An Adaptive InCon MPPT Algorithm Considering Irradiance Slope Tracking for PV Application

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Abstract— **In this paper, a new adaptive InCon MPPT algorithm, considering irradiance slope tracking and zero oscillation (ZA-InCon) for PV application is presented. The convectional InCon algorithms are used to extract maximum available power from photovoltaic panels, but these algorithms oscillate around maximum power point and, since they have no conception of PV panel I-V characteristic they may confuse under rapidly changing environmental conditions. The artificial perturbation and deviation from maximum power point result in high power losses and lower implementation efficiency. The proposed ZA-InCon algorithm identifies steady state operation mode and sets operating point near the maximum power point. The environmental condition changes can be estimated from current natural perturbation and the step size is adjusted accurately for irradiance slope tracking. To validate the proposed algorithm, it is compared with conventional InCon algorithm under different environmental conditions by simulation. A boost converter is used to realize the proposed ZA-InCon algorithm.**

Keywords— ***boost converter, incremental conductance (InCon), Maximum power point tracking (MPPT), Photovoltaic (PV) cell, Renewable energy.***

I. Introduction

In recent years, due to increase in the global energy demand and the concern over environmental issues, caused by consumption of traditional energy sources like fossil fuels, renewable energy sources such as solar and wind are expanded [1-2]. PV panels are commonly used to convert solar energy to electricity. Main obstacles of these panels are the high cost of implementation and low efficiency, so the implementation methods are important to minimize these obstacles.

PV panels have nonlinear I-V characteristic, and the maximum power point varies non-linearly with solar irradiance and environment temperature. Maximum power point tracking (MPPT) algorithms are commonly used to implement PV systems efficiently. MPPT is usually implemented by the boost dc-dc converter, which is commonly used to increase the low PV panel voltage to higher level, suitable for being converted to the required AC voltage.

There are several MPPT algorithms, developed in recent years [3]. Some of them are summarized as follow:

1. Fractional open-circuit voltage (FOCC)/short-circuit current (FSCC) uses only one voltage/current sensor, so it eliminates one sensor losses. Maximum power point voltage/current is assumed to be constant and independent from environmental conditions. The accuracy of this method is not guaranteed and it is suitable for low power implementations [4].
2. A maximum power point tracking algorithm with a single voltage sensor is presented in [5-6]. In this algorithm there isn't any current sensor, so current sensor periodic losses have been removed and it is easy to implement.
3. In perturb and observe (P&O) algorithm, the voltage is increased or decreased by a fixed step size in the direction of reaching maximum power point. It reduces oscillation around maximum power point, and speeds up convergence under rapidly changing environmental conditions [7-8].
4. Incremental conductance (InCon) algorithm uses PV power slope to identify maximum power point. If the slope is zero, the PV panel is operating at maximum power point. It acts well under rapidly changing environmental conditions [9-10].
5. Fuzzy logic controllers (FLC) use fuzzy theory and usually track maximum power point by computing the change of the PV panel P-I characteristic slope [11-12].
6. Artificial neural network uses intelligent computation to track maximum power point. It has high accuracy, but increases calculation burden and implementation difficulty [13].

All aforementioned algorithms result in oscillation around maximum power point in steady state operation. Since they have no conception of PV panel I-V characteristic, they may confuse under rapidly changing environmental conditions. This causes power losses and decreases implementation efficiency.

In [14] and [15] an adaptive P&O MMPT algorithm is presented, which considers irradiance sudden change to adjust step size. However, it cannot detect steady state operation and identify irradiance changing slope, so it still suffers from oscillation around maximum power point and low efficiency.

A ZA-P&O MPPT algorithm is given in [16]. It can track irradiance slope change and detect steady state operation, so it has decreased losses, but it needs to toggle oscillations to detect steady state operation, and uses two variables to identify irradiance change slope, causing in lower efficiency.

In this paper, a new adaptive InCon MPPT algorithm (ZA-InCon) for PV panel application is proposed, which eliminates oscillations around maximum power point in steady state, decreases losses and improves tracking speed under varying environmental conditions. The steady state operation is identified by the algorithm and a new operating point near the maximum power point is set. The steady state losses are reduced by eliminating artificial perturbation. Irradiance slope estimation enables the algorithm to set an adaptive step size and track maximum power point accurately. The proposed ZA-InCon algorithm increases steady state operation efficiency by suppressing the oscillations. Also, it eliminates the confusion caused by irradiance change, and the step size is adjusted accurately for maximum power point tracking.

II. Photovoltaic System Modeling

Block diagram of the implemented system is shown in Fig.1, including PV panel, power converter and a battery bank as the load, together with a maximum power point tracking block, and a PI controller.

In this section, the PV panel model, conventional InCon MPPT algorithm, and its limitation are presented.

A. PV panel modeling

A PV cell single diode equivalent circuit is shown in Fig.2. If only R_s is considered and R_p is neglected, the mathematical equation is expressed as fallows [17]:

$$I = I_{pv} - I_o[\exp\{\frac{q(V+R_sI)}{KAT})\}-1 \quad (1)$$

Where I_{pv} is the photocurrent, I_o is diode reverse saturation current, q is electron charge, K is the Boltzmann's constant, A is diode ideality factor, T is the photovoltaic array working temperature in kelvin, R_s is the series resistance, V is PV cell terminal voltage and I is PV cell terminal current.

Photovoltaic cells in series and parallel configuration form a PV panel. Consider a PV panel has n_s cells in series and n_p cells in parallel. The mathematical equation is expressed as follows:

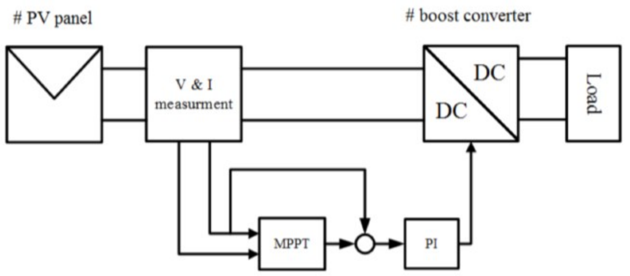

Fig. 1. Maximum power point tracking system block diagram

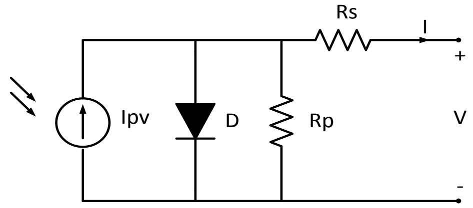

Fig.2. equivalent circuit of photovoltaic array single diode model

$$I = n_pI_{pv} - n_pI_o[\exp\{\frac{q(n_pV + n_sIR_s)}{n_sn_pKAT}\}-1] \quad (2)$$

$$I_o = I_{rs}(\frac{T_{cell}}{T_{ref}})^3 \exp[\frac{qE_G(\frac{1}{T_{ref}}-\frac{1}{T_{cell}})}{KA}] \quad (3)$$

$$I_{rs} = \frac{I_{sc}(T_{ref})}{[\exp(\frac{q*V_{oc}}{KAT_{ref}})-1]} \quad (4)$$

Photocurrent (I_{pv}) mainly depends on solar irradiation and photovoltaic array working temperature, which is given by:

$$I_{pv} = [I_{sc} + \alpha(T - T_r)]\, G \quad (5)$$

Where I_{sc} is short circuit current, α is photovoltaic array short circuit temperature coefficient, T_r is reference temperature and G is irradiance in kW/m^2.

Open circuit voltage can be calculated by putting $V=V_{oc}$ and I=0 in equation (2), yielding the following:

$$V_{oc} = (\frac{KT_{cell}A}{q})*\ln[\frac{I_{pv}}{I_o}+1] \quad (6)$$

The environment irradiance and temperature change affect the PV panel characteristics in different ways. A change in irradiance mostly affects proportionally the short circuit current, while open circuit voltage remains the same. A change in temperature affects PV panel open circuit voltage. Big environmental changes are expected from the irradiance, while temperature is changed slowly. In this study, it is focused on

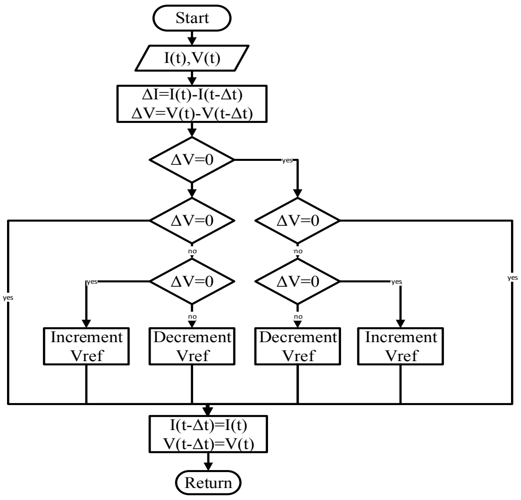

Fig. 3. Flowchart of the conventional incremental conductance algorithm

irradiance changes and temperature changes are neglected. Therefore, i_{pv} will be proportional to G:

$$I_{pv} = \gamma\, G \quad (7)$$

B. Conventional InCon algorithm

The conventional incremental conductance algorithm's flowchart is given in Fig.3. The basic rule is very simple; P-V curve slope is zero at the maximum power point. If the slope is positive, maximum power point is at the left, but if it is negative, maximum power point is at the right.

$$\begin{cases} \dfrac{dP}{dV} = 0 & \text{MPP} \\ \dfrac{dP}{dV} > 0 & \text{MPP in left} \\ \dfrac{dP}{dV} < 0 & \text{MPP in right} \end{cases} \quad (8)$$

P-V curve slope is given by:

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V\frac{dI}{dV} \approx I + V\frac{\Delta I}{\Delta V} \quad (9)$$

The maximum power point can be tracked by comparing instantaneous conductance to the incremental conductance.

$$\begin{cases} \left|\dfrac{\Delta I}{\Delta V}\right| = -\dfrac{I}{V} & \text{MPP} \\ \left|\dfrac{\Delta I}{\Delta V}\right| > -\dfrac{I}{V} & \text{MPP in left} \\ \left|\dfrac{\Delta I}{\Delta V}\right| < -\dfrac{I}{V} & \text{MPP in right} \end{cases} \quad (10)$$

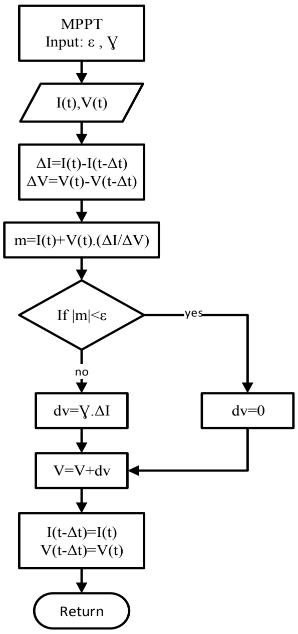

Fig. 4. Flowchart of the proposed ZA-InCon algorithm

In this algorithm, the maximum power point cannot be reach exactly, so the algorithm oscillates around the maximum power point. The step size for the incremental conductance maximum power point tracking algorithm is commonly fixed. Therefore, the power drown from PV panel with a larger step size contributes to faster dynamics but excessive steady state operation oscillations. This situation is reversed when MPPT is operating with a smaller step size. Thus, the MPPT with fixed step size should make a satisfactory tradeoff between the dynamics and oscillation, and it can only track irradiance changes when it moves with a given rate. This issue causes serious drawbacks to the conventional incremental conductance algorithm, while the proposed ZA-InCon algorithm tackles those limitations.

III. PROPOSED MPPT ALGORITHM

The proposed ZA-InCon MPPT algorithm is developed based on steady state operation detection and adaptive step size determination.

The conventional InCon MPPT algorithms oscillate around the closest possible voltage at three levels in steady state operation. This artificial perturbation allows the algorithm to identify environmental condition change. The ZA-InCon algorithm identifies steady state operation and sets the operating point voltage at the closest value; losses are minimized in this operating mode.

The environmental change is identified by PV panel current change, which generates a natural perturbation. This natural perturbation enables the algorithm to identify environmental changes, a clear operation removing redundant oscillations caused by environmental change detection and can cause confusion. This enable algorithm act when it is necessary, and adjust an accurate step size based on irradiance change slope, instead of oscillating continuously. The proposed ZA-InCon flowchart is given in Fig.4.

A. Adaptive step size determination

The panel voltage is considered constant during a sampling period and it is updated at the end of each period. The panel currant changes by a change in the solar irradiance. This current change acts as a natural perturbation. Moreover, when irradiance changes with the slope δG during the sampling time (Δt), the tracking error (e) has the following relationship with δG:

$$e \propto \frac{\delta G}{K_i} \qquad (11)$$

Where K_i is the coefficient of the integral part of PI controller. Therefore the algorithm has accurate knowledge of irradiance change magnitude and slope, which can help to detect the displacement of maximum power point voltage and current. If irradiance change slope is low, MPPT algorithm should take smaller step size to track maximum power point accurately. This situation is reversed when the irradiance change slope is high.

The magnitude of the panel's current change resulting from the irradiance change is given by:

$$\Delta i_{pv} = K_i e \Delta t \qquad (12)$$

Equation (12), can be denoted as:

$$K_i e = \frac{\Delta i_{pv}}{\Delta t} \qquad (13)$$

Where Δt is the MPPT algorithm sampling time. Combining Eq. (13) with Eq. (11) yields:

$$\delta G \propto \frac{\Delta i_{pv}}{\Delta t} = K\frac{\Delta i_{pv}}{\Delta t} \qquad (14)$$

Where K is a constant. After δG is calculated, we can adjust the step size in proportion to δG:

$$\Delta v_{step} = \alpha.\delta G \qquad (15)$$

Where α is constant. Substituting from Eq. (14) into Eq. (15) yields:

$$\Delta v_{step} = \beta.\frac{\Delta i_{pv}}{\Delta t} \qquad (16)$$

Where β is a constant. The algorithm sampling time (Δt) is constant for a specific implemented PV system, so Eq. (15) can be reduced to:

$$\Delta v_{step} = \gamma \Delta i_{pv} \qquad (16)$$

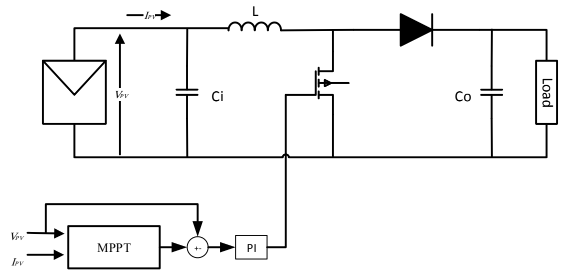

Fig. 5. Photovoltaic system circuit diagram with a buck-boost converter

With γ being a constant.

Therefore, the voltage step size is proportional to PV panel current changes due to the varying irradiance.

B. Steady state operation detection

Conventional MPPT algorithms change PV panel voltage and measure the effect on the PV panel power (or some other parameters), to search for maximum power point. This artificial perturbation reduces the efficiency of power extraction. ZA-InCon MPPT algorithm, however, uses natural perturbation to detect irradiance change. The change in PV panel current makes it possible to identify steady state operation. If P-V characteristic slope is lower than a small value ε, it is assumed the steady state condition.

$$\left| I + V\frac{\Delta I}{\Delta V} \right| < \varepsilon \qquad (17)$$

The power drown from PV panel with a larger ε contributes to faster dynamics but excessive steady state losses, and comparatively low efficiency. This situation is reversed while the MPPT is operating with a smaller ε. So, the ZA-InCon MPPT algorithm should make a satisfactory tradeoff between the dynamics and efficiency.

IV. SIMULATION

To validate the proposed ZA-InCon MPPT algorithm, the conventional InCon and ZA-InCon MPPT algorithms are simulated in MATLAB/SIMULINK, under the same environmental condition. The system shown in Fig.4 has been simulated by SIMULINK, with the following details:

1. A photovoltaic PV panel with V_{oc}=200 volts, I_{sc}=5 amperes, and FF=0.8, under standard test conditions (G=1 kw/m^2 and T=25 °C).
2. A boost converter with C_i=100 pf, C_o=10 μf, L=1 mH, and switching frequency f_s=20 kHz.
3. A battery bank with V=200 volts, capacity=4.5 Ah, and Soc=70% as a load.
4. A PI controller with k_i=0.003, and k_p=750.

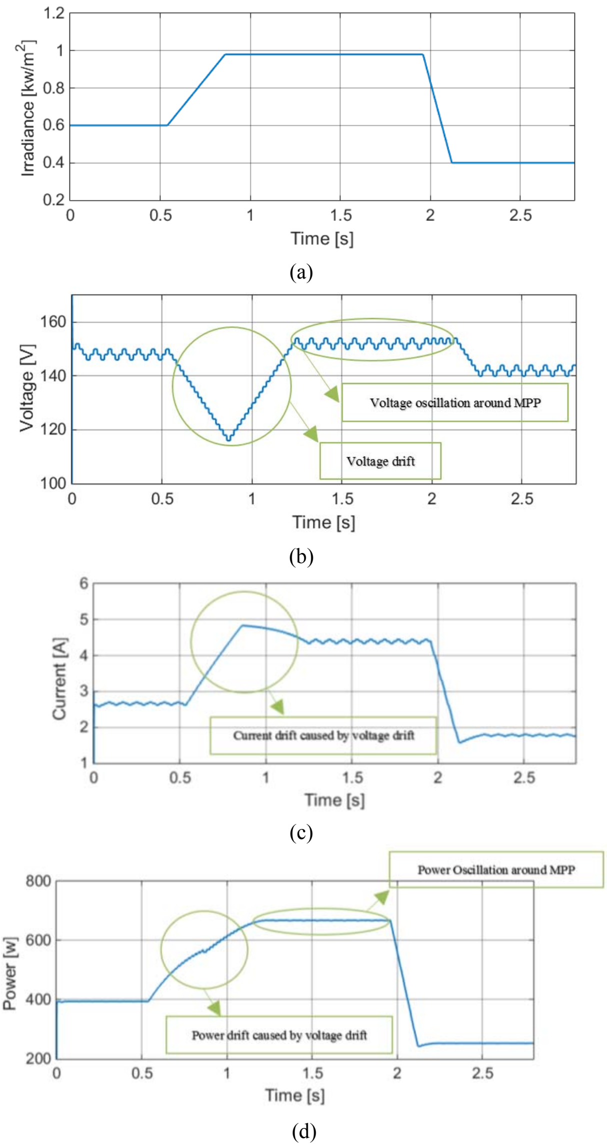

Fig.6. Conventional InCon algorithm when irradiance slope starts during a falling edge: (a) irradiance, (b) PV panel voltage, (c) PV panel current, (d) PV panel power

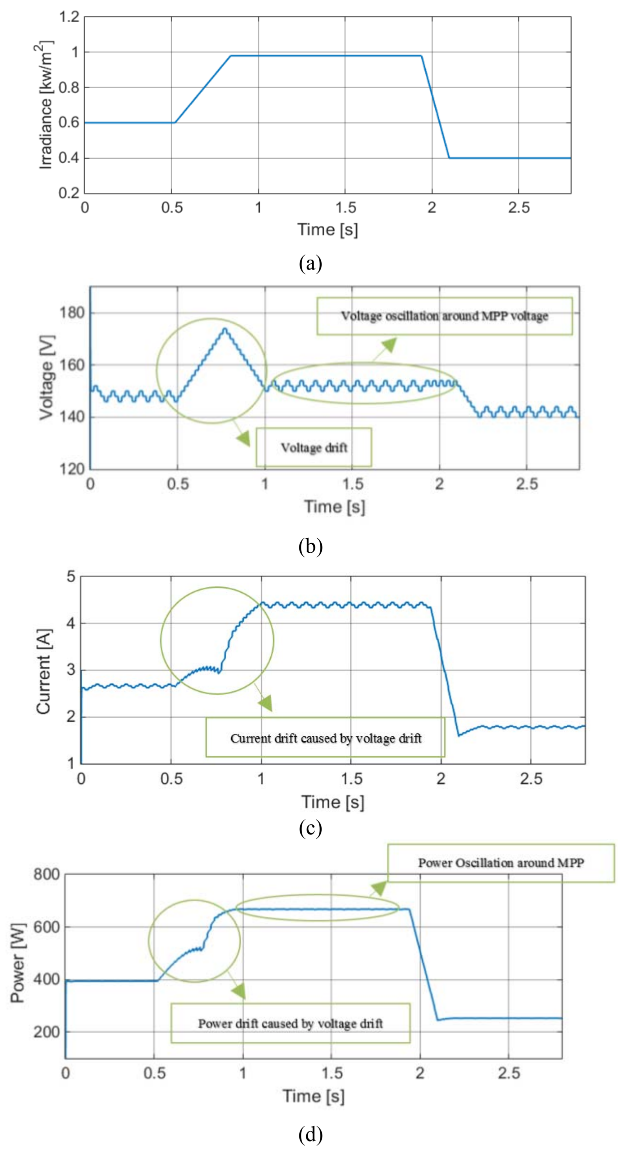

Fig.7. Conventional InCon algorithm when irradiance slope starts during a rising edge: (a) irradiance, (b) PV panel voltage, (c) PV panel current, (d) PV panel power

5. A controller containing MPPT algorithm.

Simulation starts with constant irradiance of 0.6 kw/m^2. At t=0.52s, it starts increasing at t=1.94s with a slope of 0.18kw/m^{2}s until t=0.84s, then it remains constant until t=1.94s, hen it decreases with a slope of 3.6kw/m^{2}s^{-1} until 0.4 kw/m^2, thereafter, it remains constant.
The conventional InCon with sampling period 0.04s and voltage step size $\Delta v_{step} = 2$ volts, simulates under two cases:

1. Irradiance starts increasing, during a falling edge; In Fig.6 irradiance starts increasing in a falling edge and the algorithm detects an increase in the power, so it keeps going in the same direction, even if it is wrong, therefore PV panel voltage drifts from actual maximum power point voltage.
2. The irradiance slope starts increasing during a rising edge; the conventional InCon algorithm is tracking maximum power point with a fixed step size for different irradiance slopes, In Fig.7 irradiance starts increasing in a rising edge and the algorithm detects an increase in the power, so it keeps going in the same direction, although the algorithm goes in correct direction, but it may drift from actual maximum power point caused by fixed tracking step size.

This deviation from correct maximum power point, causes significant losses, therefore the conventional InCon MPPT algorithm suffers from low implementation efficiency.
The proposed ZA-InCon MPPT algorithm is presented in Fig.8, improves this drawbacks, it detects steady state operation, with only calculating P-V characteristic slope, so PV panel operates in a smooth way. The environmental changes is identified with PV panel natural current perturbation, and it identifies the

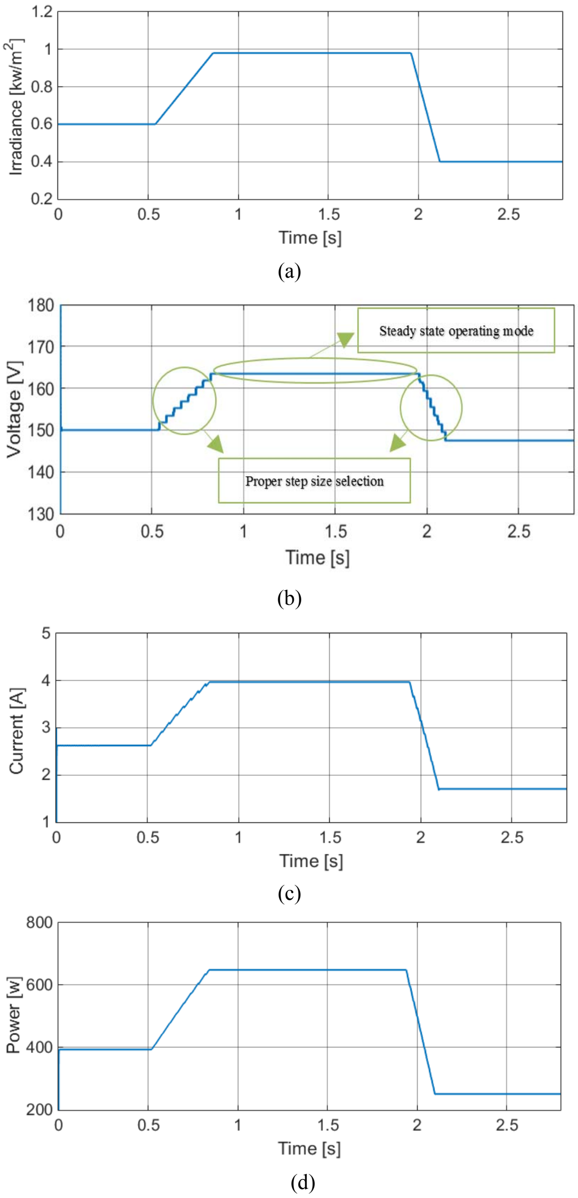

Fig.8. ZA-InCon algorithm operation in steady state and transient mode: (a) irradiance, (b) PV panel voltage, (c) PV panel current, (d) PV panel power

accurate step size due to the irradiance change slop to track maximum power point. The proposed ZA-P&O algorithm decreases losses, and causes an efficient implementation.

V. CONCLUSION

A new maximum power point tracking algorithm for PV application is presented in this paper. The proposed ZA-InCon algorithm calculates P-V characteristic slope to detect steady state operation and set PV panel voltage near the maximum power point voltage, therefore it removes artificial perturbations, and increases tracking efficiency. Moreover, the algorithm identifies irradiance change slope and adjust an accurate step size to track environmental changes, so the losses caused by confusion or drift from maximum power point is removed. The algorithm reduced steady state losses and improved transient behavior, with a similar implementation complexity. The proposed algorithm validates with simulations.

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