Design and Implementation of PV MPPT Controller based on Modified P&O algorithm using FPGA for satellite systems

Hatem Taha R. M. Mostafa Usama Abouzayed Fawzy Eltohamy

Electrical power and Energy department, Military Technical College

Cairo, Egypt

Hatemtahas79@gmail.com R_mostafa05@yahoo.com u.abozayed@mtc.edu.eg ftohamy72@yahoo.com

Abstract*—A proposal of Maximum Power Point Tracking (MPPT) controller for photovoltaic satellite using Partially modified perturb and observe (P&O) technique and implemented using FPGA is introduced. An enhanced high frequency variable step-size P&O algorithm is accomplished and fully well programed using a hard-ware description language (VHDL). Thereafter, the amended MPPT algorithm is implemented on "Spartan-3A/3AN FPGA Starter Kit" FPGA. Simulation and Experimental results are executed and exhibit that the proposed algorithm overcome the disadvantages of the conventional algorithm that can be summarized into tracking speed, reduction of output power oscillation in steady state operation and significant deviation of voltage and power due to sudden change in solar insolation.

Keywords— *photovoltaic array;* P&O *algorithm; variable step size;* FPGA.

I. INTRODUCTION

A solar PV-based power generation system is the most common renewable energy sources used in space vehicles and the prime factor that impact its performance is the operating point at which the solar PV array operates. The characteristics of a solar PV array is mainly influenced by the changes of the ambient conditions which are the solar insolation and atmospheric temperature. The PV array optimum operating point is realized at the point at which the maximum power is extracted for any given load. Therefore, MPPT of the PV array under different values of ambient temperature and solar insolation is substantial and prerequisite to outperform the PV efficiency[1],[2].

Several MPPT techniques are available including conventional methods and artificial intelligent methods. The conventional methods, such as fractional open-circuit voltage, fractional short-circuit current, perturb and observe (P&O) and incremental conductance (Inc Cond) are easy implemented but provide lower performance. On the other hand, Artificial Intelligent methods, such as fuzzy logic and neural network give better performance, but their structures are more sophisticated and require hardware processor with relatively high performance features. These algorithms are implemented on digital processor and becomes applicable to control DC-DC power switching converters [1],[5].

This paper is organized as follow; solar array basics and characteristics are reviewed in the second section. MPPT P&O algorithm is presented in the third Section. Matlab simulation is illustrated in the fourth section. FPGA overview is presented in the fifth Section. FPGA hardware implementation is introduced in the sixth Section. The experimental results are illustrated in the seventh Section. Finally, conclusions are drawn in last Section.

II. SOLAR ARRAY (SA) BASICS AND CHARACTERISTICS

PV Cell is a device of a semiconductor junction represents the smallest and basic photovoltaic element that converts incident radiation to a potential across the cell, with usable electrical power. One of solar cell fundamental characteristics is the energy conversion efficiency (η). Its value depends mainly on the cell material type and cell temperature[2].

A combination of a solar cells that joint in either series and/or parallel forms a PV module, consequently a series or/and parallel joint combination of a PV modules comprise a PV array. The mathematical model of Photovoltaic array may be given as shown in Eq. 1, and Eq. 2, is more adequate and applicable in practical applications [4].

$$I = N_p[I_{ph} - I_{o1}\left(e^{\frac{q\left(\frac{V}{N_S}+\frac{I}{N_p}R_S\right)}{KT}} - 1\right) - I_{o2}\left(e^{\frac{q\left(\frac{V}{N_S}+\frac{I}{N_p}R_S\right)}{nKT}} - 1\right) - \frac{\frac{V}{N_S}+\frac{I}{N_p}}{R_p}\ ] \quad (1)$$

$$I = N_p[I_{ph} - I_o\left(e^{\frac{q\left(\frac{V}{N_S}+\frac{I}{N_p}R_S\right)}{nKT}} - 1\right) - \frac{\frac{V}{N_S}+\frac{I}{N_p}}{R_p}\ ] \quad (2)$$

where; I , V, I_{ph}, I_o, R_S , R_p, N_s, N_p, q, k and T are respectively represents the PV output-current that is proportional to temperature, the PV output-voltage, the photocurrent that is proportional to light intensity, the reverse saturation current of the array, the equivalent value of series-resistance, the equivalent value of parallel-resistance, the series-attached cells number, the parallel-attached cells number, electron charge ($1.6 \times 10{-}19C$), Boltzmann's constant ($1.38 \times 10{-}23\ J/K$), junction temperature in kelvin [4],[6].

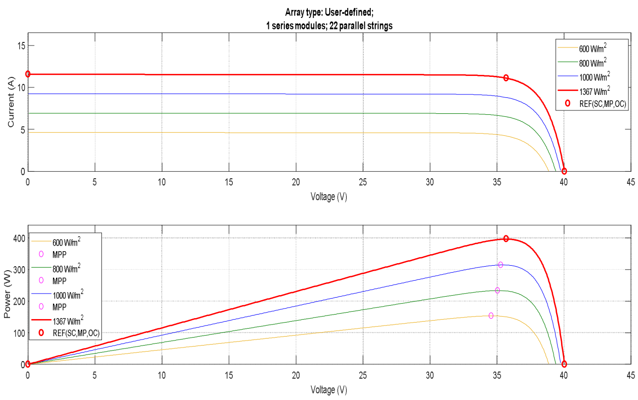

Fig. 1. PV array (I_V) and (P_V) characteristic curves at variable solar insolation and constant temperature 28deg C

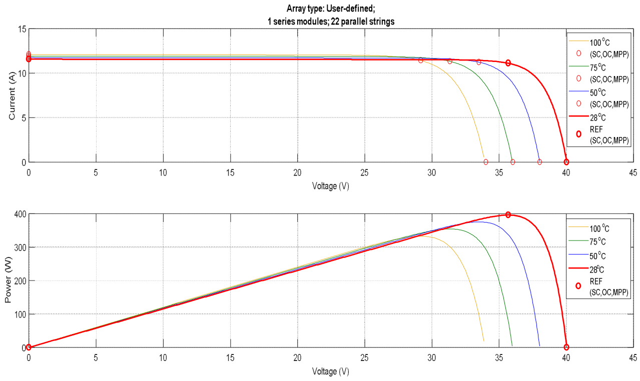

Fig. 2. PV array *I_V* and *P_V* characteristic curves at variable temperature and constant solar insolation 1367 w/m^2.

Generally, PV array characteristic *I-V* curve exhibits nonlinear relation at the output of solar PV array which obviously appears between voltage and current under a specific ambient conditions. As drawn in Fig. 1, and Fig. 2, maximum power for PV array is realized at only particular one point which require certain algorithm to track this optimal nominated point [2],[3],[4].

III. PERTURB AND OBSERVE (P&O) MPPT ALGORITHM

MPPT system is a power conversion system composed of pulse width modulated dc-dc converter controlled by certain MPPT algorithm to excavate the maximum power independently of solar insolation and temperature and connected in series between load and PV array. MPPT controller algorithms may be on-line (direct) or off-line (indirect). Perturb and observe algorithm is on-line technique as it based on actual and continuous reading of current and voltage delivered from the PV array[5][7][10].

For P&O technique implementation there are two common approaches are used. Firstly, reference voltage control which depend on using a voltage as a perturbation variable, in this type a proportional–integral controller (PI) is usually utilized to adjust the delivered duty cycle to MPPT switching mode power converter. Secondly, direct duty cycle ratio control, no need for PI controller, a perturbation variable is a duty cycle[10], [11],[12],[13].

The tracking principle of P&O algorithm established upon measuring PV outputs (current and voltage) and consequently power calculation is performed, then, PV panel is perturbed and three probable cases can appear, if (*dp/dv>0*), the location of the operating point lies on the left part of MPP of the P-V curve. Hence, PV panel next perturbation is to increase the voltage, else if (*dp/dv<0*), the location of the operating point lies on the right part of MPP of the P-V curve. Hence, PV panel next perturbation is to decrease the voltage till reaching MPP which is fulfilled at (*dp/dv=0*) As shown in Fig. 3. [6], [7], [8].

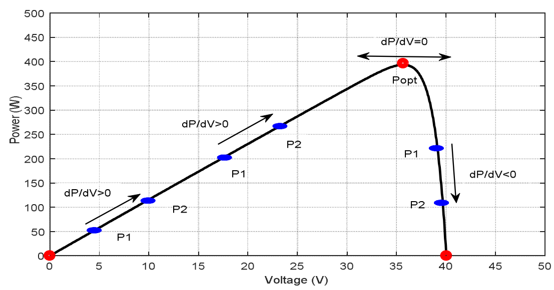

Fig. 3. : P&O MPP tracking Algorithm Concept

Several advantages of P&O approach can be summarized into simplicity, PV panel independent, exhibits acceptable performance at quietly solar insolation variation, periodic tuning does not required, and finally, easily implemented in both analog and digital platforms. But, this approach has the disadvantages of low efficiency at low solar insolation or sudden solar insolation variation, low tracking speed that makes the process relatively slow.

Two main factors that mainly affect the P&O tracking performance which are tracking time and steady state oscillations that basically count on the step-size of the perturbation variable. Small step-size value causes low response with lower steady state oscillation but the step-size increase leads to the opposite.

Therefore enhanced variable step-size P&O algorithm is proposed to eliminate these drawbacks and also operates with high switching frequency to increase the perturbation rate. So, duty ratio will be designated as a function of PV power as mentioned in Eq. 3. [13], [24].

$$\Delta D = M[P(t) - P(t-1)\ ] \tag{3}$$

Where; *M*, is a constant value that control the step-size value and to determine MPPT convergence accuracy, *P(t)* and *P(t-1)*, are the power at certain time and previous time respectively.

IV. MATLAB SIMULATION RESULTS

The model of MATLAB/Simulink concerned with the proposed system is composed of four blocks as exhibited in Fig. 4, first block represents input solar insolation and temperature that affect the PV array, second block is the PV array which is modeled using solar cell of type AZUR space solar power (TJ Solar Cell 3G30C) and constructed from 22 parallel string and 15 series-connected module per string with open-circuit voltage V_{oc}, (40.035V), Short-circuit current I_{sc}, (11.55A), Max-power voltage V_{mpp}, (35.689V) and Max-power current I_{mpp}, (11.11A) , third block is the SA MPPT controller which includes both the buck converter and the enhanced proposed P&O algorithm where, a buck converter is connected in series between PV and load and controlled by P&O algorithm controller that deliver duty cycle to the MOSFET of buck. the last block is the load[14], [15].

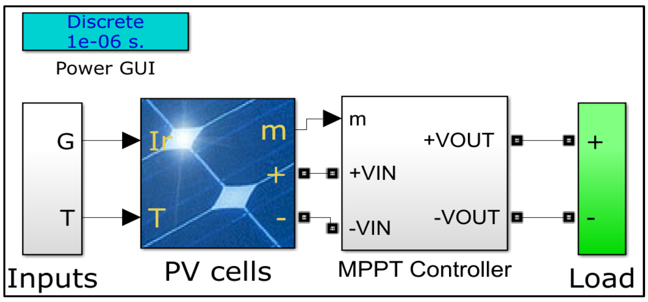

Fig. 4. Blocks of standalone PV with buck converter controlled by P&O MPPT algorithm

Fig. 5, presents that the designed high frequency buck converter has the parameters $L = 220\ \mu H$, $C_{in} = 2000\mu F$, $C_{out} = 2200\ \mu F$, $F_{sw} = 100\ kHz$, n-channel Power MOSFET (IRFP260N), schottky diode (EN220A) and $R_L = 15\Omega$ [15][16][17][18].

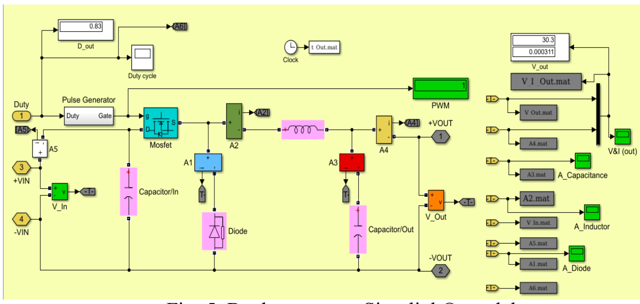

Fig. 5. Buck converter Simulink® model

Fig. 6,7,8; illustrate the difference of duty cycle behavior and output voltage behavior when using conventional and Modified P&O algorithm with different step-size ($\Delta D = 0.001$, 0.01, 0.1) at different switching frequencies (100 Hz & 10 KHz) to track the MPP. Using small step-size lead to decrease the steady state oscillations but long time is required to reach MPP, moreover, it slackens the response to the change of solar insolation or temperature. Increasing the switching frequency is an approach can be used to resolve the slow response [10], [11], [12], [13].

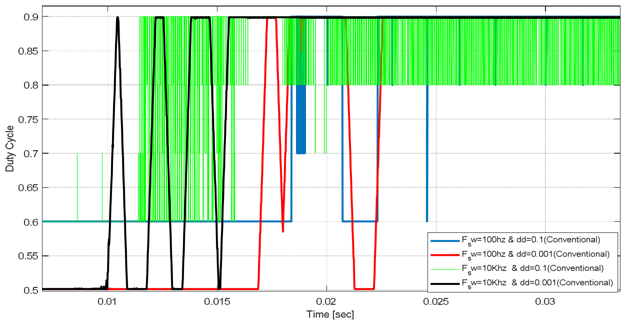

Fig. 6.Duty cycle behavior under different step-size and different frequencies when applying conventional P&O algorithm

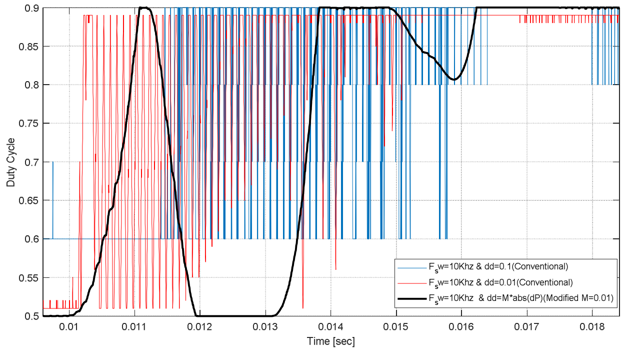

Fig. 7.Duty cycle behavior under different step-size at 10 KHz when applying conventional and Modified P&O algorithm

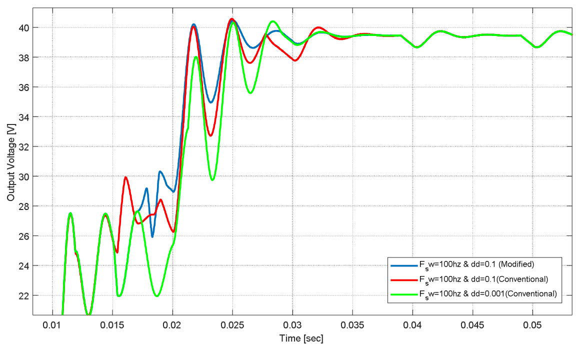

Fig. 8.Output voltage behavior to reach MPP under different step-size at 100Hz when applying conventional/Modified P&O algorithm

Fig.9; Iintroduces a comparison between the behavior of Conventional P&O and Modified P&O in tracking MPP under rapid change of solar insolation when applying 100Hz switching frequency (F_sw). And it is clear that the Modified algorithm has fast response to avoid the deviation due to sudden change and to reach steady state oscillation[10][11][12][13].

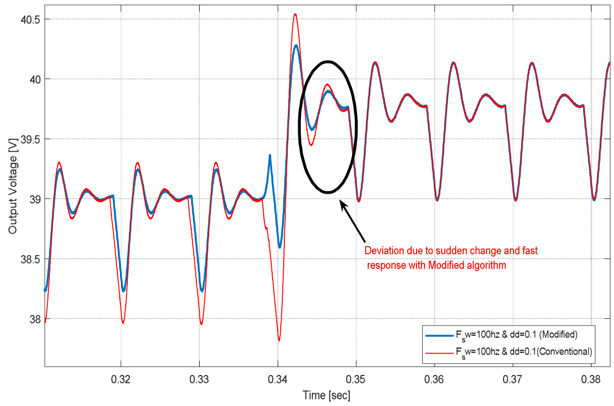

Fig. 9.MPPT using Conventional and Modified P&O under sudden variation of solar insolation from 800w/m^2 to 1367 w/m^2 at (F_sw =100HZ)

Fig.10, shows that the Modified algorithm with switching frequency (1KHz) has faster response than Modified algorithm with switching frequency (100Hz) because of increasing the rate of perturbation [10][11][12][13].

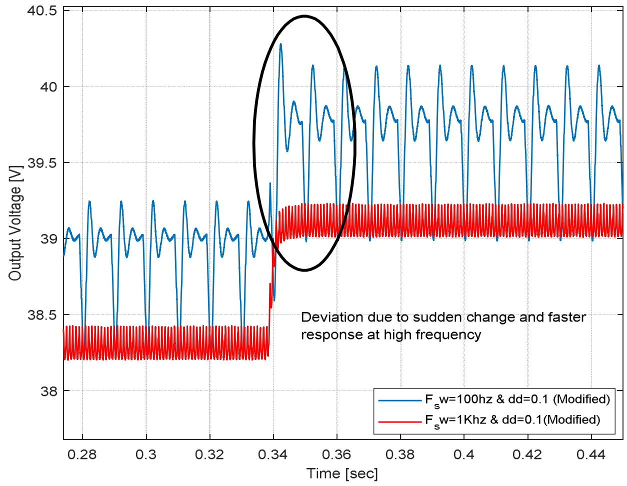

Fig. 10.MPPT using Modified P&O under sudden variation of solar insolation from 800w/m^2 to 1367 w/m^2 at (F_sw =100 HZ, 1 KHz)

V. HARDWARE IMPLEMENTATION

In the present paper, FPGA based design and realization of the SA MPPT-controller employing modified P&O technique shall be presented. FPGA submit flexibility in design with high performance in time which is close to application-specific integrated circuits (ASIC). Moreover the advantage of high performance implementation of complicated algorithms with low cost, concurrency and effective real time implementation, and high speed reconfigurable hardware. In the present work, the Xilinx "Spartan-3A/3AN FPGA Starter Kit" is used. The general block diagram of the implemented SA MPPT-controller using modified P&O algorithm is presented in Fig. 11 [22], [23].

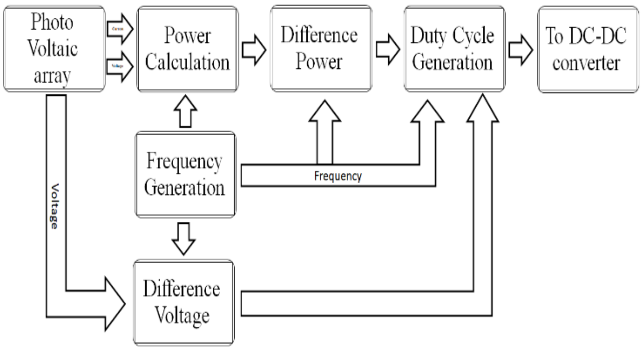

Fig. 11. General Block diagram of the SA MPPT-controller.

The main modules that form the schematic diagram of the proposed SA MPPT-controller based on P&O algorithms is presented in fig.12. It consists of four main modules; photovoltaic array module, frequency generation module, P&O SA MPPT controller module, and duty cycle generation module. These modules are designed by writing a VHDL code by using the Xilinx package ISE 14.7, and simulated by using the ModelSim 10.5 simulator. The input to the SA MPPT controller module either from the photovoltaic module which contain saved data from the matlab model or from real SA in which the analog data is converted through ADC [25],[26],[27].

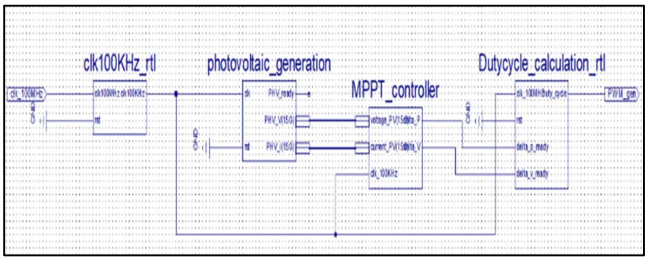

Fig. 12. Schematic diagram of the SA MPPT controller.

Frequency generation module is utilized to produce the operating frequency (switching frequency) or the clock cycle with a certain width for the MOSFET of the DC-DC converter. This module converts the clock cycle of the crystal oscillator that is located in the used FPGA kit of 50 MHz to 100 KHz (20 ns to 10 us) [28],[29].

Photovoltaic array module is used to generate the photovoltaic voltage and photovoltaic current of the photovoltaic array which are generated using a Matlab program and stored in a ROM inside the FPGA kit in order to test the implemented design using a real values of photovoltaic voltage and the photovoltaic current.

SA MPPT-controller based on P&O algorithm module is utilized to detect and track the MPP of the generated photovoltaic voltage and current. The photovoltaic array module output is delivered to the SA MPPT-controller module. The SA MPPT-controller module based on P&O algorithm consists of six sub-modules; power calculation sub-module, D- Flip Flop sub-module, Power Difference sub-module, Voltage Difference sub-module, Power Comparator sub-module, and Voltage Comparator sub-module. Fig. 13, shows the schematic diagram of the implemented P&O SA MPPT-controller module.

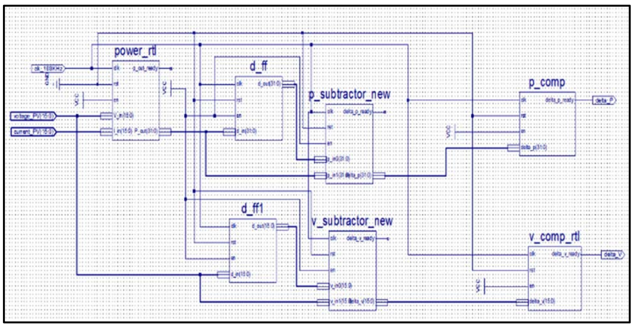

Fig. 13. Schematic diagram of the P&O MPPT-controller module.

Firstly, the power generated from the photovoltaic is calculated by multiplying the PV voltage by the PV current. Then the calculated power will be directed to the Power Difference sub-module and the measured generated PV voltage will be directed to the Voltage Difference sub-module.

The Power Difference sub-module and Voltage Difference sub-module are designed to calculate the difference between the present and previous power values or voltage values respectively that are generated from photovoltaic array module. Finally, the compared power values of the Power Comparator sub-module, and the compared voltage values of the voltage Comparator sub-module are used together to control the duty cycle width, which controls the operation of the controlled switch (MOSFET) of DC-DC converter that control the output voltage value.

The D- Flip Flop sub-module has two function in the proposed design; firstly, it is used to delay the present value of the power value in order to take a decision of MPPT according to the comparison between the power difference and the voltage difference values of the same photovoltaic voltage and current. In case of absence of D-flip flop sub-module comparison between the power and the voltage values will be performed between the present voltage values and the previous power value, due to the delay that occurs inside the power calculation sub-module. Finally, storing the present value of the power and the voltage values to calculate the difference between the previous and present values of the power and voltage.

The Duty Cycle Generation module is used to generate the Pulse Width Modulation (PWM) duty cycle ratio, which is utilized to control the output voltage from the DC-DC converter. The main component in this module is the N-bit counter component, which is used to calculate the exact width for the generated duty cycle. Also N-bit register that containing the input data and comparator for comparing register output with data input. Simulation results for Duty cycle generation module according to the MPPT algorithm shall be discussed in the next section [27],[29],[30].

VI. EXPERIMENTAL RESULTS

Model-Sim simulation results are clarified in Fig.14 through Fig. 16. Model-Sim is a tool that integrates with Xilinx ISE to provide simulation and testing. Simulation is used to make sure that the logic of a design is correct and make sure that the design will behave as expected when it is downloaded onto the FPGA. Fig.14 shows the simulation results for constant Duty cycle generation module.

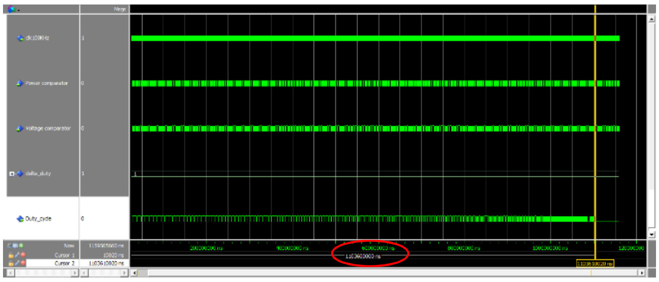

Fig. 14. Model-Sim simulation results for Duty cycle generation module using constant ΔD = 0.001.

Fig. 14, presents the generation of constant duty cycle that is used to track the maximum power point of the photovoltaic array module when using a constant delta duty cycle value (ΔD = 0.001). The SA MPPT-controller takes about 1.1036 seconds, and it looks like oscillating between "0" and "1"; this due to the value of the power oscillate around the maximum point with used constant ΔD. To reduce the tracking time of the maximum power point for the output power from photovoltaic array module when the constant delta duty cycle value (ΔD) is increased to be 0.01 instead of 0.001. Fig.15 shows the simulation results for constant Duty cycle generation module.

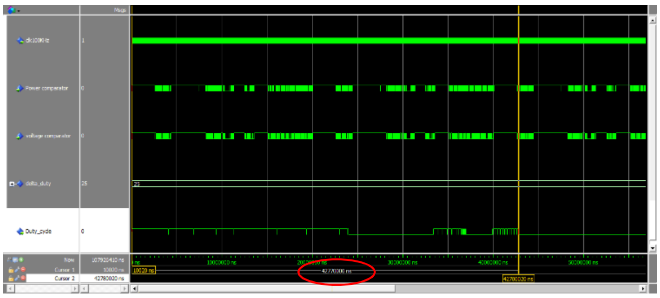

Fig. 15. Model-Sim simulation results for Duty cycle generation module using constant ΔD = 0.01.

As shown in Fig. 15, The SA MPPT-controller takes about 0.4277 seconds (less than previous time), due to using larger value of constant ΔD that reduces the elapsed time required to track the maximum power point; but also, it looks like oscillating between "0" and "1"; this due to the large value of the power oscillation around the maximum point which decrease the tracking accuracy.

To manage this problem a variable step-size perturbation algorithm is proposed. A modification should be implemented in the duty cycle module in order to obtain variable step-size values of duty cycle as mentioned before. Fig.16 shows the simulation results for variable Duty cycle generation module.

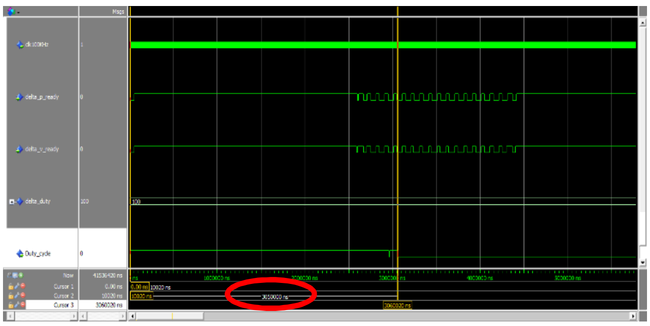

Fig. 16. Model-Sim simulation results for Duty cycle generation module using variable ΔD.

As shown Fig. 16, the modified SA MPPT-controller takes about 0.00305 seconds (less than constant ΔD) to reach the maximum power point, and decrease the steady-state oscillations (increase accuracy). the time required for tracking the maximum power point is decreased, due to the value of the duty cycle ΔD begins with large values at the starting of tracking algorithm and becomes very small at the convergence of the maximum power point MPP that leads to decrease the steady-state oscillations (accuracy is increased).

VII. CONCLUSIONS

In this paper, a direct duty cycle control P&O algorithm is designed, simulated and implemented using an FPGA for PV MPP real time tracking. The drawbacks of this technique is resolved by using enhanced and modified variable step-size perturbation P&O MPPT-controller with parameter ΔD_{var} and high switching frequency that increase the rate of perturbation, consequently, slow response to reach MPP and deviation due to sudden solar insolation change is eliminated. Moreover, small oscillation around MPP is realized which increase the accuracy. FPGA implementation provide fast processing which is considered a physical approach to improve the time response. Finally, the proposed Modified SA MPPT-ontroller algorithm and FPGA hardware implementation improves the performance of the PV system in both dynamic and steady state conditions.

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