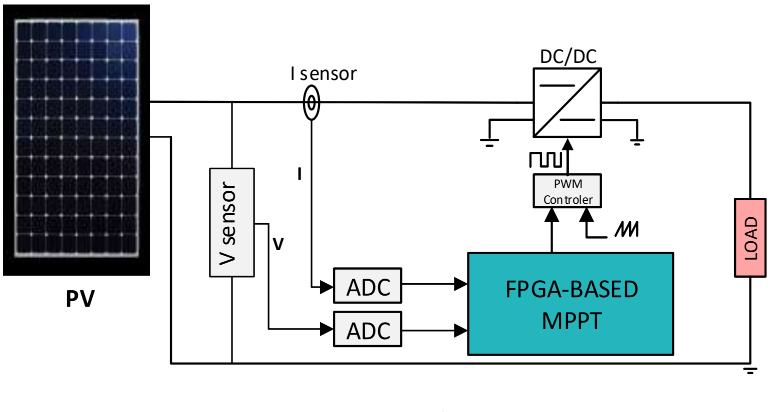
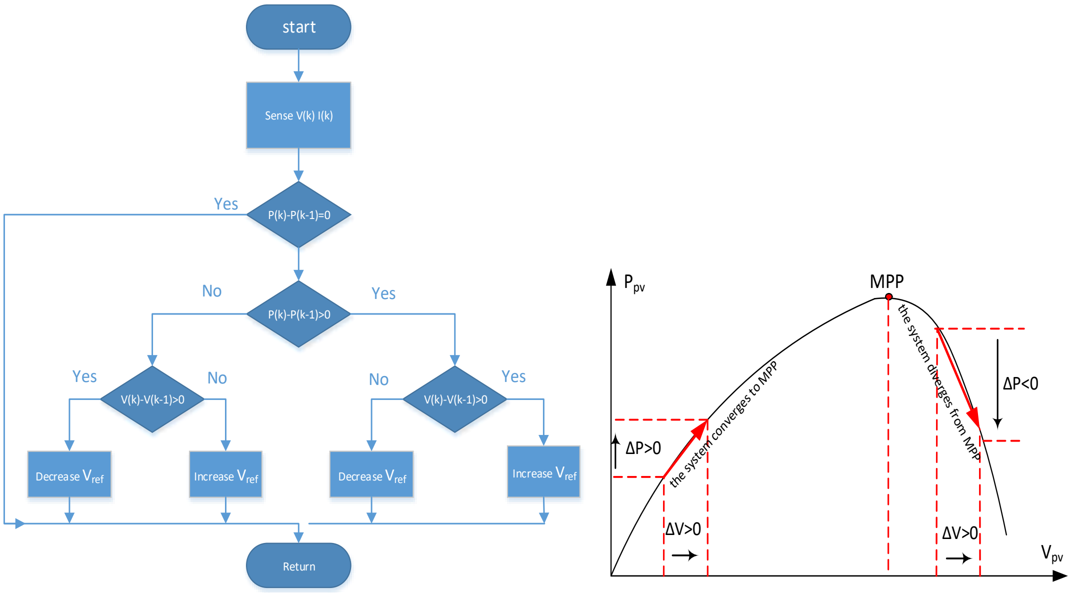


Figure 4. Bloc diagram of the PV system



(a) (b)

Figure 5. (a) Flow chart of MPPT the P&O algorithm and (b) The behavior of P&O MPPT algorithm with P-V curve

3. THE PROPOSED MPP TRACKER

3.1. Theory of the Proposed Technique

As mentioned above, using the conventional P&O, we can't reach rapid tracking in addition to achieve excellent accuracy. To overcome this disadvantage, the proposed P&O MPPT technique joins strong accuracy and high speed tracking, by using two clever keys. The first key is the adaptation of the new P&O tracker to attain higher sampling frequency. The second key is the using of an automatic and smart two steps switcher. The sampling frequency of the P&O inputs signals (*V* and *I*) is shaped by their switching variations. The Figure 6 illustrates a simplified signal form. As a simplified example, the *V(t)* signal can be written by Equation 9.

$$V(t) = Sin(w * t + \varphi) + k * t \tag{9}$$

It is clear, if $\boldsymbol{t_a}$ and $\boldsymbol{t_b}$ are a successive time sampling, the conventional P&O algorithm moves away from the MPP. For that reason, the sampling frequency is computed using the following expression.

$$F_{max} \leq \frac{1}{t_c - t_a} \tag{10}$$

Using the High pass and Low pass filtering, the *V(t)* can be split into $V_1(t)$ and $V_2(t)$. Figure 7 illustrates the ideal forms of V_1 and V_2.

$$V_1(t) = Sin(w * t + \varphi) \tag{11}$$

$$V_2(t) = k * t \tag{12}$$

The proposed P&O algorithm aim to compute the $V_2(t)$ sampling instead of *V(t)* sampling. The same process concerns the *I(t)* signal.

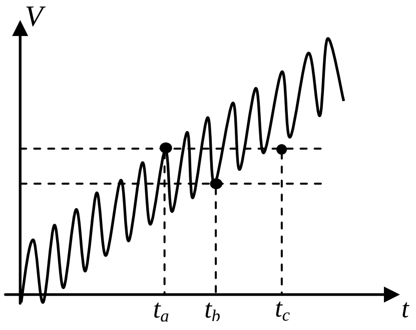


Figure 6. Simplified voltage form

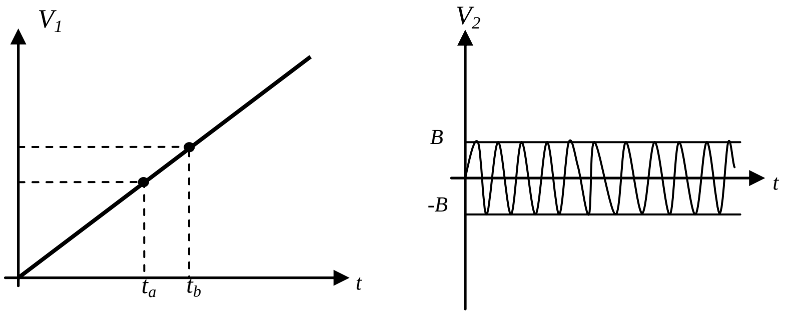


Figure 7. V1 and V2 forms

As a result, the new maximum sampling frequency will be greater than the classic P&O one. Therefore, the new perturbation step can be reduced significantly without losing tracking speed. In addition to the mentioned improvement, an automatic and smart two perturbation steps switcher, D_{min}*Step* and D_{max}*Step*, is integrated. The D_{max}*Step* is used once the power point remains faraway from the MPP. The perturbation step or the duty cycle step switch from D_{min}*Step* to D_{max}*Step* every time a maximum successive same way incrementing, of D_{min}*Step*, is reached. The switch from D_{max}*Step* to D_{min}*Step* appears with the opposed D_{max}*Step* perturbation. The Figure 8 summarizes the switching activities.

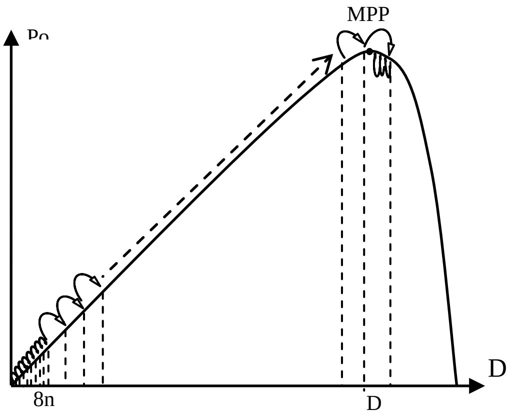


Figure 8. The proposed MPPT switching activities

3.2. Architecture of the Proposed MPP Tracker

The proposed architecture uses the main parts of a P&O tracker in addition to the included new parts. The classic P&O tracker exploits principally an adder-subtractor coupled with perturbation analyzer and a fixed *Dstep* input constant. The Figure 9 represents the simplified architecture of a P&O tracker.

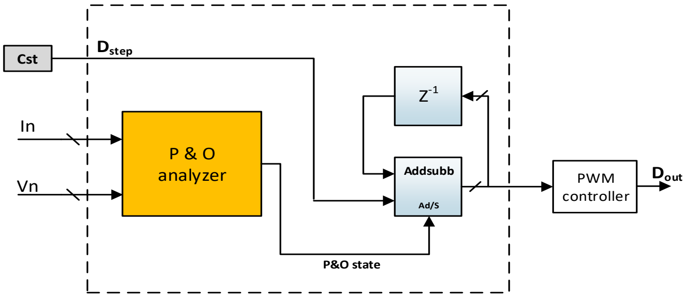


Figure 9. Simplified architecture of a P&O tracker

The developed MPP tracker multiplexes the two duty cycle steps by a permanent processing of the P&O state. The P&O State Analyzer is a new introduced parte. It computes the P&O state and/or the external control. The smart switching is enabled and disabled using the external control, which allows the two modes, the classic mode and the proposed mode. The low-pass filtering is achieved by the two FIR filters. The first for the current signal and the second for the voltage signal (Figure 10).

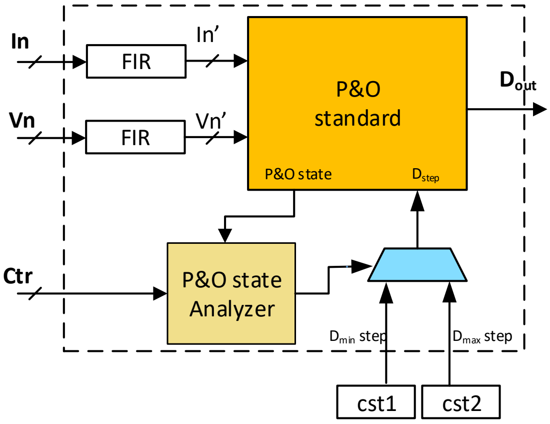


Figure 10. The developed MPP tracker architecture

The proposed solution can be implemented in a low-cost FPGA based platforms and can achieved very high performances. The next section describes the FPGA implementations and results.

4. FPGA IMPLEMENTATION AND RESULTS

To validate the new algorithm, a Kyocera KC200GT solar panel with DC-DC boost converter are used. The FPGA implementation results are tested using a low-cost Xilinx Spartan-3E FPGA. Different and switched insolation intensity are applied in order to confirm the high performances and stabilities, in addition to very low complexity requirement, compared to the recently developed MPPT algorithms. The Figure 11 presents the PV panel output power using 500W/m^2, 1000W/m^2, 800W/m^2, 900W/m^2, 700W/m^2 and 600W/m^2 successively. The PV output voltage and current are exposed in Figure 12 and Figure 13 respectively. The Hardware co-simulation is performed with the Spartan-3E Starter Kit (Figure 14). The step switch from $D_{min}Step$ to $D_{max}Step$ is clearly shown in Figure 15. It is observed for the 500W/m^2-to-1000W/m^2 variation.

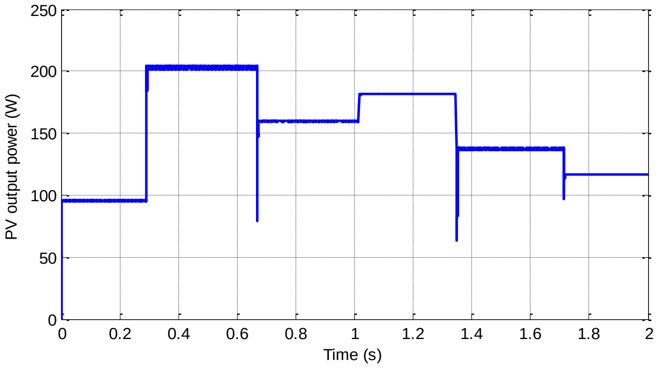


Figure 11. The PV output power using the proposed MPPT

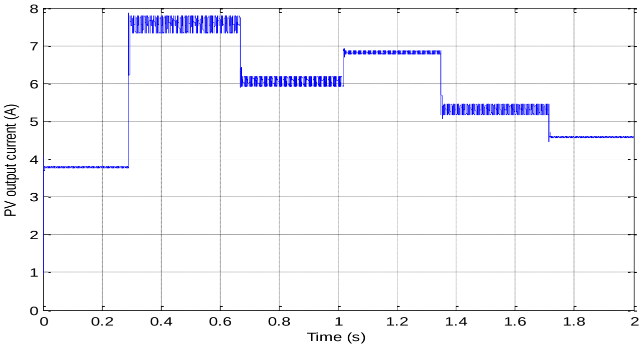


Figure 12. The PV output current using the proposed MPPT

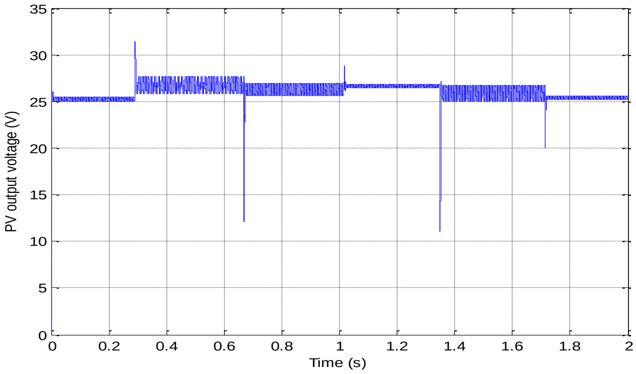


Figure 13. The PV output voltage using the proposed MPPT

Figure 14. Xilinx Spartan-3E FPGA Kit

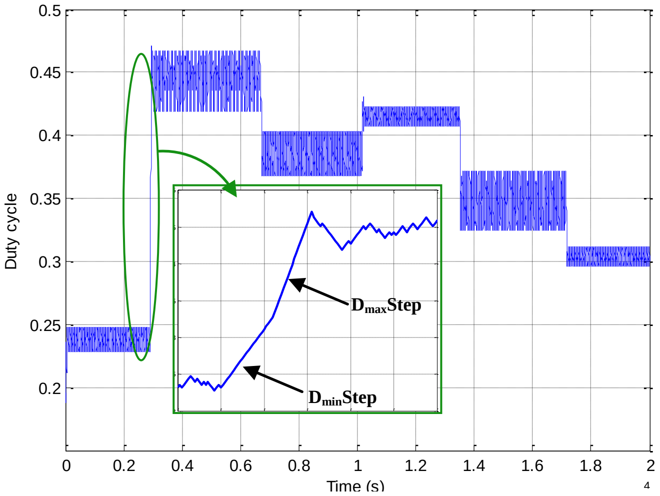


Figure 15. Duty cycle variation

The FPGA logic utilization summary are presented Table 1. Furthermore and to demonstrate the performance of the developed architecture, a brief comparison are don. Table 2 summaries the comparison.

Table 1. Device Utilization Summary

Logic Utilization	Used	Available	Utilization
Number of Slice Flip Flops	120	9,312	1%
Number of 4 input LUTs	97	9,312	1%
Number of occupied Slices	113	4,656	2%
Total Number of 4 input LUTs	97	9,312	1%
Number of bonded IOBs	43	232	18%
Number of BUFGMUXs	1	24	4%

Table 2. The performances comparison

Parameters	Proposed	[21]	[22]	[23]
Response time (ms)	<100	106	113	<100
Efficiency (%)	99,54	96.41	99,22	99,66
Complexity	Very-low	Low	Medium	Medium
Sensors	Current-Voltage	Current-Voltage	Current-Voltage	Current-Voltage

5. CONCLUSION

In this paper, a new FPGA-based Maximum Power Tracker for photovoltaic systems has been presented. Derived from the P&O MPPT method, smart algorithm improvements have been achieved. The proposed algorithm is designed to track the MPP using a reduced hardware complexity while keeping the accuracy close to artificial intelligence based trackers.

The novel algorithm has been confirmed using *Kyocera KC200GT* solar panel with DC-DC boost converter. Simulations and Xilinx FPGA implementation results show that the new P&O algorithm gives convergence rapidity and accuracy close to the recently developed MPPT algorithms, with lesser complexity. The comparative study with the latest works confirms the advantages of the proposed improvements.

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