Improved performance low-cost incremental conductance PV MPPT technique

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Nahla E. Zakzouk¹, Mohamed A. Elsaharty¹, Ahmed K. Abdelsalam¹ [⊠], Ahmed A. Helal¹, Barry W. Williams²

¹Electrical and Control Engineering Department, Arab Academy for Science and Technology (AAST), Alexandria, Egypt ²Electronics and Electrical Engineering Department, Strathclyde University, Glasgow, UK are E-mail: kadry_2012@yahoo.com

Abstract: Variable-step incremental conductance (Inc.Cond.) technique, for photovoltaic (PV) maximum power point tracking, has merits of good tracking accuracy and fast convergence speed. Yet, it lacks simplicity in its implementation due to the mathematical division computations involved in its algorithm structure. Furthermore, the conventional variable step-size, based on the division of the PV module power change by the PV voltage change, encounters steady-state power oscillations and dynamic problems especially under sudden environmental changes. In this study, an enhancement is introduced to Inc.Cond. algorithm in order to entirely eliminate the division calculations involved in its structure. Hence, algorithm implementation complexity is minimised enabling the utilisation of low-cost microcontrollers to cut down system cost. Moreover, the required real processing time is reduced, thus sampling rate can be improved to fasten system response during sudden changes. Regarding the applied step-size, a modified variable-step size, which depends solely on PV power, is proposed. The latter achieves enhanced transient performance with minimal steady-state power oscillations around the MPP even under partial shading. For proposed technique's validation, simulation work is carried out and an experimental set up is implemented in which ARDUINO Uno board, based on low-cost Atmega328 microcontroller, is employed.

1 Introduction

The modern industrial society, population growth, and the interest in the environmental issues have greatly increased the need of new and clean renewable energy sources [1]. Among the latter, photovoltaic (PV) solar energy has become nowadays a real promising renewable/ alternate energy source due to its several advantages such as; absence of noise or mechanical moving parts, low operation cost, no emission of CO2 or other harmful gases, flexibility in size, and its convenience with stand-alone systems in addition to grid-connected ones where they can be installed close to load centres, saving transmission lines losses [2, 3]. Although PV energy has recently received considerable attention, high installation cost and low conversion efficiency of PV systems set a difficulty against its use on a large scale [4]. Furthermore, the non-linear behaviour and dependency of PV panels on the atmospheric temperature and irradiance level create one of the main challenges facing the PV sector's penetration to the energy market [5]. To minimise these drawbacks, PV operation at the maximum power point is a necessity which in turn maximises the PV system efficiency. Various maximum power point tracking (MPPT) techniques have been presented in literature [6-9]. They differ in the tracking accuracy, convergence speed, dynamic response under sudden environmental changes, required sensors, hardware implementation, and dependency on PV module parameters.

The most commonly used MPPT algorithms are perturb and observe (P&O) and incremental conductance (Inc.Cond.) methods [10]. P&O algorithm is widely used in PV stand-alone systems for its simple implementation [11–14]. In these PV systems, MPPT algorithms are preferably realised using low cost microcontrollers in order to cut down the entire system cost. Thus, the P&O, being an arithmetic-division-free algorithm, is a convenient choice to be implemented by these controllers. On the other hand, Inc.Cond. is more complex in structure than P&O as it inhibits many mathematical divisions which increase the computational burden

[15]. However, regarding these techniques performance, P&O can easily lead to erroneous judgment and oscillation around the maximum power point (MPP) which results in power loss [16]. Hence, Inc.Cond. technique is a better candidate especially during rapidly varying environmental conditions. This is because, when compared with P&O method, Inc.Cond. can accurately track the MPP, with less steady-state oscillations and faster response during changes thus increasing the tracking efficiency [17–21].

In addition, many modifications have been introduced to fixed step-size used in the Inc.Cond. method to change it to a variable one that gets smaller towards the MPP [22–28]. The latter improves the technique performance and solves the trade-off between tracking accuracy and convergence speed. However, conventional variable step-size, automatically adjusted according to the PV power change with respect to PV voltage change (ΔP / ΔV), can affect the MPPT performance due to the digression of this step size, particularly under sudden changes [29, 30].

This paper aims at combining the advantages of simple algorithm structure with high system performance during transients in one MPPT technique. Hence, 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 minimise power oscillations around the MPP and effectively improve the MPPT dynamics during sudden changes. This will result in a total division-free variable-step technique which does not only have the merits of enhanced steady-state and transient performance but also has simple algorithm implementation. This reduces the processing real-time, enabling the algorithm to be implemented by low-cost microcontrollers which in turn reduces system costs.

This paper is organised in eight sections. Following the introduction, the investigated PV system is presented. The following two sections explain the conventional and the proposed

Inc.Cond. techniques regarding their algorithm structure and the applied variable step-size. The simulation and experimental results, which verify the superiority of the proposed technique over the conventional one, are illustrated in the fifth and sixth sections, respectively. An assessment is performed for the proposed MPPT technique under partial shading conditions in the seventh section. Finally, a conclusion is presented in the eighth section.

2 PV system under investigation

The considered PV system consists of a PV module, a DC–DC boost converter and a battery load as shown in Fig. 1*a*.

2.1 PV mathematical model

A practical PV device can be represented by a light-generated current source and a diode altogether with internal shunt and series

resistances as shown in Fig. 1*b*. A PV module 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 [31]

$$I = I_{\rm pv} - I_o \left[\exp\left(\frac{V + R_{\rm s}I}{V_{\rm t}a}\right) - 1 \right] - \frac{V + R_{\rm s}I}{R_{\rm p}} \tag{1}$$

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



Fig. 1 PV system under consideration

a Schematic diagram

b PV cell single diode model

c I-V and P-V characteristics at given conditions, I-V and P-V curves of KD135SX_UPU PV module

d Under three irradiance levels at 25°C and

e For three different cell temperatures at irradiance of 1000 W/m^2



Fig. 2 Inc. Cond. algorithm flowchart (a) conventional

2.2 Boost converter

The design of boost converter, shown in Fig. 1, can be summarised as follows [32]

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

$$\Delta i_L = \frac{VD}{Lf_{\rm sw}} \tag{3}$$

where V is the PV output voltage, V_{battery} is the battery load voltage and D is the duty ratio determined by the applied MPPT algorithm to directly control the boost chopper switching. Δi_L is the change in inductor current, L is the chopper inductor and f_{sw} is the chopper switching frequency.

2.3 MPPT

Equation (1) shows that a PV module has non-linear I-V characteristics that depend on the irradiance level and PV cells' temperature. Fig. 1*c* shows the I-V and P-V curves of a PV module, at a given cell temperature and irradiance level, on which it's notable that the PV panel has an optimal operating point, the MPP. In the region left to the MPP, the PV current is almost constant and the PV module can be approximated as a constant current source. On the other hand, right to the MPP, the PV current begins a sharp decline and the PV module can be approximated as a constant voltage (CV) source. The PV module characteristic curves vary with the changing irradiance level and cell temperature [5], as shown in Figs. 1*d* and *e*. The PV module short-circuit current is linearly dependent on the irradiance level



unlike the open-circuit voltage which almost independent of it. On the other hand, PV cell temperature significantly affects the open-circuit voltage value whereas it has a negligible effect on the short circuit current value.

As the PV module characteristic curve shifts with changing irradiance or cell temperature, the MPP moves. Hence, continuous tracking to the MPP becomes mandatory to maximise 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. technique can be considered as an appropriate candidate [17–21].

3 Conventional variable-step Inc.Cond. technique

The structure of the conventional variable-step Inc.Cond. technique can be illustrated in the following two sections;

3.1 Conventional Inc.Cond. algorithm

Inc.Cond. technique is based on the slope of the PV module P-V curve [6] where

$$\frac{\mathrm{d}P}{\mathrm{d}V} = 0 \quad \text{at MPP} \tag{4}$$



Fig. 3 Effect of irradiance change on MPP

a Peak PV power shift, MPPT performance adopting

b Conventional $\Delta P / \Delta V$ based variable step

c Proposed ΔP based variable step

$$\frac{\mathrm{d}P}{\mathrm{d}V} > 0 \quad \text{left to MPP} \tag{5}$$

$$\frac{\mathrm{d}P}{\mathrm{d}V} < 0 \quad \text{right to MPP} \tag{6}$$

Since

$$\frac{\mathrm{d}P}{\mathrm{d}V} = \frac{\mathrm{d}(IV)}{\mathrm{d}V} = I + V \frac{\mathrm{d}I}{\mathrm{d}V} \cong I + V \frac{\Delta I}{\Delta V} \tag{7}$$

Then

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V} \quad \text{at MPP} \tag{8}$$

$$\frac{\Delta I}{\Delta V} > \frac{-I}{V} \quad \text{left to MPP} \tag{9}$$

$$\frac{\Delta I}{\Delta V} < \frac{-I}{V} \quad \text{right to MPP} \tag{10}$$

The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the Inc.Cond. $(\Delta I/\Delta V)$ and accordingly the voltage perturbation sign is determined till reaching the MPP [7]. The flowchart of the conventional Inc.Cond. algorithm is shown in Fig. 2*a*. If the irradiance increases (decreases), that is, PV current increases (decreases), the MPP moves to the right (left) with respect to PV voltage. To compensate for this movement, the MPPT must increase (decrease) the PV module's operating voltage.

When compared with other simple, low cost MPPT algorithms as P&O [12], 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 and improving system response under rapidly changing conditions [16–21]. However, regarding the algorithm structure, conventional Inc.Cond. algorithm includes a number of division calculations and a relatively complex decision making process which in turn raises the need of a more powerful microcontroller featuring higher clock frequency, larger memory and floating-point calculation capability, decreasing the possibility of achieving a low cost system solution [15].



For a fixed-step Inc.Cond. algorithm, a smaller step-size slows down the MPPT while a larger one increases 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 convergence speed and tracking accuracy. The conventional variable step-size depends on the PV power change divided by the PV voltage change ($\Delta P/\Delta V$) [23]. For a direct control scheme which directly controls the converter switching without external control loops, the considered step is the change in the converter duty ratio (ΔD) as shown in (11).

$$\Delta D(\text{conv.}) = N_1 \left| \frac{\Delta P}{\Delta V} \right| \tag{11}$$

where

$$\Delta P = P(k) - P(k-1) \tag{12}$$

$$\Delta V = V(k) - V(k-1) \tag{13}$$

$$\Delta D = D(k) - D(k-1) \tag{14}$$

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

4 Proposed variable-step Inc.Cond. technique

An enhancement is introduced in the structure of the conventional Inc.Cond. algorithm to eliminate all its division computations and simplify its implementation. Moreover, the conventional variable step is modified to improve its performance. The proposed step size is used by the proposed division-free Inc.Cond. algorithm to directly control the converter switching.

4.1 Proposed division-free Inc.Cond. algorithm

A modification is introduced to the Inc.Cond. algorithm in order to eliminate all the division computations in the algorithm. Using (8)–(10), the following modifications can be implemented



Fig. 4 Simulation results of the conventional Inc.Cond. method adopting the conventional $\Delta P / \Delta V$ based variable step under varying irradiance

a Overall PV power with zoom at

- b Start-up
- *c* First step change

d Second step change



Fig. 5 Simulation results of the modified Inc.Cond. method adopting the proposed ΔP based variable step under varying irradiance

a Overall PV power with zoom at

b Start-up

c First step change

d Second step change

Table 1 Simulation performance indicators of the conventional and proposed techniques under two step changes in irradiance

Condition	Variable-step MPPT method	Transient		Steady-state	
		Undershoot, % P _{PV}	Settling time, s	Oscillations at MPP, W	MPPT efficiency, %ζ
start-up	Conv. $(\Delta P / \Delta V)$	84.96	0.024	4.25	98.7
from 1000 W/m ² to 400 W/m ²	Conv. ($\Delta P / \Delta V$)	66.63	0.04	1.5	98.7 98.6
from 400 W/m ² to 700 W/m ²	Proposed (Δ <i>P</i>) Conv. (Δ <i>P/</i> Δ <i>V</i>) Proposed (Δ <i>P</i>)	43.67 89.35 28.5	0.014 0.022 0.01	0.0025 3.5 0.022	99.94 98.3% 98.4

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

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

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

Unifying the denominators in (15)–(17) to $V(\Delta V)$, this denominator can be eliminated from the first equation as it is equalised to zero whereas only V is eliminated from the denominator of the other two equations as it is always positive and its sign won't affect these equations. Thus, manipulating (18)–(20) results in

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

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

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

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

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

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

- $(V \bullet \Delta I) + (I \bullet \Delta V) > 0$ && $\Delta V < 0$ right to MPP (23)
 - $(V \bullet \Delta I) + (I \bullet \Delta V) \langle 0 \&\& \Delta V \rangle 0$ right to MPP (24)

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

The flowchart of the proposed algorithm is given in Fig. 2b where

the removal of all the division computations in the algorithm is compensated by applying arithmetic/logic mathematical operations. Thus, algorithm structure complexity is minimised which in turn reduces processing real-time and enables the algorithm to be implemented by low cost microcontrollers.

4.2 Proposed variable step-size

The conventional step-size presented in (11), being dependant on the change of the PV power with respect to PV voltage change, exhibits dynamic performance deterioration during sudden irradiance changes. Furthermore, steady-state power oscillations notably arise around the MPP. This can be explained as follows.

4.2.1 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 would not settle exactly at the MPP. Instead, it oscillates around the MPP, changing the sign of the increment after each ΔP measurement [19, 20]. It is clear, from Fig. 3*a*, that in the regions close to the MPP and right to it (CV region), the change in PV voltage (ΔV) is too small resulting in large $\Delta P/\Delta V$ steps. Although, these large step-sizes increase the tracking speed at start of PV operation, they can enlarge the steady-state power oscillations affecting the PV system accuracy which in turn decreases the algorithm efficiency.

4.2.2 During varying irradiance conditions: The conventional variable step may show poor transient performance during sudden irradiance changes. As shown in Fig. 3*a*, 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 converter duty ratio change (ΔD) thus shifting the operating point far away from the new MPP. Notable transient decrease in



Fig. 6 Power tracking nature on module P-V curves for a Conventional technique adopting $\Delta P/\Delta V$ step b Proposed division-free technique with ΔP step



Fig. 7 Simulation results of the conventional Inc.Cond. method adopting $\Delta P/\Delta V$ based variable step under varying temperature

- a Overall PV power with zoom at
- b Start-up
- c First step change

d Second step change

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.

To overcome the latter, this paper proposes a variable step-size which depends only on the PV power change (ΔP). The proposed step size is used by the MPPT algorithm to directly control the converter switching, thus it represent the change in the converter duty ratio as shown in (26)



Fig. 8 Simulation results of the proposed l Inc.Cond. method adopting ΔP based variable step under varying temperature

a Overall PV power with zoom at

b Start-up

c First step change

d Second step change

$$\Delta D(\text{prop.}) = N_2 |\Delta P| \tag{26}$$

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.

Table 2 Simulation performance indicators of the conventional and proposed techniques under two step changes in temperature

Condition	Variable-step MPPT method	Transient		Steady-state	
		Undershoot, % P _{PV}	Settling time, s	Oscillations at MPP, W	MPPT efficiency, %ζ
Start-up	Conv. $(\Delta P / \Delta V)$	85.4	0.025	4.4	98.7
From 25 °C to 40 °C	Conv. $(\Delta P/\Delta V)$	100	0.045	0.013	98.7 99.68
	Proposed (<i>AP</i>)	2.94	0.0075	0.003	99.94
From 40 °C to 15 °C	Conv. $(\Delta P / \Delta V)$	28.74	0.03	2	99.45
	Proposed (<i>AP</i>)	4.87	0.019	0.005	99.83

It is observable, from the PV module 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 minimises 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. 3b and c. 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. To reach the new MPP 'M', the MPPT algorithm must decrement the duty ratio *D*. Hence, the algorithm performance is affected by the variable step adopted to achieve this decrement.

For the conventional 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 notable transient power loss occurs and the algorithm takes long time to reach the new MPP 'M'.
For the 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.

5 Simulation work

Simulation work has been carried out to compare the steady-state and transient performance of the conventional Inc.Cond. technique applying the conventional $\Delta P/\Delta V$ dependent variable step-size with



Fig. 9 Experimental results

a Conventional technique execution time adopting $\Delta P / \Delta V$ step

b Proposed technique execution time adopting ΔP step

c Conventional technique performance adopting $\Delta P / \Delta V$ step

d Proposed division-free technique performance with ΔP step, using KD135X-UPU panel under steady-state conditions (800 W/m² and 23 °C) a 50 µs/div, b 50 µs/div, c 1 s/div, ch1: 5 V/div, ch2: 2 A/div, chM: 20 VA/div, d 1 s/div, ch2: 2 A/div, chM: 20 VA/div



Fig. 10 Experimental setup

a Low cost PV emulator schematic diagram

b P-V, I-V characteristic curves of PV simulating circuit for two different values of R_s c Test-rig photography

that of the proposed division-free Inc.Cond. method adopting the proposed ΔP based variable step-size. This is performed under two step changes in irradiance levels (from 1000 to 400 W/m² at 0.2 s then from 400 to 700 W/m² at 0.4 s.), at 25 °C. A KD135SX_UPU PV module is utilised with specifications given in Appendix. Moreover, the applied DC–DC boost converter parameters are given as follows:

Chopper inductance (*L*): 2.3 mH, Switching frequency (f_{sw}): 15 kHz and $V_{battery} = 3 \times 12$ V

Figs. 4 and 5 show the performance of the conventional technique and that of the proposed one respectively during the considered step changes in irradiance while Table 1 gives their steady-state and transient performance parameters. It can be concluded that; under varying irradiance conditions, both techniques can successfully track the PV maximum power yet with different levels of tracking accuracy, speed and transient undershoot.

Figs. 4*a*–*d* show transient and steady state performance of the conventional method at start-up, first and second irradiance step changes respectively. The latter is repeated for the proposed technique as shown in Figs. 5*a*–*d*. It is observable, that the elimination of the division by ΔV in the proposed step-size has limited the large increase in the step thus minimising the steady-state oscillations around the MPP on the penalty of slower tracking speed at the beginning of PV system operation. However, during sudden irradiance changes, the proposed variable step gives better transient performance and faster response.

Considering Table 1, the MPP tracking time, acquired by the proposed technique, is reduced by 33.3% and by 54.55% of that achieved by the conventional technique at the first and the second step changes respectively. Furthermore, the proposed step succeeded in reducing the power undershoot by almost 24.8%,

23% and 60.85% of the maximum tracked PV power at 1000 W/m², 400 W/m² and 700 W/m² respectively. Finally, the minimal steady-state power oscillations, encountered by the proposed technique, enhance its MPPT efficiency when compared with that of the conventional technique. Tracking efficiency can be defined as the percentage ratio of the tracked PV power by the considered MPPT algorithm at certain environmental conditions to the peak PV power under same conditions.

The 3D Figs. 6a and b illustrate PV power, tracked by the conventional and the proposed techniques respectively, against PV voltage and time. These figures give more clarification on both techniques' tracking performance on the P-V curves of the PV module during the considered step changes in irradiance. It is clear that the proposed technique exerts less steady-state power oscillations around the MPP of each P-V curve relative to each irradiance level. Furthermore, it shows faster response during irradiance changes with less power undershoot.

For further verification of the superiority of the proposed technique under changes, both techniques are retested at fixed irradiance of 1000 W/m^2 under two step changes in temperature (from 25 °C to 40 °C at 0.2 s then from 40 °C to 15 °C at 0.4 s.)

Figs. 7 and 8 show the performance of the conventional technique and that of the proposed one respectively during the considered step changes in temperature while Table 2 gives their steady-state and transient performance parameters. It can be concluded that; under varying temperature conditions, both techniques can successfully track the PV maximum power yet with different levels of tracking accuracy, speed and transient undershoot.

Figs. 7*a*–*d* show transient and steady state performance of the conventional method at start-up, first and second temperature step changes respectively. The latter is repeated for the proposed



Fig. 11 Step change experimental results, using a PV emulator, at $T_{sampling} = 450 \,\mu s$ for

- *a* Conventional technique adopting $\Delta P / \Delta V$ step, *b* Proposed division-free technique adopting ΔP step
- c Zoom of Fig. 11a
- d Zoom of Fig. 11b, Step change experimental results, using a PV emulator, at $T_{\text{sampling}} = 350 \,\mu\text{s}$ for e Proposed division-free technique adopting $\Delta \! P$ step
- f Zoom of Fig. 11e

technique as shown in Figs. 8a-d. It is observable, that the elimination of the division by ΔV in the proposed step-size has limited the large increase in the step thus minimising the steady-state oscillations around the MPP on the penalty of slower tracking speed at the beginning of PV system operation. However, during sudden temperature changes, the proposed step gives better transient performance and faster response.

Considering Table 2, the MPP tracking time, acquired by the proposed technique, is reduced by 81.25% and by 36.67% of that achieved by the conventional technique at the first and the second step changes respectively. Furthermore, the proposed step succeeded in reducing the power undershoot by almost 25.4%, 97% and 23.87% of the maximum tracked PV power at 25 °C, 40 °C and 15 °C respectively. Finally, the minimal steady-state

power oscillations, encountered by the proposed technique, enhance its MPPT efficiency when compared with that of the conventional technique.

Hence, simulation results show that the proposed technique's steady-state and transient performances outweigh those of the conventional one, owing to its applied ΔP -based variable step-size, yet with simpler implementation due the entire division calculations elimination from its algorithm structure. This is done under sudden irradiance changes as well as under sudden temperature changes which in turn verifies the effectiveness and superiority of the proposed variable-step Inc.Cond. technique under different environmental changes.

6 Experimental work

The merit of division elimination, from the Inc.Cond. algorithm, mainly lies in simplifying its structure and enhancing its performance when being implemented by low cost microcontrollers. To clarify the latter, an experimental rig employing ARDUINO Uno board, based on low cost Atmega328 16-bit microcontroller, is set and tested.

The conventional Inc.Cond. technique, featuring several division computations and applying the $\Delta P / \Delta V$ step-size, as well as the proposed division-free IncCond. method, adopting the ΔP step-size, are both implemented using ARDUINO Uno board. The execution time for both schemes has to be measured in order to choose the most convenient sampling time. Hence, it is calculated by programming a pilot pin to toggle during program execution and triggers a digital output. Fig. 9a shows the program execution time for the conventional technique which is 400 µs while Fig. 9b shows that of the proposed technique which is 300 µs. It is clear that the elimination of the many division calculations in the proposed algorithm decreases the execution time and consequently simplifies the controller operation. However, for fair comparison, same sampling time is chosen for both techniques which is 450 µs (to exceed the larger execution time of the conventional algorithm).

A real-time comparison between the proposed Inc.Cond. technique and the conventional one is carried out to verify the superiority of the former. This is carried out during fixed and changing environmental conditions as illustrated in the following sections.

6.1 Stable environmental conditions

First, the performance of both the conventional and proposed variable-step Inc.Cond. techniques, are tested under fixed environmental conditions (800 W/m² and 23 °C). A KD135SX_UPU PV panel is employed. Fig. 9*c* shows the performance of the conventional technique employing $\Delta P / \Delta V$ -based variable step-size while Fig. 9*d* shows that of the proposed division-free technique applying ΔP -based step. The proposed step-size minimises the steady-state oscillation around the MPP, thus maximising tracking accuracy.

6.2 Sudden changing irradiance conditions

To compare the transient performance of both techniques under sudden changes, a step change should be created.

This is not practical with roof-mounted PV panels as their surrounding environmental conditions are uncontrollable. Thus, the need of PV module simulator to replace actual PV panel is mandatory. However, these simulators are expensive instruments and not always affordable. Thus, a lower-cost way of simulating I-V and P-V curves similar in nature to those generated by a PV panel is applied in [33]. This paper presents a simplified circuit which employs a variable resistance (R_s) in series with a variable voltage DC power supply and the MPPT tracker (boost converter) is connected at its output. This circuit produces a P-V curve that exhibits a peak point for the tracker to lock on. Changing the variable series resistance will result in another P-V change with a new MPP to track.

							2		
Work, publication	Power	Converter	Switching	MPPT technique	Hardware programmed platform	Accuracy-power	Tracking	Tracking	Price of
year	rating	type	trequency			oscillations	efficiency, %	speed	programmer
[27] (2014)	80 W	Buck	100 kHz	Inc.Cond.	FPGA XC3S400	2.7 W (3.4%)	98.8	2.5 ms	\$38.5
[<mark>9</mark>] (2013)	200 W	Boost	50 kHz	P&O-based on PI controller	DSP TMS320F240	20 W (10%)	95	20 ms	\$25.64
[34] (2012)	240 W	Buck-boost	50 kHz	Improved PSO	DSP TMS320F240	8 W (3.33%)	96.5	40 ms	\$25.64
[35] (2014)	800 W	Boost	I	Zero-oscillation adaptive step P&O	Microcontroller TI C2000	20 W (2.5%)	98.75	1s	\$24
[14] (2012)	1080 W	Buck	10 kHz	P&O	DSP TMS320F2812	20 W (1.85%)	97.9	0.5 s	\$23.32
[26] (2013)	1080 W	Buck	10 kHz	Inc.Cond.	DSP TMS320F2812	20 W (1.85%)	96.8	0.5 s	\$23.32
[36] (2011)	10 W	Buck	100 kHz	Load-current based MPPT	DSP TMS320F28335	0.04 W (0.4%)	97	80 ms	\$21.17
[37] (2011)	54 W	Boost	25 kHz	PI-P&O	DSP TMS320F28335	7 W (13%)	93	1 s	\$21.17
(38) (2012)	150 W	Buck	I	Fuzzy-based P&O	DSP TMS320F28335	2 W (1.3%)	98.5	1.5 s	\$21.17
[39] (2014)	210 W	Boost	I	Adaptive P&O-fuzzy MPPT	DSP TMS320F28335	1 W (0.5%)	95.2	20 ms	\$21.17
[25] (2011)	110 W	Boost	50 kHz	Inc.Cond.	Microcontroller C515C	15 W (1.4%)	96.8	0.5 s	\$19.6
[<mark>21</mark>] (2014)	40 W	DC/DC	10 kHz	TS fuzzy-based Inc.Cond.	Embedded controller	1 W (2.5%)	97.5	2 s	\$4.46
[40] (2014)	87 W	SEPIC	20 kHz	Modified Inc.Cond.	asricaatu izainlauz Microcontroller PIC 18f4520	1.5 W (1.7%)	66	0.2 s	\$4.26
28] (2015)									
[41] (2013)	250 W	flyback	40 kHz	PI-Inc.Cond.	Embedded controller dsPIC33FJ06GS202	14 W (5.6%)	97.2	5 s	\$3.95
proposed	120 W	Boost	15 kHz	Modified step-size division-free Inc.Cond.	Microcontroller Atmega328	4 W (3.33%)	98.33	40 ms	\$2.00





Fig. 12 Assessment of proposed IncCond. MPPT algorithm under partial shading

a System block diagram

b P–*V* characteristics under uniform irradiance

c PV characteristics under partial shading

d Output PV power under sudden partial shading using conventional IncCond. MPPT

e Output PV power under sudden partial shading using proposed IncCond. MPPT

Similarly, a simplified PV simulating circuit is employed, in this paper, as shown in Fig. 10*a*. This circuit simulates the PV source when exposed to sudden step change in irradiance. It consists of a DC power supply with CV of 28 V and two parallel resistances of 3.2 Ω each in order to represent R_s . When the switch S is on, the two resistances are in parallel and R_s is 1.6 Ω and this gives a *P*–*V* curve of almost 120 W peak power. When S is opened, R_s becomes 3.2 Ω and a step decrease in the current *I* occurs which results in a step decrease in the power level to about 60 W as shown in Fig. 10*b*.

Figs. 11a and b show the performances of the conventional and the proposed Inc.Cond. techniques respectively, under a step

decrease in the PV simulator power level (from 120 to 60 W). It is clear that the $\Delta P/\Delta V$ step applied in the conventional scheme exhibits more steady-state power oscillations around the MPP than those acquired by the proposed ΔP step-size employed in the modified scheme. Meanwhile, when zooming around both schemes' transient response during the step-change, as shown in Fig. 11*c* and *d*, the conventional step-size shows slower response with settling time (t_s) equals to 400 ms which is four times that of the settling time experienced by the proposed step ($t_s = 100$ ms).

Thus, at the same sampling time, the proposed technique shows better performance due to its employed ΔP -based step-size.

However, since this division-free technique exhibits less processing time (300 µs), its performance can be retested at a sampling time of 350 µs which is less than that adopted in the previous case. This improves the sampling rate which fastens system response during changes. Fig. 11e shows the proposed algorithm performance during the step decrease in power level at a sampling time of 350 µs. A zoom around this step-change is given by Fig. 11f. The settling time (t_s) of the proposed scheme, in this case, is 40 ms which is less than half that exhibited by the same scheme applying 450 µs sampling time shown in Fig. 11d.

In conclusion, experimental results verify that the proposed step-size enhances system steady-state and transient performance during changes. Meanwhile the division computations elimination reduces the program execution time enabling the user to improve the sampling rate which introduces further enhancement to the technique response during transients. The test rig for the considered system in this section is shown in Fig. 10c.

The proposed MPPT technique, implemented by Atmega328 microcontroller, is compared with several experimental prototypes presented in most recent publications, as shown in Table 3.

Obviously, when compared with low-price microcontrollers' prototypes [21, 28, 40, 41], the proposed algorithm gives faster MPPT during sudden changes. On the other hand, prototypes of faster response [9, 27, 39] employ much more expensive microcontrollers than that applied in the proposed work. Moreover, the proposed prototype experiences one of the high tracking efficiencies of more than 98%. In addition, it shows low steady-state power oscillations giving acceptable accuracy. Hence, being implemented by low-cost Atmega328 microcontroller, the proposed division-free algorithm, with the modified step-size, achieves the best compromise between MPPT dynamic response, steady-state performance and employed microcontroller cost. Consequently, its functionality is validated offering an economical efficient solution for stand-alone PV MPPT.

7 Partial shading assessment

This section investigates the performance of the proposed Inc.Cond. MPPT algorithm under partial shading operating condition. Moreover, a comparison between the conventional and modified proposed Inc.Cond. MPPT algorithms is carried in this section under partial shading conditions.

To test the modified Inc.Cond. MPPT technique, under partial shading conditions, two KD135SX_UPU PV modules are connected in series with a bypass diode connected in shunt with each module as illustrated in Fig. 12a. First, both modules operate at normal conditions (at 1000 W/m², 25 °C), then at t = 0.3 s, one module is partially shaded (working at 700 W/m).

Ideally, in the first case the total maximum PV power is 270 W, while during partial shading; maximum PV power is reduced to 200 W. When comparing the conventional and modified MPPT techniques during the previous conditions, the following performance results;

• As shown in Fig. 12d, the conventional MPPT technique shows high steady-state power oscillations with tracking efficiency of 96% and 90.5% during normal and partial shading conditions respectively. Moreover, during the change, settling time is about 0.2 s and the PV power under-shoot is almost 18.5%.

• On the other hand, in Fig. 12e, the modified MPPT technique shows faster response with settling time of 0.1 s and reduced PV power under-shoot of 6.6%. Moreover, it almost eliminates steady-state PV power oscillations showing more accurate results and higher tracked PV power. This results in much enhanced tracking efficiency of 99.7% and 94.3% during normal and partial shading conditions respectively.

Hence, the modified division-free Inc.cond. MPPT technique, adopting the proposed variable step-size, shows enhanced steady-state and transient response during partial shading conditions when compared with the conventional variable-step division-included Inc.Cond. technique.

8 Conclusion

In this paper, a low-cost variable-step MPPT technique is proposed based on Inc.Cond. algorithm. The modified algorithm features full elimination of the involved division computations, which simplifies its structure and reduces the required real processing time, thus facilitating algorithm implementation by low-cost microcontrollers in order to cut down system costs. Furthermore, the proposed associated variable step, being solely dependent on PV power change, shows minimal steady-state power oscillations around the MPP in addition to improved transient performance under sudden changes. The effectiveness of the proposed technique is verified by simulation and experimental results.

9 References

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10 Appendix

See Table 4 KD135SX_UPU module specifications AT 25 °C, 1000 W/m²

nominal short circuit current (I _{SCn})	8.37	А
nominal open circuit voltage (V _{OCn})	22.1	V
maximum power current (I _{MPP})	7.63	Α
maximum power voltage (V _{MPP})	17.7	V
maximum output power (P _{max})	135	W
current/temp. coefficient (<i>K</i> _i)	5.02e ⁻³	A/°C
voltage/temp. coefficient (K_v)	-8e ⁻²	V/°C
series cells	36	-