Modified Variable-step Incremental Conductance Maximum Power Point Tracking Technique for Photovoltaic Systems

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***Abstract*—Among various photovoltaic (PV) maximum power point tracking (MPPT) techniques, variable-step incremental conductance (Inc.Cond.) method is widely employed with the merits of high tracking accuracy and fast convergence speed. Yet, mathematical division computations are mandatory for the algorithm's structure which in turn adds more complexity to its implementation. Moreover, conventional variable step, depending on the change of the array power with respect to the array voltage, encounters steady-state oscillations and dynamic problems especially under sudden irradiance changes. This paper proposes a modified variable-step Inc.Cond. MPPT technique featuring division-free algorithm, simplified implementation, and enhanced transient performance with minimal steady-state power oscillations around the MPP. Simulation and experimental results are presented for concept realization and performance evaluation**.

Keywords—PV array; MPPT; incremental-conductance algorithm; variable step-size.

I. INTRODUCTION

The economic and industrial development in addition to the interest in environmental issues have greatly increased the need of new and clean renewable energy sources in order to reduce the utilization of the natural resources of fuel and improve energy efficiency and power quality issues. Among the renewable energy sources that have been studied, photovoltaic (PV) energy is promising with minimal environmental impact [1]. They have the merits of direct electrical energy conversion, utilization in rural areas, absence of noise or moving parts, low operation cost, and flexibility in size [2-3]. However, the PV modules' high production cost in addition to their low energy density and low conversion efficiency are the major obstacles to their use on a large scale [3]. Furthermore, the non-linear behavior and dependency of the PV arrays on the atmospheric temperature and irradiance level create one of the main challenges facing the PV sector's penetration to the energy market [4]. Hence, PV maximum power point tracking (MPPT) is mandatory to maximize the PV system efficiency [5]. Various techniques, presented in literature, differ in the tracking convergence speed, steady-state accuracy, dynamic performance under fast changing conditions, sensors need, ease of hardware implementation, and PV module dependency [6-9].

Presently, the most commonly used algorithms are perturb and observe (P&O) and incremental conductance (Inc.Cond.) methods. Although P&O algorithm is widely used in stand-alone systems for its simple implementation [10-13], it can easily lead to erroneous judgment and oscillation around the maximum power point (MPP) which results in power loss [14]. On the other hand, when compared to P&O method, Inc.cond. technique can accurately track the MPP, with less steady-state oscillations and faster response especially under rapidly varying environmental conditions, thus increasing the tracking efficiency [15-18]. However, Inc.Cond. is more complex in structure than P&O as it inhibits many mathematical divisions which increase the computational burden [19].

Many modifications have been introduced to conventional Inc.Cond. method in order to improve its performance and solve the tradeoff between tracking accuracy and convergence speed. Most use variable step-size that gets smaller towards the MPP [20-25]. Conventional variable step-size, automatically adjusted according to the derivative of power with respect to voltage (dP/dV) of the PV array, shows fast response at the starting of PV operation. However, the performance of the MPPT may get greatly affected due to the digression of this step size, particularly when the insolation changes quickly [26].

In this paper, a modified Inc.Cond. algorithm is proposed featuring full elimination of the division calculations thus, simplifying the algorithm structure. In addition, a variable step-size is proposed which only depends on the PV power change (ΔP), thus eliminating its division by the PV voltage change (ΔV). The proposed step-size can minimize the oscillations around the MPP and simultaneously improve the MPPT dynamics during sudden changes. This will result in a total division-free variable-step algorithm which does not only have the merits of the conventional Inc.Cond. method but also has simple implementation like the P&O algorithm. An experimental setup is implemented in order to verify the simulation results. It's concluded that the modified algorithm with the proposed variable size can minimize the steady-state oscillations around the MPP and compromise between tracking accuracy and speed as well.

II. PV SYSTEM UNDER CONSIDERATION

The considered PV system consists of a PV array, a DC-DC boost converter and a battery load as shown in fig. 1.

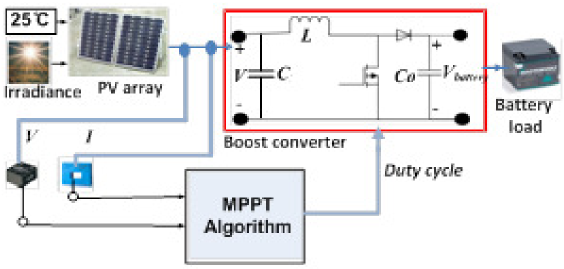


Fig. 1: PV system under consideration

A. PV Array Model

A practical PV device can be represented by a light-generated current source and a diode including internal shunt and series resistances as shown in fig. 2. A PV array is composed of several PV cells and the observation of the characteristics at its terminals results in expressing its output current by the following equation [27];

$$I = I_{pv} - I_o \left[\exp\left(\frac{V + R_s I}{V_t a} \right) - 1 \right] - \frac{V + R_s I}{R_p} \tag{1}$$

where V and I are the output PV array voltage and current respectively. I_{pv} is the photovoltaic array current which is generated by the incident light (directly proportional to the sun irradiance) and I_o is the saturation current of the array. a is the diode ideality constant and R_s, R_p are the internal series and parallel resistances of the array respectively. Finally, V_t is the thermal voltage of the array with N_s PV cells connected in series. V_t equals to $N_s\ k\ T/q$ where; q is the electron charge (1.60217646 × 10−19 C), k is Boltzmann constant (1.3806503 × 10−23 J/K), and T (in Kelvin) is the temperature of the *p–n* junction.

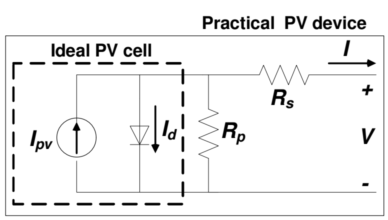


Fig. 2: PV cell single diode model

B. Boost Converter

The design of boost converter, shown in fig. 1, can be summarized as follows [28];

$$V = V_{battery}(1 - D) \tag{2}$$

$$\Delta i_L = \frac{VD}{Lf} \tag{3}$$

$$\Delta V = \frac{VD}{8\, L\, C\, f_{sw}^{\,2}} \tag{4}$$

where V is the output PV array voltage, $V_{battery}$ is the battery load voltage and D is the duty ratio of the boost chopper. Δi_L is the change in inductor current, ΔV is the change in the PV array voltage and f_{sw} is the chopper switching frequency. Finally L is the chopper inductor and C is the chopper input capacitor.

III. MPPT ALGORITHMS

Equation (1) shows that a PV array has non-linear *I-V* characteristics that depend on the irradiance level and PV cells' temperature. Fig. 3 shows the *I-V* and *P-V* curves of a PV array, at a given cell temperature and irradiance level, on which it's noticeable that the PV panel has an optimal operating point, called the maximum power point (MPP). In the region left to the MPP, the PV current is almost constant and the PV array can be approximated as a constant current (CC) source. On the other hand, right to the MPP, the PV current begins a sharp decline and the PV array can be approximated as a constant voltage (CV) source.

PV array MPP changes with different irradiance levels, as shown in fig. 4, thus continuous tracking to the MPP becomes a necessity to maximize the PV system efficiency. The latter is achieved using an MPPT algorithm which determines the appropriate duty ratio (D) that controls the switching of the DC-DC converter placed between the PV module and the load to ensure that the PV panel maximum power is extracted. A successful MPPT technique compromises between the tracking speed and steady-state accuracy and shows fast response during sudden environmental changes. According to these criteria, the Inc.Cond. algorithm can be considered as a strong candidate [15-18].

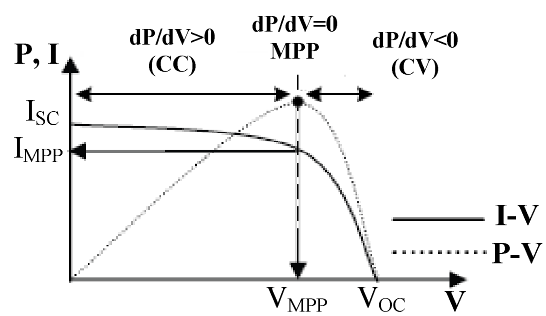


Fig. 3: PV array *I-V* and *P-V* characteristics

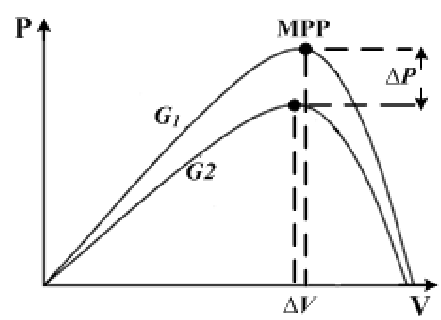


Fig.4: PV array *P-V* characteristics under two different irradiance levels

A. Conventional Inc.Cond. Algorithm

The Inc. Cond. technique is based on the slope of the array *P-V* curve [8] where;

$$\frac{dP}{dV} = 0 \quad \text{at MPP} \quad (5)$$

$$\frac{dP}{dV} > 0 \quad \text{left to MPP} \quad (6)$$

$$\frac{dP}{dV} < 0 \quad \text{right to MPP} \quad (7)$$

Since

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \quad (8)$$

Then,

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V} \quad \text{at MPP} \quad (9)$$

$$\frac{\Delta I}{\Delta V} > \frac{-I}{V} \quad \text{left to MPP} \quad (10)$$

$$\frac{\Delta I}{\Delta V} < \frac{-I}{V} \quad \text{right to MPP} \quad (11)$$

The MPP can thus be tracked by comparing the instantaneous conductance (*I/V*) to the incremental conductance (Δ*I*/Δ*V*) and accordingly the voltage perturbation sign will be determined till reaching the MPP [7]. Conventional Inc.Cond. flowchart is shown in fig. 5. However, if the irradiance increases (decreases) i.e. the array current increases (decreases), the MPP moves to the right (left) with respect to the array voltage. To compensate for this movement, the MPPT must increase (decrease) the array's operating voltage.

When compared to other simple, low cost MPPT algorithms as P&O [10], the main advantage of Inc.Cond. algorithm is that it can determine the accurate direction to reach the MPP thus decreasing the steady state oscillations especially under rapidly changing conditions [14-18]. However, regarding the algorithm structure, conventional Inc.Cond. includes a number of division calculations and a relatively complex decision making process which in turn raises the need of a more powerful microcontroller, decreasing the possibility of achieving a low cost system solution [19].

B. Proposed Inc Cond. Algorithm

A modification, to the conventional Inc.Cond. technique, is presented in order to eliminate all the division computations in the algorithm thus simplifying its structure. Using (9) - (11), the following modifications can be implemented:

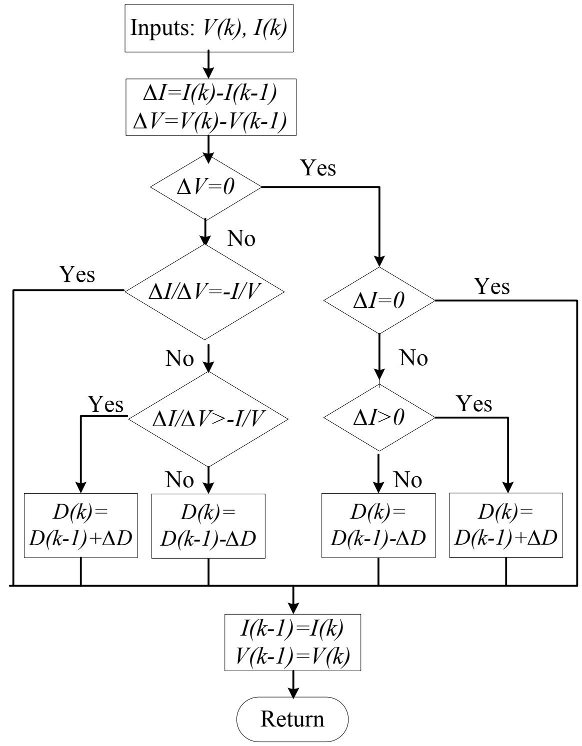


Fig. 5: Flowchart of conventional Inc.Cond. algorithm

$$\frac{\Delta I}{\Delta V} + \frac{I}{V} = 0 \quad \text{at MPP} \quad (12)$$

$$\frac{\Delta I}{\Delta V} + \frac{I}{V} > 0 \quad \text{left to MPP} \quad (13)$$

$$\frac{\Delta I}{\Delta V} + \frac{I}{V} < 0 \quad \text{right to MPP} \quad (14)$$

Unifying the denominators in (12) - (14):

$$\frac{V(\Delta I) + I(\Delta V)}{V(\Delta V)} = 0 \quad \text{at MPP} \quad (15)$$

$$\frac{V(\Delta I) + I(\Delta V)}{V(\Delta V)} > 0 \quad \text{left to MPP} \quad (16)$$

$$\frac{V(\Delta I) + I(\Delta V)}{V(\Delta V)} < 0 \quad \text{right to MPP} \quad (17)$$

In (15) the denominator can be eliminated as it is equalized to zero whereas in (16) and (17), *V* can be eliminated from the denominator as it is always positive and its sign won't affect the equations. Thus, (15) – (17) can be simplified as:

$$V(\Delta I) + I(\Delta V) = 0 \quad \text{at MPP} \quad (18)$$

$$\frac{V(\Delta I) + I(\Delta V)}{\Delta V} > 0 \quad \text{left to MPP} \quad (19)$$

$$\frac{V(\Delta I) + I(\Delta V)}{\Delta V} < 0 \quad \text{right to MPP} \quad (20)$$

Finally, in order to eliminate the division calculations, the Inc.Cond. algorithm rules can be rewritten as follows:

$$V(\Delta I) + I(\Delta V) = 0 \quad \text{at MPP} \tag{21}$$

$$(V(\Delta I) + I(\Delta V) > 0)\ \&\&\ (\Delta V > 0) \quad \text{left to MPP} \tag{22}$$

$$(V(\Delta I) + I(\Delta V) > 0)\ \&\&\ (\Delta V < 0) \quad \text{right to MPP} \tag{23}$$

$$(V(\Delta I) + I(\Delta V) < 0)\ \&\&\ (\Delta V > 0) \quad \text{right to MPP} \tag{24}$$

$$(V(\Delta I) + I(\Delta V) < 0)\ \&\&\ (\Delta V < 0) \quad \text{left to MPP} \tag{25}$$

The flowchart of the proposed algorithm is given in fig. 6. The removal of all the complicated division computations in the algorithm, minimizes its structure complexity which, in turn, reduces the processing real-time and furthermore enables the algorithm to be implemented by low cost microcontrollers.

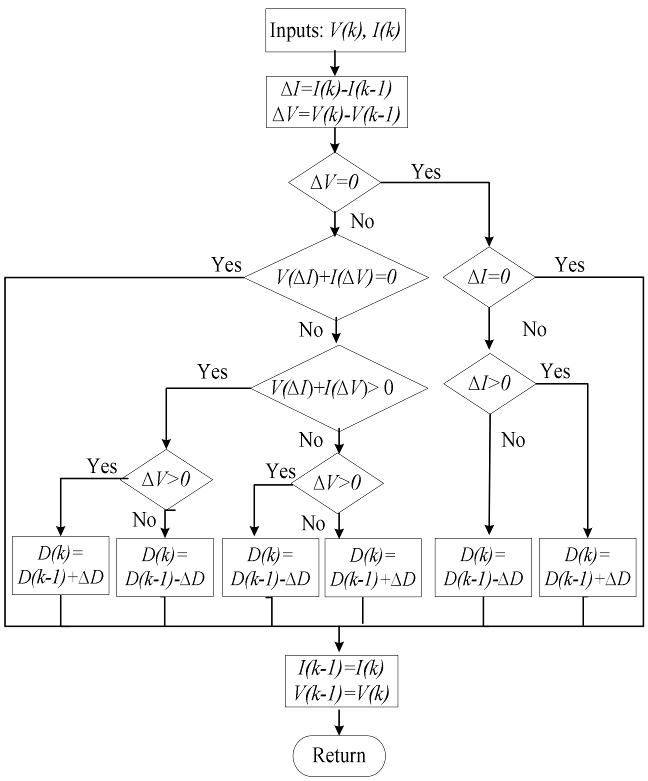


Fig. 6: Flowchart of the proposed modified Inc.Cond. algorithm

IV. VARIABLE STEP-SIZE CONTROL

For a fixed-step Inc.Cond. algorithm, a smaller step-size slows down the MPPT while a larger one would increase the steady-state oscillations around the MPP. A solution to this conflicting situation is to have a variable step-size that gets smaller towards the MPP in order to balance the competing aims of tracking speed and accuracy.

A. Conventional Variable Step-Size

The conventional variable step-size (ΔD) depends on the PV power change divided by the PV voltage change ($\Delta P/\Delta V$) [21] where;

$$\Delta D = N_1 \left| \frac{\Delta P}{\Delta V} \right| \tag{26}$$

where;

$$\Delta P = P(k) - P(k-1) \tag{27}$$

$$\Delta V = V(k) - V(k-1) \tag{28}$$

$$\Delta D = D(k) - D(k-1) \tag{29}$$

and N_1 is the scaling factor which is tuned at the design stage to adjust the conventional step-size to compromise between the tracking accuracy and its convergence speed.

Although this step-size can show fast response at the starting of PV operation, it can exhibit dynamic problems during sudden irradiance changes. Furthermore, steady-state power oscillations noticeably arise around the MPP. This can be explained in the following subsections;

1. During stable environmental conditions

Because of unavoidable factors as measurement error, ripples and noise, the condition that $\Delta I/\Delta V$ and - I/V to be exactly equal would never be satisfied. Thus, the operating point won't settle exactly at the MPP. Instead, it oscillates around the MPP, changing the sign of the increment after each ΔP measurement [15, 18]. It's clear, from fig. 3, that in the regions close to the MPP and right to it (constant voltage region), the change in PV voltage (ΔV) is too small resulting in large $\Delta P/\Delta V$ steps. Although, these large step-sizes increase tracking speed at start of PV operation, they can increase the steady-state power oscillations affecting the PV system accuracy which in turn decreases the algorithm efficiency.

2. During varying irradiance conditions

The conventional variable step may show low transient performance during sudden irradiance changes. As shown in fig. 4, when the irradiance changes from G_1 to G_2, there is a considerable power change (ΔP) while the PV voltage change (ΔV) is relatively too small. Since the step-size depends on $\Delta P/\Delta V$, this will result in a large change in the converter duty ratio (D) thus shifting the operating point far away from the new MPP. Noticeable transient decrease in the PV power occurs and the algorithm takes longer time to reach the new MPP. Consequently, the transient power loss will increase, decreasing the tracking efficiency.

B. Proposed Variable Step-Size

The proposed variable step-size, which depends only on the PV power change (ΔP), is presented as follows;

$$\Delta D = N_2 \left| \Delta P \right| \tag{30}$$

where N_2 is the scaling factor which is tuned at the design stage to adjust the proposed step-size to compromise between the tracking accuracy and its convergence speed.

It's observable, from the array *P-V* curve, that the change in PV power (ΔP) is small around the MPP and large away from it. Thus, the step-size, which depends on ΔP, will be large away from the MPP and decreases around the MPP to compromise between the steady-state power oscillations and the tracking speed. Unlike the conventional variable step which depends on two rippled parameters (ΔP and ΔV) and their division, the proposed variable step depends only on ΔP. Removing the division by ΔV, from the step-size, adds more simplification to the algorithm and eliminates large step-size variations that occur at small PV voltage changes. Although this may slow down the tracking process at the starting of operation, it minimizes the steady-state oscillations around the MPP thus improving the tracking accuracy and efficiency. Furthermore, this reduces the shift of the operating point away from the MPP during sudden irradiance changes which results in better transient performance with fast dynamic response and less transient power loss.

For further explanation, an illustrative example is shown in fig.7. When the irradiance decreases from G_1 to G_2, the operating point shifts from **'A'** to **'B'**, resulting in a considerable ΔP due to PV current change (ΔI) while ΔV is almost zero. In order to reach the new MPP **'M',** the MPPT algorithm must decrement *D*. Hence, the algorithm performance is affected by the variable step adopted to achieve this decrement.

- For ΔP / ΔV dependent step, the almost zero ΔV will result in a large step-size that vastly decrements *D* and shifts the operation to point **'C'**. Hence, a noticeable transient power loss occurs and the algorithm takes long time to reach the new MPP '**M'**.
- For proposed ΔP based step, the large step-size is avoided and *D* is decremented to shift the operating point to **'D'** which is close to the MPP '**M'**. This will fasten the tracking process and reduce transient power loss.

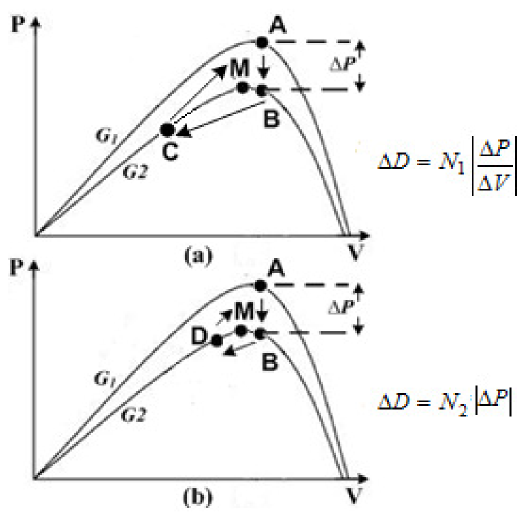


Fig. 7: MPPT algorithm performance, under irradiance change, when adopting (a) $\Delta P/\Delta V$ based variable step, (b)proposed ΔP based variable step

V. SIMULATION AND EXPERIMENTAL RESULTS

Simulation work has been carried out and an experimental setup has been implemented for the system shown in fig. 1 in order to check the validity and feasibility of the proposed modified Inc.Cond. technique and the proposed variable step-size. A KD135SX_UPU solar array is used, datasheet is shown in Table I. Moreover, the DC-DC boost converter parameters are given as follows:

- Input capacitance (C): 1000 μF
- Chopper inductance (L): 2.3 mH
- Switching frequency (f_{sw}): 15 kHz

TABLE I. KD135SX_UPU ARRAY SPECIFICATIONS AT 25°C, 1000 W/M²

Nominal Short Circuit Current (I_{SCn})	8.37	***A***
Nominal Open Circuit Voltage (V_{OCn})	22.1	***V***
Maximum Power Current (I_{MPP})	7.63	***A***
Maximum Power Voltage (V_{MPP})	17.7	***V***
Maximum Output Power (P_{max})	135	***W***
Current /Temp. Coefficient (K_i)	5.02e^{-3}	***A/°K***
Voltage/Temp. Coefficient (K_v)	-8e^{-2}	***V/°K***
Series Cells	36	----

A. *Simulation Results*

Simulation work has first compared the effect of the conventional variable step-size ($\Delta P/\Delta V$ dependent) with that of the proposed variable step-size (ΔP dependent), on the performance of the conventional Inc.Cond. algorithm, under two step changes in irradiance levels (from 1000W/m^2 to 400W/m^2 at 0.2 sec then from 400W/m^2 to 700W/m^2 at 0.4 sec as shown in fig. 8. Figures 8.a-c show transient and steady state performance at 1000 W/m^2, 400 W/m^2 and 700 W/m^2 respectively. MPP tracking time, undershoot and steady-state power oscillations are determined at each irradiance level as shown in Table II. It's observable, that the elimination of the division by ΔV in the proposed step-size has limited the large increase in the step thus minimizing the steady-state oscillations around the MPP on the penalty of slower tracking speed at the starting of PV operation. However, during sudden irradiance changes, the proposed step gives better transient performance as shown in figures 8.b, 8.c. Considering Table II, the tracking time decreased by 56.25% at the first step change and by 44% at the second step change. Furthermore, the proposed step succeeded in reducing the power undershoot by almost 17.75% of the PV power at 1000 W/m^2, 35% at 400 W/m^2 and 71.5% at 700 W/m^2. Simulation results show that the proposed variable step outweighs the conventional one from the steady-state and transient performance points of view.

The proposed modified Inc.Cond. algorithm adopting the proposed variable step-size is simulated and compared with the conventional algorithm employing the same step-size. Figures 9. a-c show the transient and steady-state performance of the former at 1000 W/m^2, 400 W/m^2 and 700 W/m^2 respectively. From figures 8 and 9 and Table II, it's noticed that the performance of the proposed technique with the proposed variable-step is almost similar to that of the conventional Inc.Cond. algorithm applying the same variable step, but at extremely simpler implementation (division free).

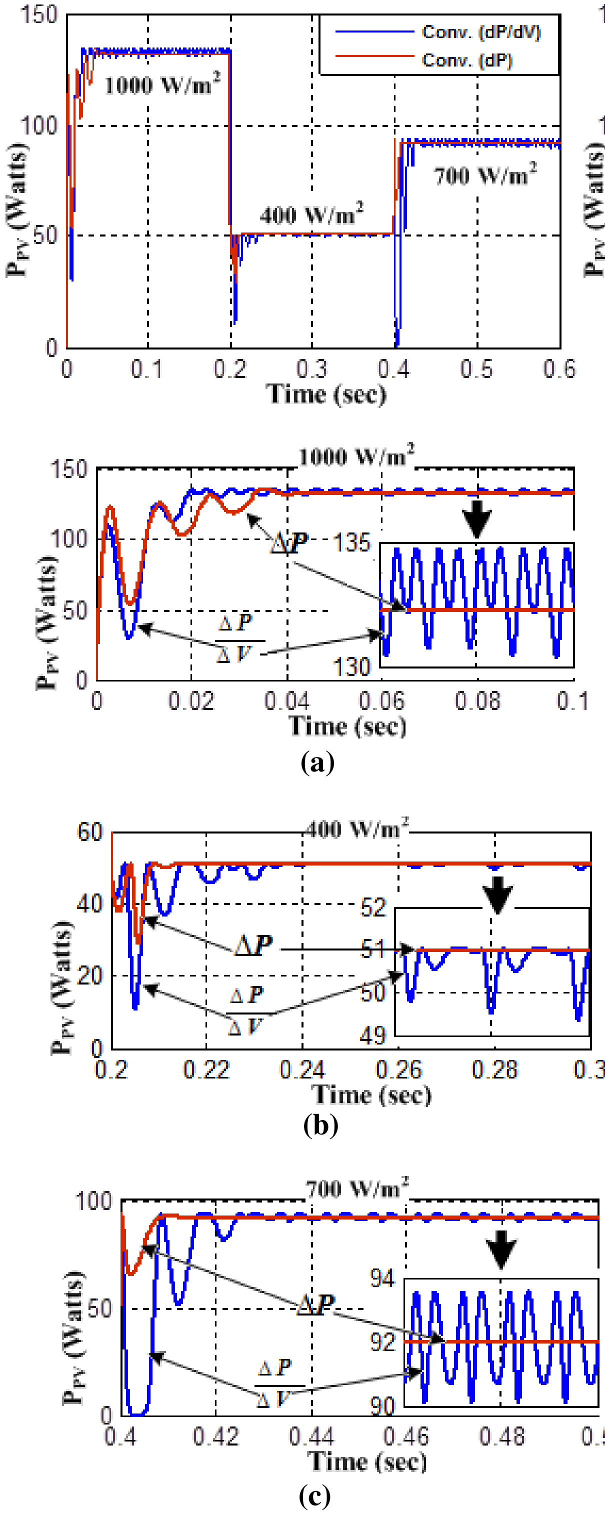


Fig. 8: Simulation results for transient and steady-state performance of conventional Inc. Cond. method adopting $\Delta P/\Delta V$ versus ΔP dependent variable steps under step irradiance changes (a) 1000 W/m^2, (b) 400 W/m^2, (c) 700 W/m^2

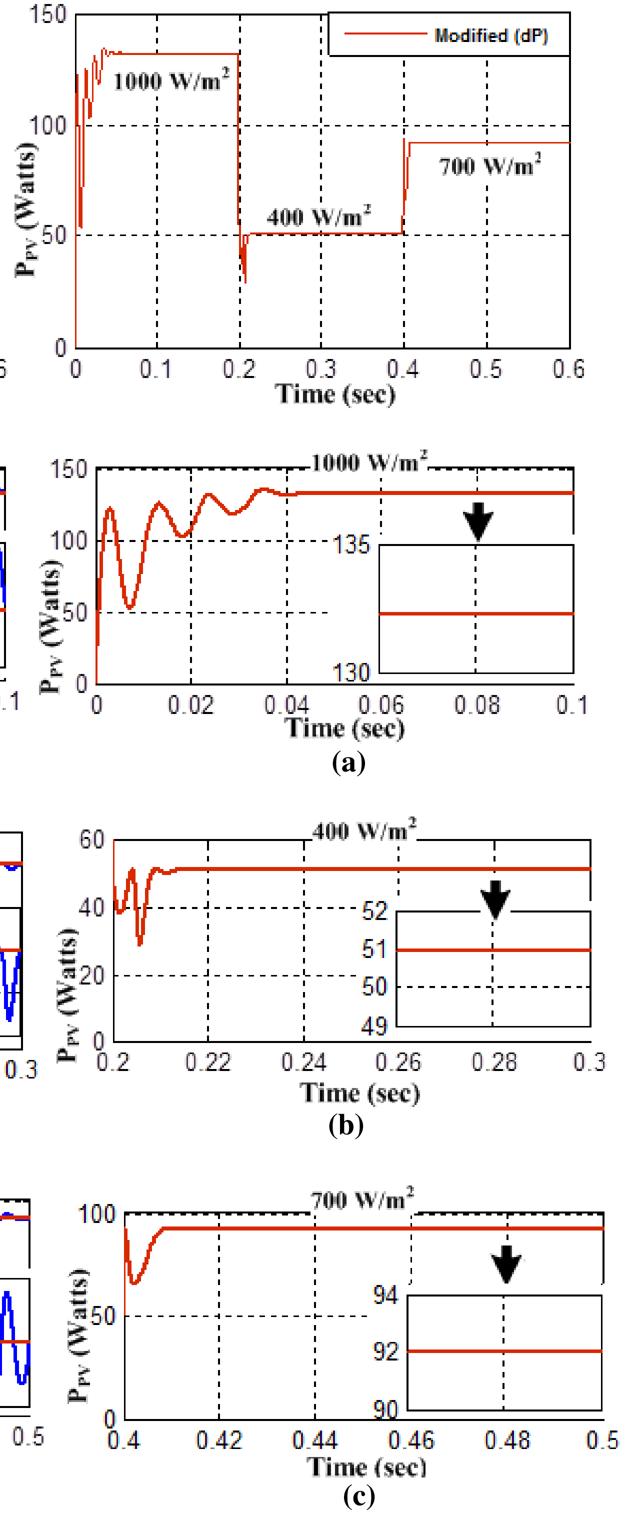
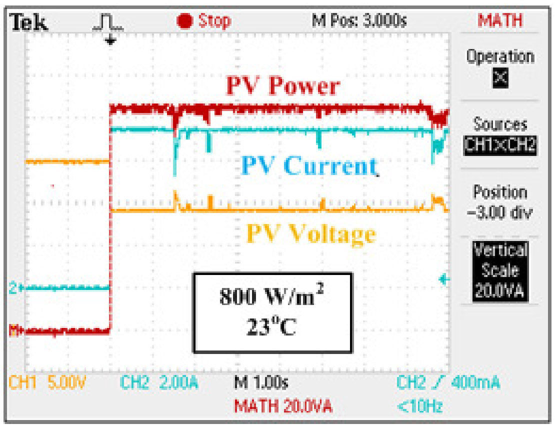


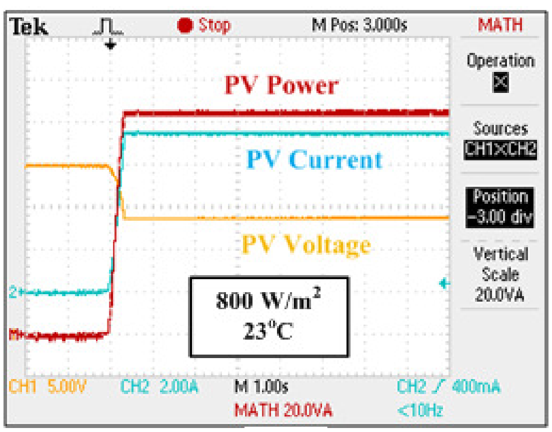
Fig. 9: Simulation results for transient and steady-state performance of the proposed modified Inc.Cond. method adopting the proposed ΔP dependent variable step under step irradiance changes (a) 1000 W/m^2, (b) 400 W/m^2, (c) 700 W/m^2

B. *Experimental Results*

An experimental setup, demonstrating the presented system, has been established in order to compare between the considered two step-sizes and between the conventional Inc.Cond. algorithm and its proposed modified alternative. Figures 10.a and 10.b show the transient and steady-state performance of the conventional and the proposed variable step-sizes respectively when applied by the conventional Inc.Cond. technique. It's shown that the proposed step-size minimizes the oscillation around the MPP, thus maximizing the tracking accuracy though it slows down the tracking process at the operation start. Then, the proposed modified Inc. Cond. algorithm, when adopting the proposed variable-step, is tested. Fig. 11 shows that the latter has the same efficient performance of the conventional Inc.Cond. algorithm, adopting the same step-size, yet with much simpler realization.



(a)



(b)

Fig. 10: Experimental results for transient and steady-state performance of conventional Inc. Cond. method adopting; (a) $\Delta P/\Delta V$ based variable step, (b) Proposed ΔP based variable step

VI. CONCLUSION

A modified variable-step Inc.Cond. MPPT technique has been proposed in this paper. The presented technique featured division-free algorithm, hence simplifying the structure implementation. In addition, the proposed associated variable step, being solely dependent on the array power change, showed minimal steady-state power oscillations around the MPP in addition to improved transient performance under sudden irradiance changes. Simulation and experimental results validate the effectiveness of the proposed variable-step simplified technique.

TABLE II. ANALYSIS OF SIMULATION RESULTS REGARDING TRANSIENT AND STEADY-STATE PERFORMANCE PARAMETERS

Irradiance (W/m^2)	**Variable-step MPPT method**	**Transient**		**Steady-state**
		Undershoot	***Settling Time (s)***	***oscillations at MPP (W)***
1000 W/m^2	Conv. ($\Delta P/\Delta V$)	77.6%	0.02	4.24
	Conv. (ΔP)	59.85%	0.045	0.012
	Modif. (ΔP)	59.85%	0.045	0.012
400 W/m^2	Conv. ($\Delta P/\Delta V$)	78.6%	0.032	1.65
	Conv. (ΔP)	43.7%	0.014	0.0025
	Modif. (ΔP)	43.7%	0.014	0.0025
700 W/m^2	Conv. ($\Delta P/\Delta V$)	100%	0.025	3.45
	Conv. (ΔP)	28.5%	0.014	0.022
	Modif. (ΔP)	28.5%	0.014	0.022

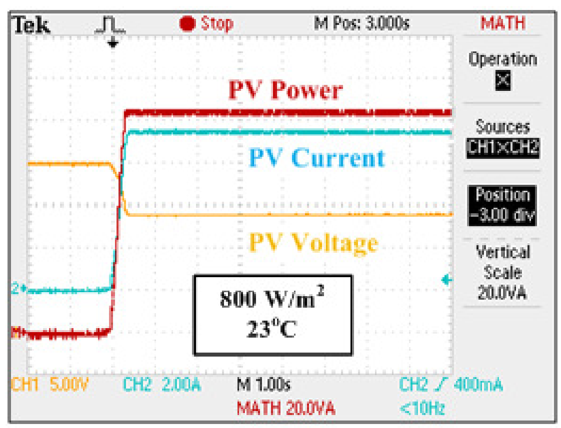


Fig. 11: Experimental results for transient and steady-state performance of the proposed modified Inc. Cond. method adopting proposed ΔP based variable step

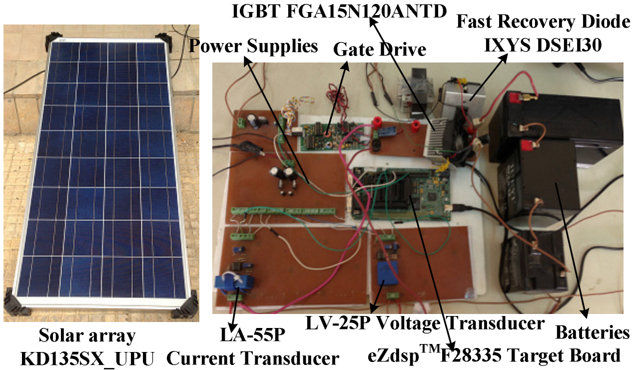


Fig. 12: Test rig photograph

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