A Comparative analysis of Maximum Power Point Tracking Techniques for Battery Operated PV Systems at Different Temperatures

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***Abstract*—This paper presents a comparative analysis of Ripple Correlation Control (RCC) with conventional Maximum Power Point Tracking (MPPT) methods such as Perturb & Observe (P&O) and Incremental Conductance (IC). Photovoltaic (PV) array along with the buck converter and its MPPT control have been simulated for all three MPPT methods at different solar radiation levels at 25°C and 70°C and results have been compared. From the simulation results, it can be observed that P&O is much affected with slow tracking and oscillations, and IC MPPT performs better than P&O in terms of tracking, but not for ripples. Simulation results verifies that RCC MPPT is capable of solving both these problems effectively and RCC performance is better than both P&O and IC MPPT methods.**

***Keywords*—PV, MPPT, RCC, HC, P&O, IC.**

I. INTRODUCTION

Sustainable energy resources are always in high demand due of the fast and continuous depletion of fossil fuels and oil resources. Among the available green energy resources, solar energy has emerged as one of the most impactful renewable energy resources which has the potential to replace conventional energy sources. Solar energy is a free and constant source of renewable energy which is harvested using environment-friendly photovoltaic systems. However, it also suffers from some drawbacks e.g. during the day time, level of solar insolation is non uniform, moreover, increase in the environmental temperature degrades the power transfer to the load. Therefore, the power generated by solar panel is not same all the time and due to this each and every time the Maximum Power Point (MPP) of photovoltaic system gets changed [1]. Solar panel can deliver maximum power to the load for a certain value of voltage V_{MP} and current I_{MP}. This point is known as Maximum Power Point (MPP) as shown in Figure 2.

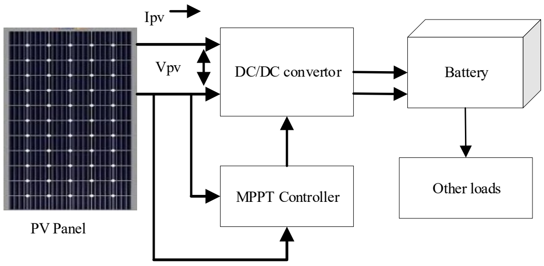


Fig. 1. Single stage battery operated PV system.

Since, the output power generated per watt by solar panel is too high, it is reasonable to improve its performance via power converters. These converters have many advantages in solar PV system like it can provide isolation between PV panel and load, extract maximum power. Moreover, converters are effective means for implementing MPPT technology [19]. MPPT algorithms are integrated with power electronic converter which can deliver maximum power by controlling its duty cycle. In Photovoltaic systems MPPT based charge controller is preferred over PWM as a typical PWM charge controller can only be able to regulate the output voltage of a Photovoltaic (PV) array, not the current, but in MPPT controller both the voltage and current can be regulated. A general block diagram of a battery-operated PV system is shown in Figure 1.

Many research works have been done on MPPT in the last few decades such as conventional methods like Perturb and Observe [1-10], Incremental Conductance [11-16], Hill Climbing [17-19] have been deployed and a large number of modifications for these techniques has been proposed in the literature. The main shortcomings of P&O, HC & IC is that these methods can only track the maximum power when the irradiation conditions are uniform and it fails to track MPP when there is a partial shading or cloudy environmental condition. Further, these methods suffer from poor convergence, slow tracking speed, and high steady state oscillations (ripples). Therefore, to track the MPP under partial shading conditions conventional methods need to be modified. Due to which different modified versions of P&O have been proposed in the literature such as Adaptive P&O with fixed step size, variable step size, etc. [2-3]. Additionally, Soft Computing/Evolutionary algorithms [19] based approaches have also been emerged along with the conventional MPPT methods such as particle swarm optimization based MPPT algorithm [20] which is useful in finding the global MPP when there are multiple PV array with large area. These methods have numerous advantages like (i) ability to handle non linearity (ii) wide exploration in search space and (iii) coherent skill to reach global optimal regions these methods is considered to be a prime choice for non-linear optimization. Even-though the above alterations have enhanced the performance of MPPT charge controllers however, it is not sufficient enough for all the environmental conditions [6, 12]. This gives a motivation to the researchers to find some alternative ways to improve the performance of MPPT charge controllers under partial shading conditions.

On the other hand, new era of MPPT algorithms in PV system have emerged when evolutionary algorithm was first applied for MPP tracking [21-22]. Due to its ability of handle nonlinear problems it has opened up new scopes of opportunities due to its simplicity, robustness and ripple removal characteristics. Ripple Correlation Control (RCC) [21-26] provides a solution to the steady state oscillations, which is mainly caused by the internal ripples present in the system due to the presence of power electronic circuitry. Since, P&O, IC, and HC methods do not consider these ripples as internal perturbations, due to which the algorithm consider them as external perturbations. As a result the output voltage and current oscillates around MPP, in turn power also oscillates. These oscillations are harmful for the battery, as it reduces its operating life span.

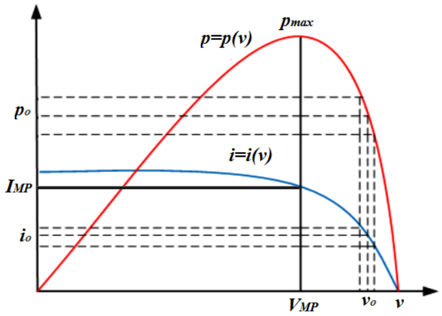


Fig. 2. Current and power of the PV panels versus voltage.

In this work, RCC MPPT with buck converter for battery connected load has been implemented and its simulation results have been compared with P&O and IC MPPT methods. This work is an extension of [27]. The organization of the paper is as follows; Section I gives introduction of MPPT and various existing methods available in literature. Section II provides mathematical formulation of P&O, IC and RCC method, along with formulation of buck converter used in the simulation. In section III, parameters specifications are given along with photovoltaic system diagram. Section IV is simulation results and discussion, followed by conclusion in section V.

II. Back Ground of the Conventional MPPT Methods

In this section, a brief overview of the conventional MPPT methods along with detailed explanation of RCC control algorithm has been discussed.

A. Perturb & Observe (P & O)

The P&O Method [1-10] utilizes additional perturbations of current or voltage array to check if the system has achieved the nominal value of voltage or current. If the power output increases when voltage is changed in a particular direction of perturbation then it means that MPP will be obtained in that particular direction of perturbation and if the power output decreases for the same voltage perturbation then the MPP can be found by reversing the direction of perturbation. Although this method is easy to implement and is cost effective the overall system is never able to attain stability because apart from adding external perturbation to it the perturbation due to the environmental changes and the inherent generated perturbation affects its stability.

This method works on concept of continuous observations of PV array output power for the input perturbations, due to changing current or voltage of PV array. The algorithm continuously modifies the reference voltage or current based on the previous value of power until reaches the MPP [6, 7]. When $dP/dV > 0$ and the operating voltage of PV array is perturbed in a specific direction, it known that perturbation moves the operating point of PV array to the MPP. P&O method will then continue to perturb the PV voltage in the same direction. When $dP/dV < 0$, the perturbation moves the operating point of PV array away from the MPP and the P&O method reverses the direction of the perturbation [8, 9].

B. Incremental Conductance (IC)

Another algorithm to locate the MPP is Incremental Conductance (INC) [11-16]. In this algorithm a relationship between power and voltage is established where ideally the derivative of power with voltage is zero. This algorithm has both hardware and software complexity and is also expensive. The main drawback of this algorithm is that it increases the computation time of MPPT

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dI}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV} \quad . \tag{1}$$

Equation 1 represents the derivative of PV output power with voltage, the PV system will operate at MPP when this equation is equal to zero i.e.

$$\frac{dP}{dV} = 0 \Rightarrow I + V\frac{dI}{dV} = 0 \Rightarrow -\frac{I}{V} = \frac{dI}{dV}\,. \tag{2}$$

Comparing the instantaneous change in conductance, dI/dV and instantaneous conductance of PV array I/V in equation 2, the position of operating point in relation to maximum power point can be revealed. Equation 3 shows the position of operating point at different values of dP/dV

$$\begin{cases} \frac{dP}{dV} > 0, for\ V < V_{MPP} \\ \frac{dP}{dV} = 0, for\ V = V_{MPP} \\ \frac{dP}{dV} < 0, for\ V > V_{MPP} \end{cases} \,. \tag{3}$$

C. Ripple Correlation Control (RCC)

Ripple correlation control is a nonlinear control approach applicable to power electronic circuits. It makes use of voltage, current, or power ripple and correlates this with switching functions to affect control [22]. The RCC solves major problems through less complex implementation. The most important factors and advantages of the RCC are the simple circuit implementation, fast computation/simulation time, there is no need for external perturbation like in P&O and IC, to generate ripple contents, converges asymptotically to the object and its converging rate can be tuned by the controller gain [21]. RCC is a method that is used to calculate the duty cycle which provides maximum power, which will be supplied to the gate of switching circuits to maintain MPP. The main advantage of RCC is that it uses inherent ripples that occur due to the power electronic elements i.e., the DC-DC convertor used in the PV system. Through the correlation of the time based derivative of voltage and power the RCC tries to identify whether this correlation is greater than zero i.e., to the left of the MPP, or less than zero i.e., to the right of the MPP, or exactly zero i.e., equal to MPP.

$$\frac{dp_{PV}}{dt}\frac{dv_{PV}}{dt} > 0\ when\ V_{PV} < V_M, \tag{4}$$

$$\frac{dp_{PV}}{dt}\frac{dv_{PV}}{dt} < 0 \text{ when } V_{PV} > V_M, \tag{5}$$

$$\frac{dp_{PV}}{dt}\frac{dv_{PV}}{dt} = 0 \text{ when } V_{PV} = V_M. \tag{6}$$

The general equation used to find the ripple content is as:

$$\tilde{x}(t) = x(t) - \bar{x}(t) \tag{7}$$

$x(t)$ is the general quantity that can be array current, voltage or power which contains both the ripple as well as moving average component. $\tilde{x}(t)$ is the ripple content whereas $\bar{x}(t)$ is the average component. From equation (7) we can easily find out the ripple content of voltage, current and power.

Figure 3 represents the RCC that has been implemented to find out the duty cycle. This RCC is different from [21-22], as it has low pass filter instead of high pass filters as in [21-22]. In this work RCC mentioned in [25] is implemented for battery operated systems for output power of 95 watts. The work differs from [25], in terms of load which is battery in this work and converter type, which is buck converter, instead of boost converter used in for grid connected load as in [25]. From the Figure 3 error is equal to the product of the ripple content of both the power and voltage.

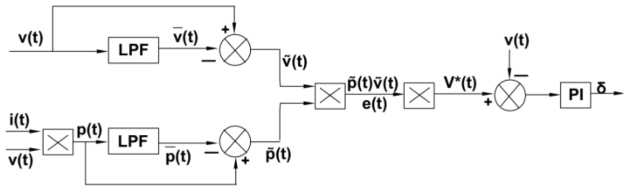


Fig. 3. RCC block of the MPPT Controller

To obtain the error $e(t)$ of power we will use the following mathematical equations;

$$p(t) = v(t) \times i(t) \tag{8}$$

Expressing i(t) and v(t) in terms of their ripple content as in (7) and using them in (8) we get,

$$p(t) = \bar{v}(t) \times \bar{\imath}(t) + \bar{\imath}(t) \times \tilde{v}(t) + \bar{v}(t) \times \tilde{\imath}(t) + \tilde{v}(t) \times \tilde{\imath}(t) \tag{9}$$

Therefore, power ripple can be expressed as;

$$\tilde{p}(t) = \bar{\imath}(t) \times \tilde{v}(t) + \bar{v}(t) \times \tilde{\imath}(t) + \tilde{v}(t) \times \tilde{\imath}(t) \tag{10}$$

We can further express the product of $\tilde{p}(t)$ and $\tilde{v}(t)$ as follows;

$$\tilde{p}(t) \times \tilde{v}(t) = \tilde{v}^2(t)\left[\bar{\imath}(t) + \bar{v}(t)\frac{\tilde{\imath}(t)}{\tilde{v}(t)}\right] + \tilde{v}^2(t)\tilde{\imath}(t) \tag{11}$$

Upon taking the derivative of $p(t)$in equation (21) w.r.t. $v(t)$ we get;

$$\frac{dp(t)}{dv(t)} = i(t) + v(t)\frac{di(t)}{dv(t)} \tag{12}$$

Linearizing, Figure 2 at point $v_0, i_0,$we get;

$$\left(\frac{di(t)}{dv(t)}\right)_{v_0} = \frac{\tilde{\imath}(t)}{\tilde{v}(t)} \tag{13}$$

Using equation (12) and (13) error can be expressed as;

$$\tilde{p}(t) \times \tilde{v}(t) = \tilde{v}^2(t)\left[\frac{dp(t)}{dv(t)}\right] + \tilde{v}^2(t)\tilde{\imath}(t) \tag{14}$$

Error is directly proportional to the magnitude of dp/dv as the average value $\tilde{v}^2(t)\tilde{\imath}(t)$ is zero over a cycle, $e(t)$ represents the distance from the MPP. When the output is on the left of MPP the average value of error is positive. When output is on the right of MPP the average value of error is negative. When the output is at the MPP the average value of error is zero. From Figure 3, it can be inferred that when the error signal passes through the first PI controller it generated the reference signal, and the difference of this reference signal & PV array voltage $v(t)$, acts as an input for the second PI controller that gives us the load angle δ, which is used to generate the PWM signal to control the switching of buck convertor.

The DC-DC converter is used to convert one level of DC voltage into another level. According to the requirements one can opt Boost, Buck or Buck-boost converter. In this work a DC-DC buck converter has been used [26]. The primary function of the buck converter is to decrease the voltage according to battery charging requirements with increase in the current for fast charging of battery.

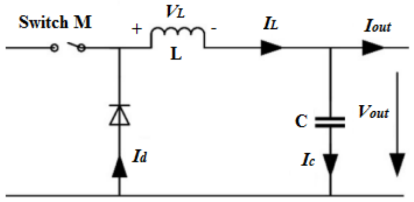


Fig. 4. Electrical Model of DC-DC Buck Converter.

III. SIMULINK MODEL OF PV SYSTEM WITH RCC MPPT

The Simulink model schematic of the PV system that is used for simulations is depicted in Figure 4, and represents a PV solar panel connected to a resistive load through a dc-dc buck converter with a variant subsystem of MPPT controller that allow to choose between these three MPPT algorithms. P&O, incremental conductance and RCC.

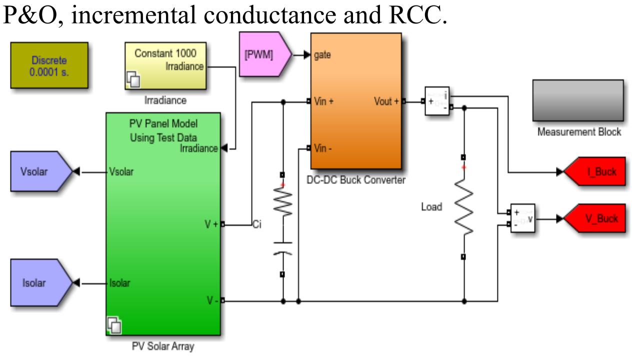


Fig. 5. Simulink Model of PV System.

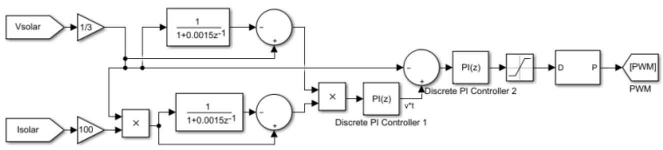


Fig. 6. MPPT variant blocks and Simulink implementation of RCC MPPT controller [25].

The PV parameters used in Simulink simulation model of this work are given in Table I. The components parameters of the buck converter used in Simulink are given in Table II. The components parameters of RCC block are given in Table III.

TABLE I

PV ARRAY SPECIFICATIONS

S.No.	Parameter Name	Value
1	Number of cells in series	n-cells = 36
2	Open circuit voltage	V_{oc}= 21.6 V
3	Short circuit current	I_{sc}= 7.34 A
4	Series resistance of PV model	R_s= 0 Ω
5	Parallel resistance of PV model	R_p= ∞ Ω
6	Diode quality factor of PV model	N=1.5
7	DC link capacitor	C_{dc}= 100 μF

TABLE II

BUCK CONVERTER COMPONENTS PARAMETERS

S.No.	Parameter Name	Value
1	Inductance	$L = 23\ \mu H$
2	Capacitance	$C = 120\ \mu F$
3	Switching Frequency	$f_{sw} = 2*10^6$
4	Sample Time	0.0001 SEC
5	Diode Resistance	$R_{ON} = 0.001\Omega$

TABLE III

RCC COMPONENTS PARAMETERS

S.No.	Parameter Name	Value
1	Time constant of LPF's	1.5 ms
2	PI controller (inside MPPT block)	$K_p = 200$
		$K_I = 5.5$
3	PI controller (outside MPPT block)	$K_p = 2e\text{-}9$
		$K_I = -0.009$

Simulation has been performed for three different types of variations, fist one is at 1000 W/m^2 at 25°C, second at 800 W/m^2 at 25°C and third is for step variation [5] as shown in Figure 7.

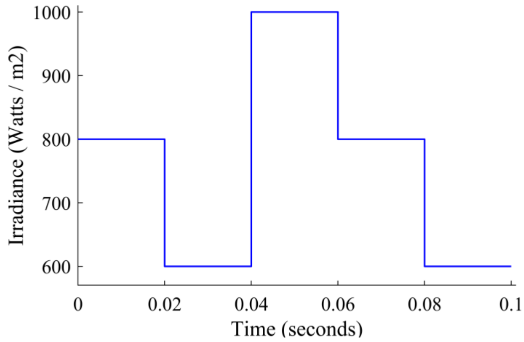


Fig. 7. Step Variation of irradiance [5].

IV. RESULTS AND DISCUSSIONS

All the simulations have been performed in MATLAB/SIMULINK 2018. First the irradiation level is fixed at 1000 W/m^2 at 25°C and 70°C, and results of voltage, current and power for all three methods i.e. perturb & observe, incremental conductance and ripple correlation control have been captured using measurement scopes. Then same process is performed for 800 W/m^2 irradiance level at 25°C and 70°C. After this simulation is performed for Step variation of irradiance as shown in Figure 7, and graph were captured. There are many research papers available of P&O and IC methods in which simulation results have been given. In this work PV model parameters have been selected as in [5], since it was also a battery connected system. This work is an extension of [27].

Figures 8, 9, and 10 shows the simulation output of P&O MPPT obtained by the simulation using the setup mentioned in figure 5. The simulation results show that conventional P&O MPPT is very much affected from being slow tracking and oscillations both. This is because of internal ripples, which are generated due to the use of power electronics components. Actually, the system in P&O case, never achieved stability, and it always oscillate around MPP point. It is due to the internally generated ripples, which are considered as perturbations in P&O MPPT. Hence, the performance of conventional P&O MPPT is not up to the mark in terms of stability, ripples and tracking.

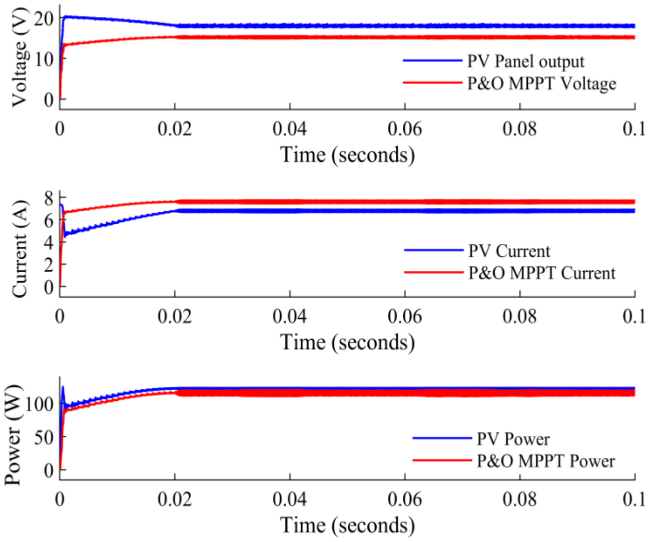


Fig 8. Voltage, Current and Power output of P&O MPPT for 1000 W/m^2 irradiance level at 25°C.

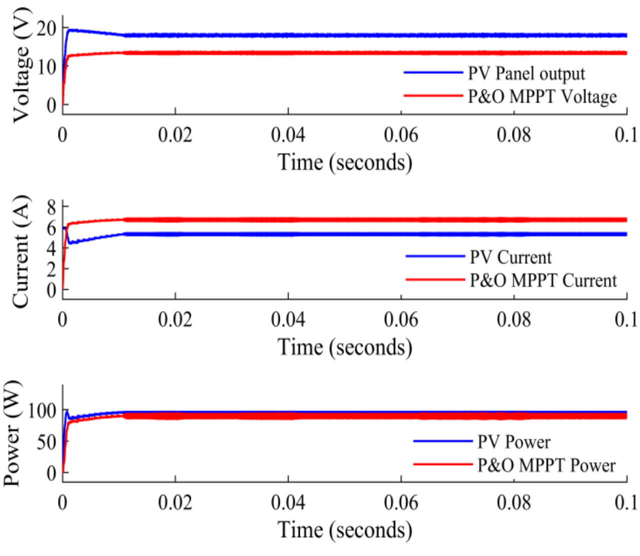


Fig 9. Voltage, Current and Power output of P&O MPPT for 800 W/m^2 irradiance level at 25°C.

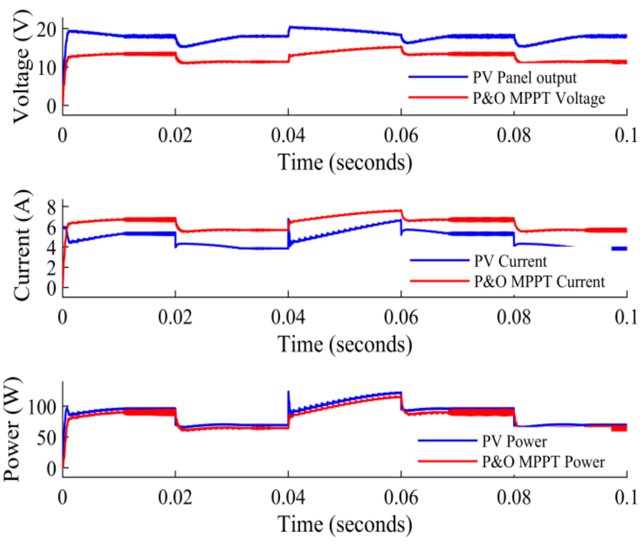


Fig 10. Voltage, Current and Power output of P&O MPPT for Step irradiance at 25°C.

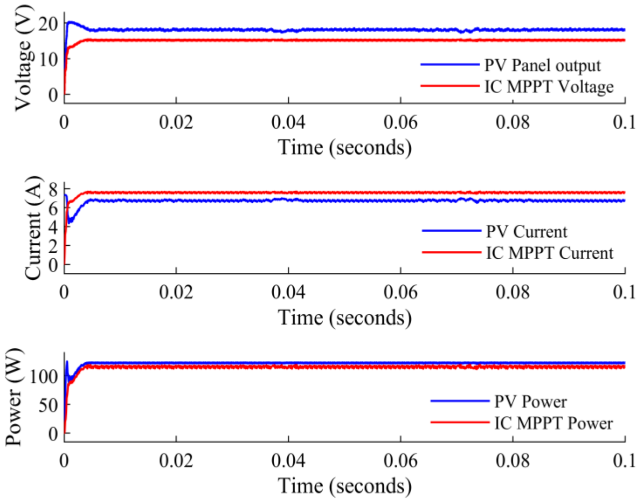


Fig 11. Voltage, Current and Power output of IC MPPT for 1000 W/m^2 irradiance level at 25°C.

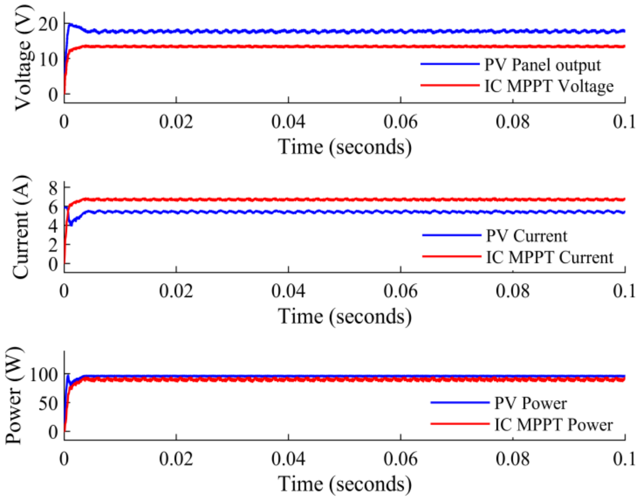


Fig 12. Voltage, Current and Power output of IC MPPT for 800 W/m^2 irradiance level at 25°C.

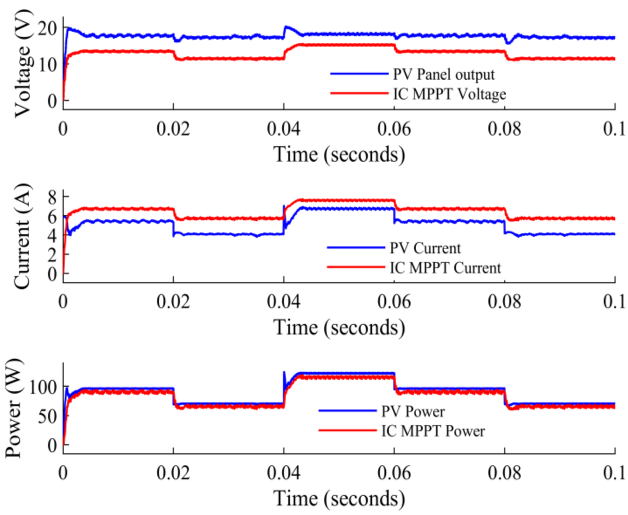


Fig 13. Voltage, Current and Power output of IC MPPT for Step irradiance at 25°C.

Figures 11, 12 and 13 shows the simulation output of IC MPPT, from these Figures it can be clearly seen that, IC tracking is better than P&O MPPT, but output still consists of oscillations in all three cases of irradiance.

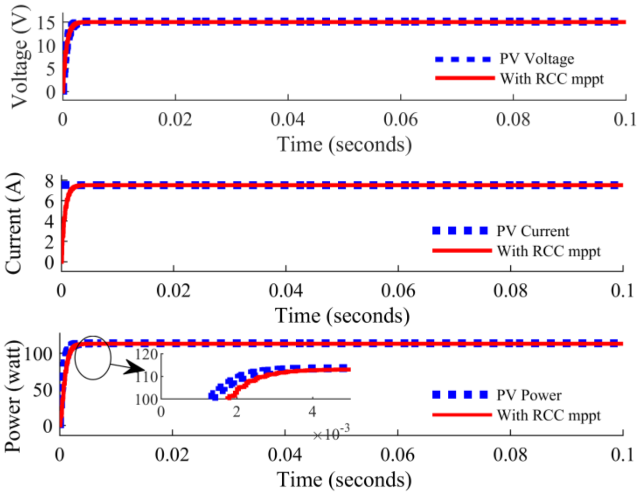


Fig 14. Voltage, Current and Power output of RCC MPPT for 1000 W/m^2 irradiance level at 25°C.

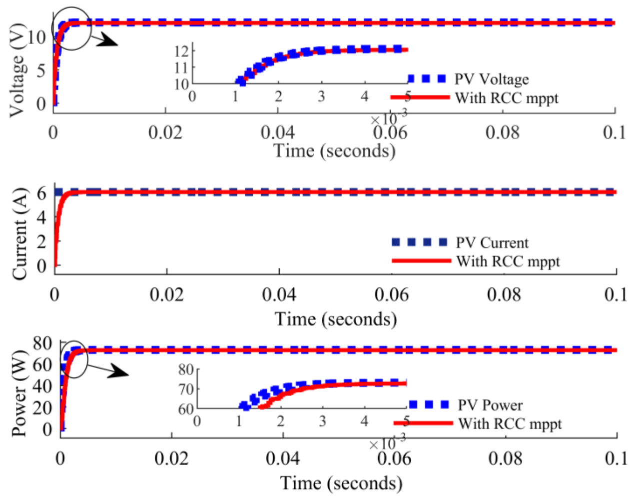


Fig 15. Voltage, Current and Power output of RCC MPPT for 800 W/m^2 irradiance level at 25°C.

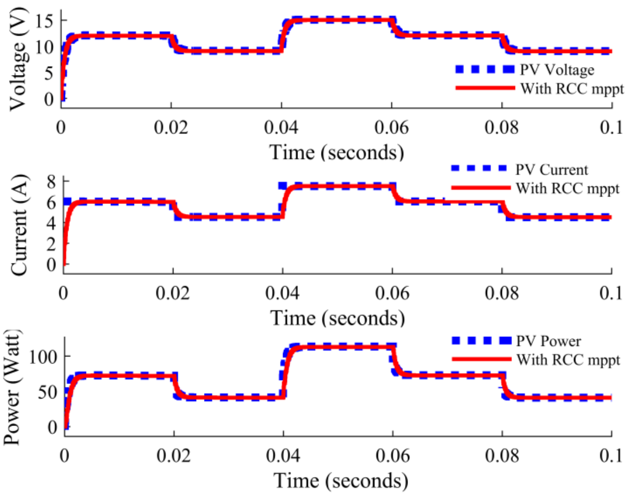


Fig 16. Voltage, Current and Power output of RCC MPPT for Step irradiance at 25°C.

From the Figures 14-16, it can be clearly seen that the problem of slow tracking and ripples (oscillations) has been solved by RCC MPPT. Simulation results verify that RCC MPPT is capable of solving both these problems effectively. Basically these ripples were internal, generated due to use of power electronic converters, and RCC utilizes these internal ripples as perturbations, and is able to eliminate them. Ripple problem is completely solved by RCC MPPT, but for tracking problem can be further improved by some adaptive control strategies.

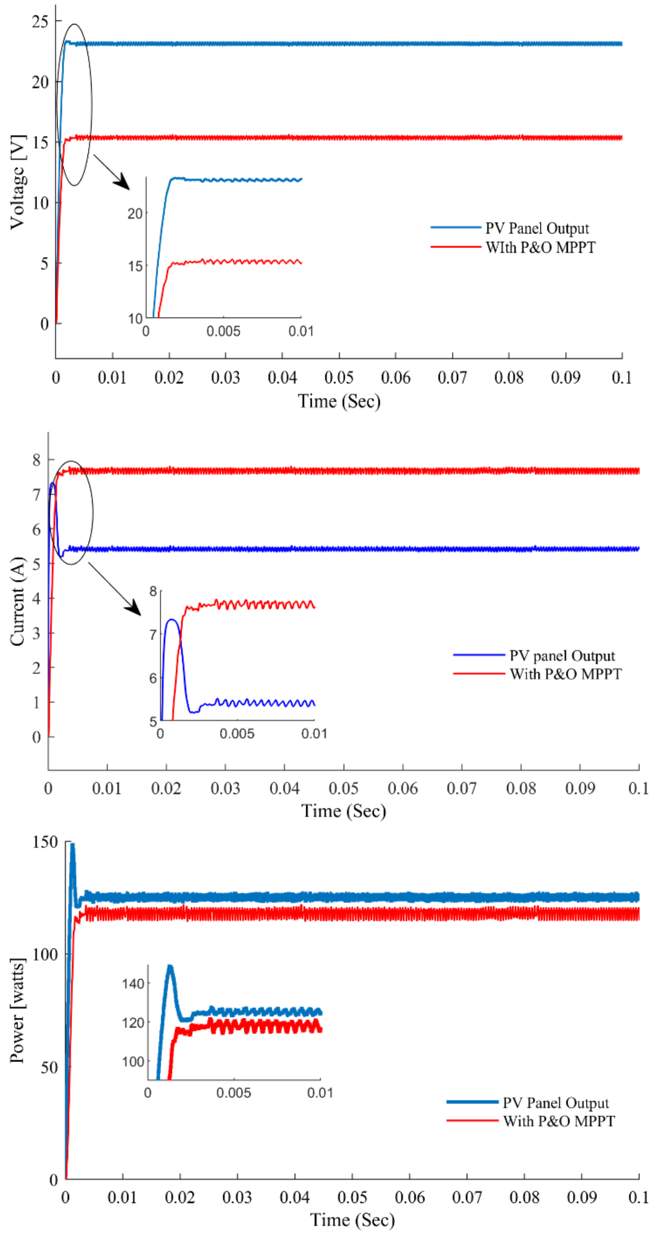
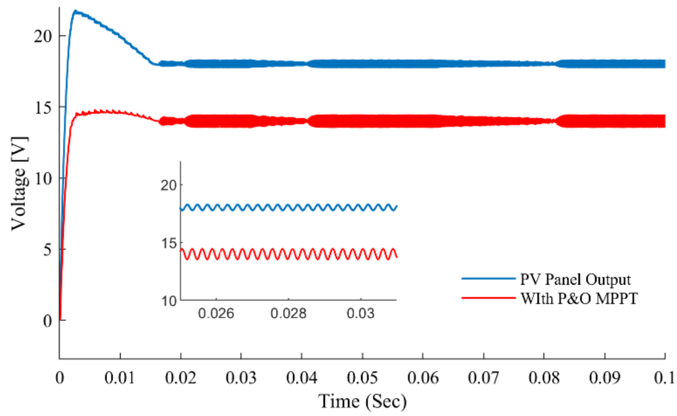


Fig 17. Voltage, Current and Power output of P&O MPPT for 1000 W/m^2 irradiance level at 70^{o}C.



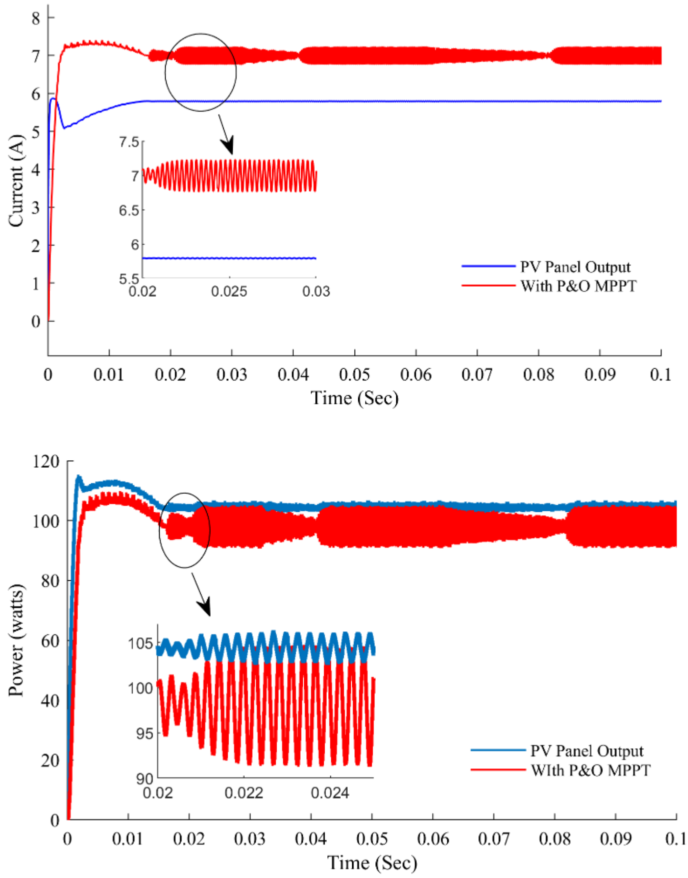
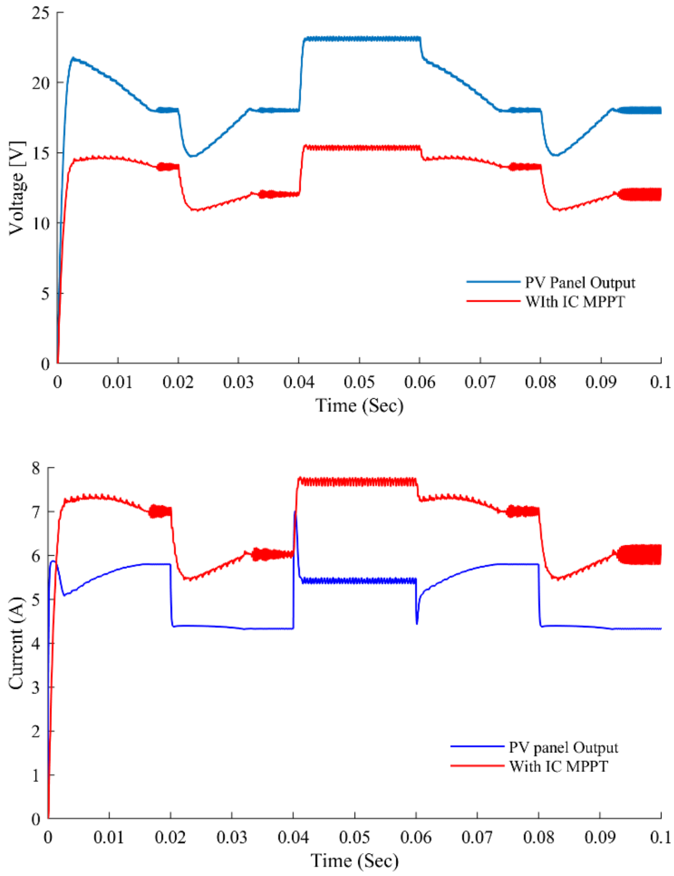


Fig 18. Voltage, Current and Power output of P&O MPPT for 800 W/m^2 irradiance level at 70^{o}C.



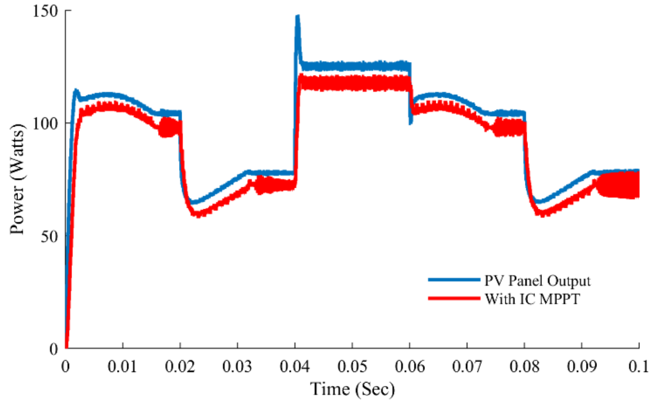


Fig 19. Voltage, Current and Power output of P&O MPPT for Step irradiance at 70°C.

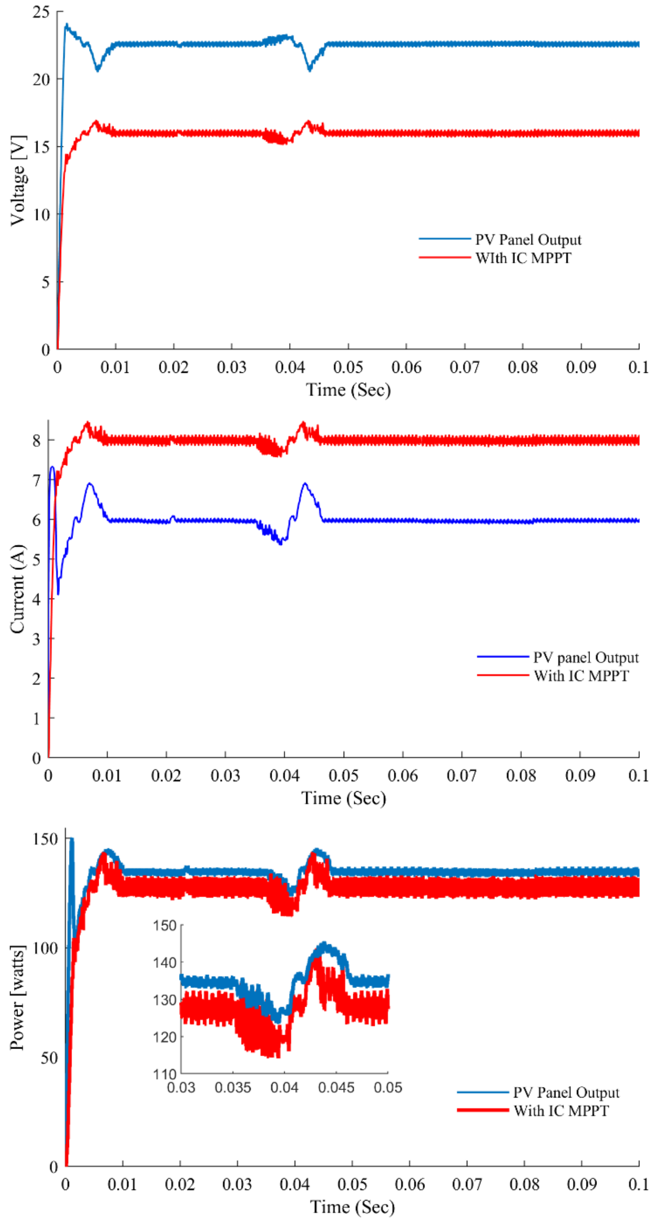


Fig 20. Voltage, Current and Power output of IC MPPT for 1000 W/m^2 irradiance level at 70°C.

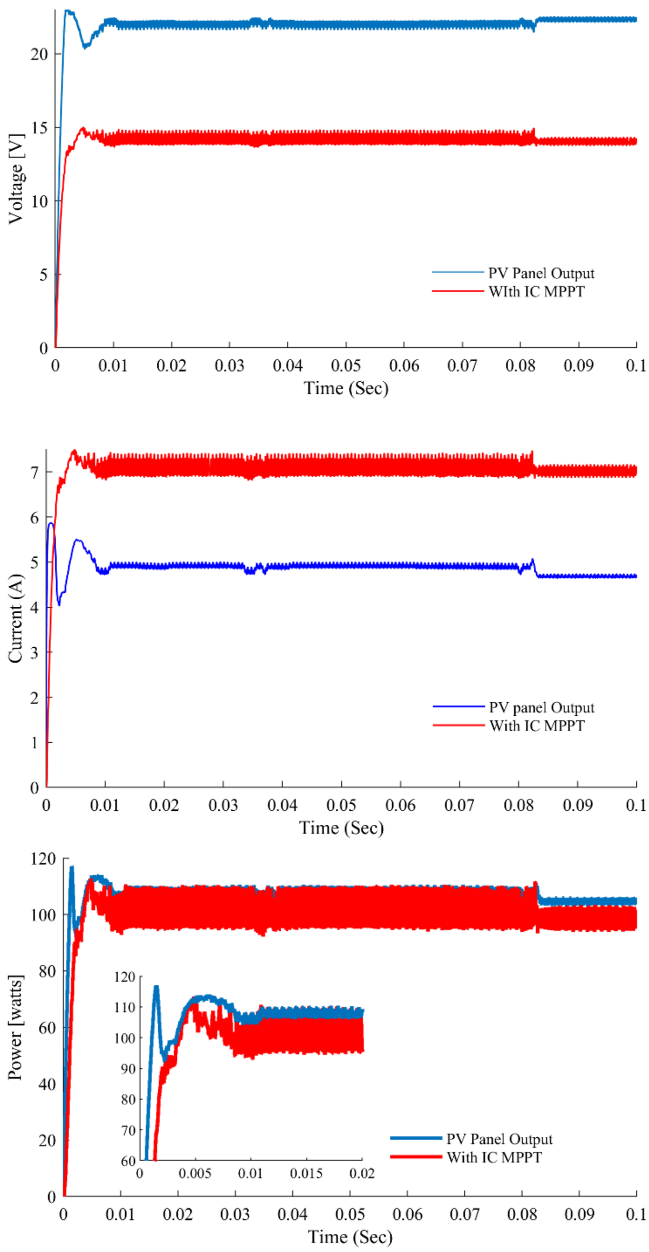
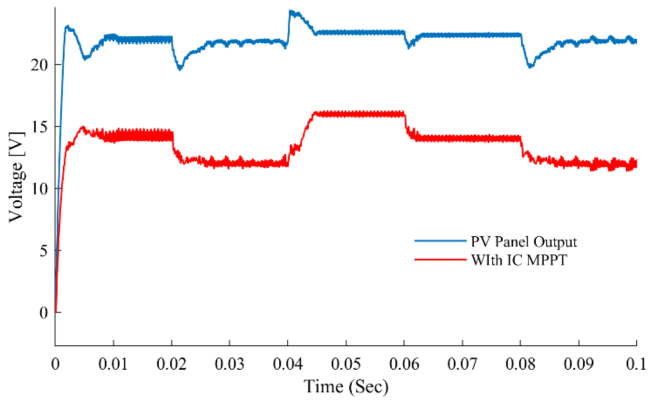
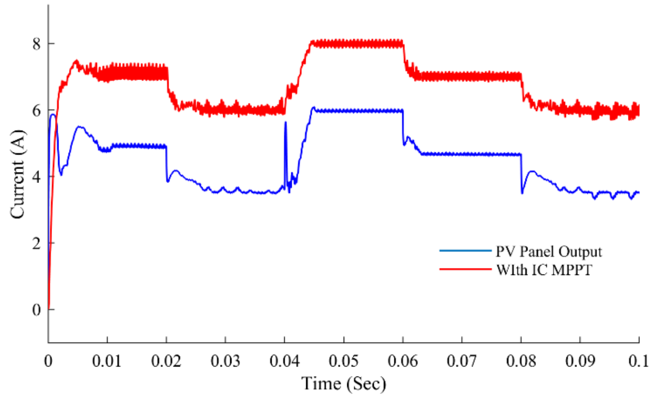


Fig 21. Voltage, Current and Power output of IC MPPT for 800 W/m^2 irradiance level at 70°C.





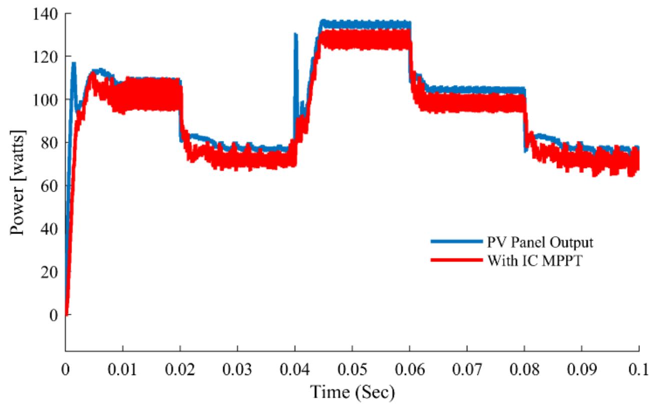
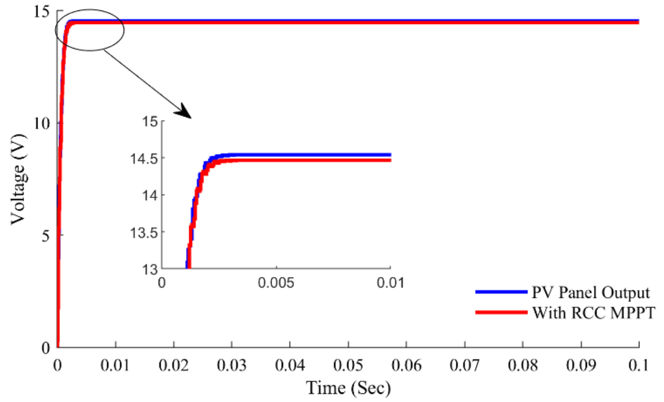
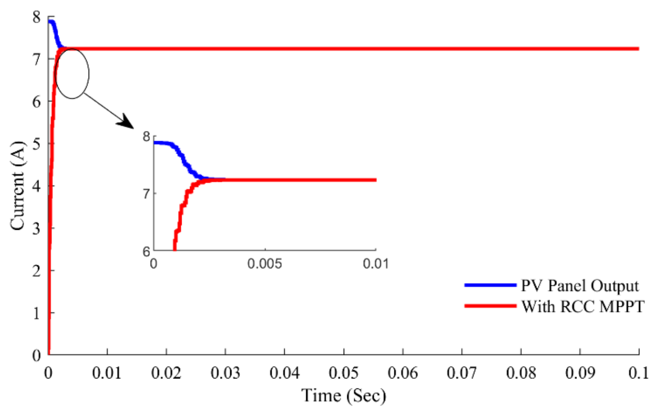


Fig 22. Voltage, Current and Power output of IC MPPT for Step irradiance at 70°C.





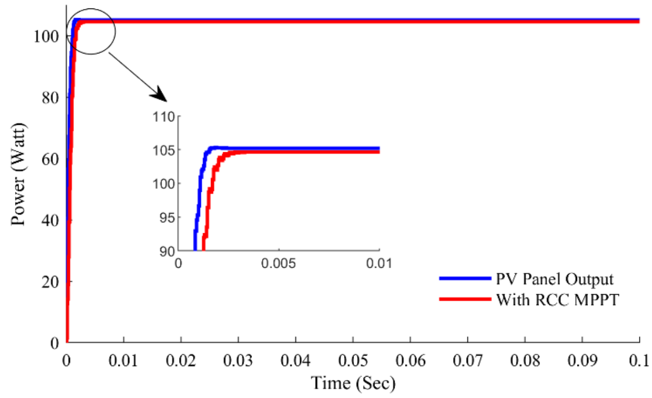
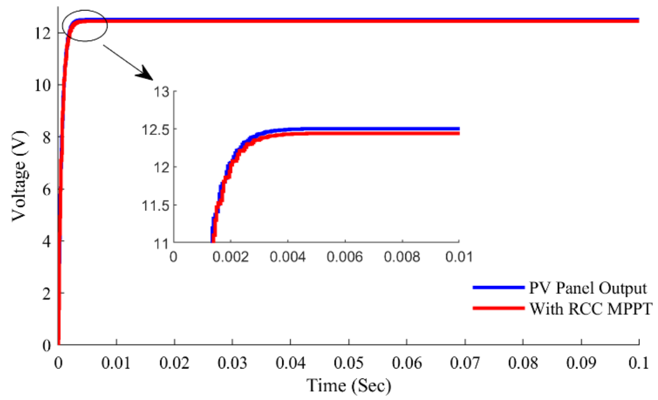
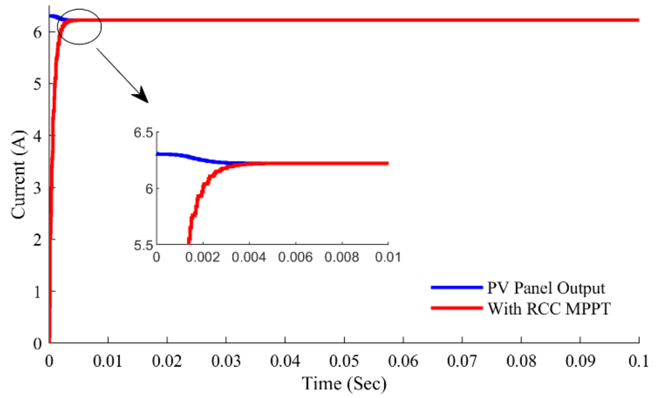


Fig 23. Voltage, Current and Power output of RCC MPPT for 1000 W/m^2 irradiance level at 70°C.





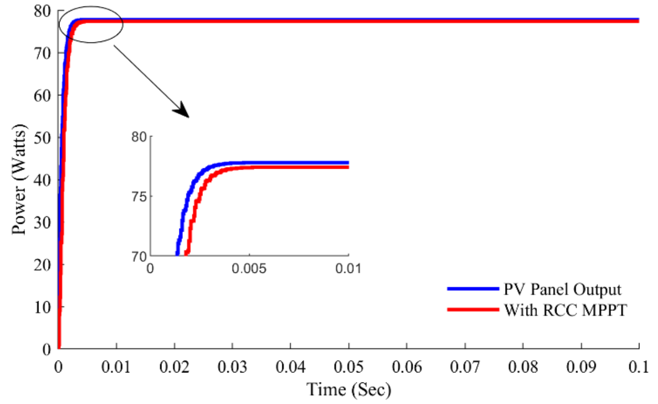


Fig 24. Voltage, Current and Power output of RCC MPPT for 800 W/m^2 irradiance level at 70°C.

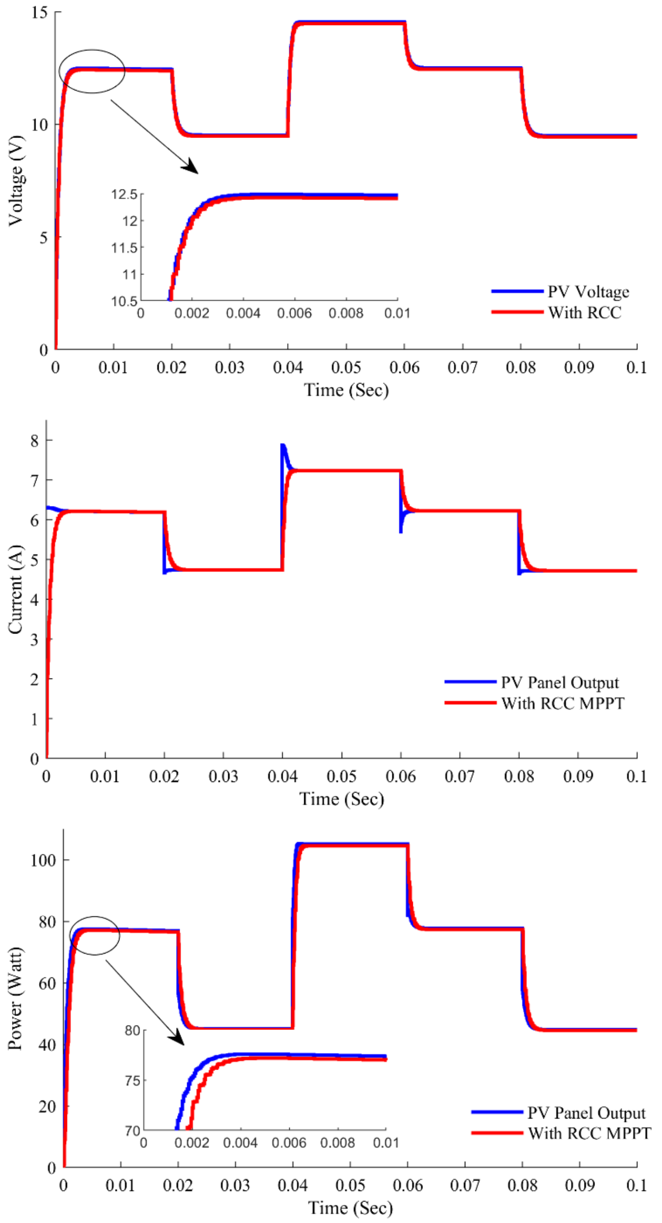


Fig 25. Voltage, Current and Power output of RCC MPPT for Step irradiance at 70°C.

From the Figures 23-25, it can be clearly seen that the problem of slow tracking and ripples (oscillations) has been solved by RCC MPPT as it performs at lower temperatures. Simulation results verify that RCC MPPT is capable of solving both these problems effectively. Basically, these ripples were internal, generated due to use of power electronic converters, and RCC utilizes these internal ripples as perturbations, and is able to eliminate them. Ripple problem is completely solved by RCC MPPT, but for tracking problem can be further improved by some adaptive control strategies.

V. Conclusion

This paper presents a comparative study between perturb & observe, incremental conductance and ripple correlation control MPPT. The PV system model used for simulation consists of the PV panel, the variant subsystem of irradiance, the buck converter and the variant subsystem of MPPT controller. This comparative analysis aims to show the improved performance of RCC method over conventional MPPT methods like P&O and IC. The simulation results show that both the methods perturb & observe and incremental conductance have oscillations in current output and hence power output in all three case i.e. 1000 w/m^2, 800 w/m^2 and step irradiance levels; whereas, RCC MPPT does not has any sort of ripples neither in current output, nor in power output, which is a good sign for longer battery life. Simulations have been performed at 25°C and 70°C, for all the techniques, from the results we can conclude that due to semiconductor properties of solar cell, the performance at 25°C is better than 70°C. Further, RCC performance can be made more improved in terms of tracking, by using a suitable adaptive control strategy. The work can be also extended by more range of temperature in analysis, with the inclusion of more MPPT techniques for comparison, along with hardware implementation.

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