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RESEARCH ARTICLE

Improved RCC-Based MPPT Strategy for Enhanced Solar Energy Harvesting in Shaded Environments

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ABSTRACT An improved ripple correlation control (iRCC) algorithm is proposed to enable conventional ripple correlation control (cRCC) to track maximum power under uniform and partial shading condition (PSC). The proposed iRCC has two parts; the first part detects the global maximum power point (GMPP) under PSC, the second part executes the ripple correlation control to operate the photovoltaic (PV) array at GMPP. The proposed iRCC stays with the second part under uniform irradiation condition and moves to the GMPP only when it detects a dynamic change in weather condition. The proposed iRCC is validated through simulation in Matlab and by hardware prototype. The performance improvement is verified in contrast with the conventional RCC method. The results showcase that the proposed iRCC algorithm accurately tracks the GMPP compared to the conventional RCC method. Consequently, the proposed iRCC method, under partial shading condition 1 (PSC-1), produce 131 % more output power compared with the cRCC method. For PSC-2, the shading resulted in power peaks such that the proposed iRCC power yield is almost equal to the cRCC method. This suggests that the proposed iRCC method can outperform the cRCC method depending on the shading pattern.

INDEX TERMS Ripple correlation control (RCC), global maximum power point (GMPP), local maximum power point (LMPP), partial shading condition (PSC).

I. INTRODUCTION

Energy harnessing is vital due to the growing demand for electricity, with several non-fossil fuel methods available. Wind energy is renewable but weather-dependent and can impact wildlife [1]. Moreover, it is dependent on the location and cannot be installed in urban areas far from the seaside. Similarly, hydro power is reliable but disrupts ecosystems and requires large infrastructure. The piezoelectric devices and electrostatic energy harvesting convert mechanical energy efficiently but produce low power [2], [3], [4]. Similarly, an emerging technology known as reverse electrowetting and magnetohydrodynamometer with liquid metal shows promise but is still experimental [5], [6], [7].

Energy coming from the sun can be harnessed through different technologies such as photovoltaic (PV), solar thermal, molten salt and artificial photosynthesis. Solar energy is an environmental friendly renewable energy resource which is constantly replenished by nature [8], [9], [10], [11], [12]. The demand of electrical energy is increasing day by day, hence the intention towards the PV technology is increasing due to various advantages [13]. PV panels are a combination of

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PV cells connected in series-parallel to convert solar energy into electricity at an acceptable power rating [14]. However, the performance of the PV system is badly impacted due to weather fluctuations. The PV panel short circuit current (I_{sc}) increases with increase in irradiance and vice versa while the increase in temperature reduces the open circuit voltage (V_{oc}) and vice versa [15]. In addition, the characteristic curves i.e., the power vs voltage (P-V) and the current vs voltage (I-V) curve also show non-linear behavior [16].

To operate the system at maximum power point (MPP), specialized algorithms are used to drive the power conditioning circuit. These algorithms are referred as maximum power point tracking (MPPT) algorithms [17], [18], [19]. Under partial shading conditions, when some of the panels receive less irradiance in the string compared to the other panels in the same string, multiple power peaks occur. The maximum peak is called global peak (GP) whereas all the other peaks are termed as local peaks (LP) [20], [21], [22].

It is important to keep track of the GP to maximize the systems efficiency. Note that the conventional MPPT algorithms like perturb ad observe (P&O) [23], [24], incremental conductance (InC) [25], ripple correlation control (RCC) [26] etc seldom work in PSC. In fact, these algorithms do not have the capability to track the GP and they trap in the local maxima. Other like artificial bee colony (ABC) [27], particle swarm optimization (PSO) [28], sliding mode control [29], model predictive control [30] and gray wolf optimization (GWO) [31] are some optimization algorithms that are used to follow the GMPP. The implementation of such artificial intelligence (AI) based algorithms is difficult in terms of computational power and complexity requirement and therefore it is not easy to implement. RCC is an efficient method to accurately and precisely following the MPP. In this paper, the list of contributions are as follows

- A modification is proposed in cRCC MPPT technology to overcome its inefficacy under partial shading
- A two staged algorithm is presented which has the capability to track the GMPPT under all kind of weather conditions.
- For swift tracking of MPP, duty modulation region is shrinked.
- The proposed iRCC method can detect the GMPP even if the two peaks appear in a narrow power difference range

The remaining paper is organized as follows. Section II explains the single diode model of a PV module so that new reader can understand the working of a PV module. The section III explains the behavior of load when it is connected to a PV module through a boost converter. Thereafter, the working of conventional RCC method and proposed improved RCC method is explained in section IV and section V respectively. The concept validation is done using two methods. The test scnarios and simulation is presented in section VI, while the hardware testing results are given in section VII. The paper ends with conclusion provided in section VIII.

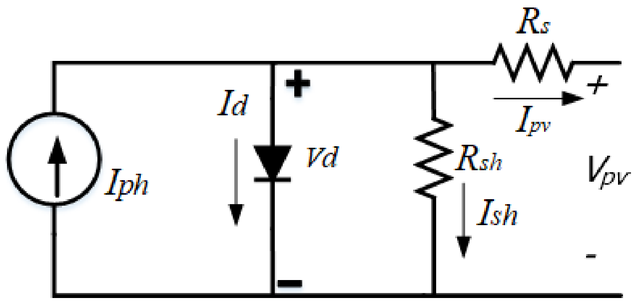

FIGURE 1. Electrical model of a practical PV device.

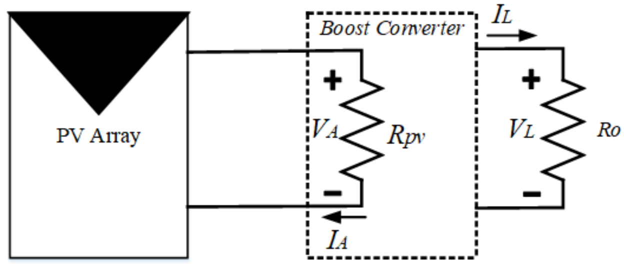

FIGURE 2. Reflection of resistive load on PV through DC-DC converter.

II. MODELING OF PHOTOVOLTAIC SYSTEM

Fig.1 shows a single-diode model of a PV panel [32]. It consist of a current source which represent the photo current, a diode to represent the PN junction and, shunt and series resistances to model the losses in the PV panel. Applying basic circuit theory results in eq. (1).

$$I_{ph} = I_d + I_{sh} + I_{pv} \tag{1}$$

where, I_{ph} is the photo current, I_d represents the diode current, I_{sh} is the current through the shunt resistance R_{sh} and I_{pv} is the output current. The current I_{sh} is calculated using eq. (2)

$$I_{sh} = \frac{V_d}{R_{sh}} \tag{2}$$

where V_d represents the potential difference across the PN junction and is given as (3)

$$V_d = V_{pv} + I_{pv}R_s \tag{3}$$

Using Shockley diode equation, I_d is calculated as eq. (4)

$$I_d = I_0 \exp((V_d/N_sV_t) - 1) \tag{4}$$

where, I_0 is the reverse saturation current of diode, V_t is thermal voltage given as $\alpha K_b T/q$, where T is temperature in kelvin, K_b is boltzman constant, q is charge on electron and α is diode ideality factor. Using the expressions in (2), (4), the eq. (1) takes the form eq. (5) given below.

$$I = I_{ph} - I_o \exp(q(V_{pv} + I_{pv}R_s)/\alpha K_b T N_s) - 1 \tag{5}$$

Solution to eq.(5) is not trivial and numerical analysis or heuristic based methods are deployed to solve this equation as presented in [33], [34], and [35].

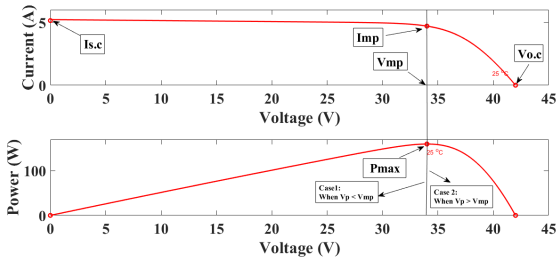

FIGURE 3. Characteristic curves of an arbitrary PV module.

III. PV INTERFACING WITH BOOST CONVERTER

In practical applications, a PV device is connected to a load through a switching converter. Based on the control input, a switching converter create an impedance match between the load and the PV source. The voltage of the PV array is not fixed and can vary from 0 to V_{oc}. To track the MPP, value of duty ratio D is altered using MPPT algorithm. The value of D, for a dc-dc boost converter, can be calculated through (6)

$$D_{mp} = 1 - \sqrt{R_{mp}/R_o} \tag{6}$$

where R_{mp} is V_{mp}/I_{mp} at STC, R_o is the load resistance. D_{mp} is the value of duty cycle at MPP. Also, assuming a lossless converter, the input output current has following relation

$$I_{pv} = I_o/(1-D) \tag{7}$$

using the expression for R_{mp} and (7), the relation between the R_{pv} and R_o is expressed as

$$R_{pv} = (1-D)^2 R_o \tag{8}$$

Note that changing duty cycle changes the I-V characteristic of the switching converter. Which implies a definite change in the operating point of the PV system. Hence, the slope of load line is given as eq. (9)

$$slope = \frac{1}{R_{pv}} \tag{9}$$

IV. CONVENTIONAL RIPPLE CORRELATION CONTROL (CRCC) MPPT

RCC utilizes inherent ripple present in current and voltage. The overall mathematical optimization is discussed at large in [36]. The power vs voltage (P-V) and current vs voltage (I-V) characteristic of a solar panel under uniform irradiance is divided in two cases as shown in Fig.3, wherein, the change in PV power for the case 1 is positive and negative for the case 2. The time base derivative of the both power and voltage determine that whether or not the correlation is greater than zero.

Case1:
When $V_{PV} < V_{MP}$

$$(dP/dt)(dV/dt) > 0 \tag{10}$$

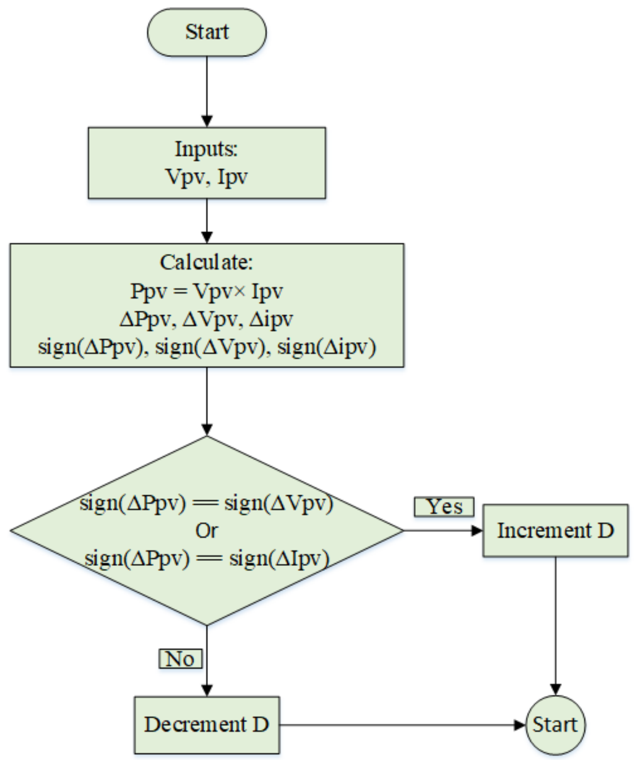

FIGURE 4. Flowchart of conventional RCC MPPT.

Case2:
When $V_{PV} > V_{MP}$

$$(dP/dt)(dV/dt) < 0 \tag{11}$$

$$d = m\int (dP/dt)(dV/dt)dt \tag{12}$$

$$Sign(x) = \begin{cases} -1 & \text{When } x < 0 \\ 0 & \text{When } x = 0 \\ 1 & \text{When } x > 0 \end{cases} \tag{13}$$

$$d = m\int sign(dP/dt)sign(dV/dt)dt \tag{14}$$

From eq. (10), it is evident that the ripple of power and voltage are in phase, i.e., the product of time-based derivative is greater than zero, and for case 2 they are out of phase because in case 2 the time based derivative is less than zero. This analysis relates to the duty cycle of the converter on the time-based derivative of the array voltage and power as expressed in eq. (12). The P-V curve shown in Fig.3, showcase that the MPP is achieved when the derivative of voltage and power is zero. Some complicated works use variations in eq. (13) by taking the Signum function over the time derivatives of voltage and power [26]. The conventional RCC MPPT is based on executing eq. (14) to compute the required duty ratio "d" for the control unit. The Signum function in eq. (14) eliminate the noise caused by the differentiation. Note that the duty ratio can be calculated

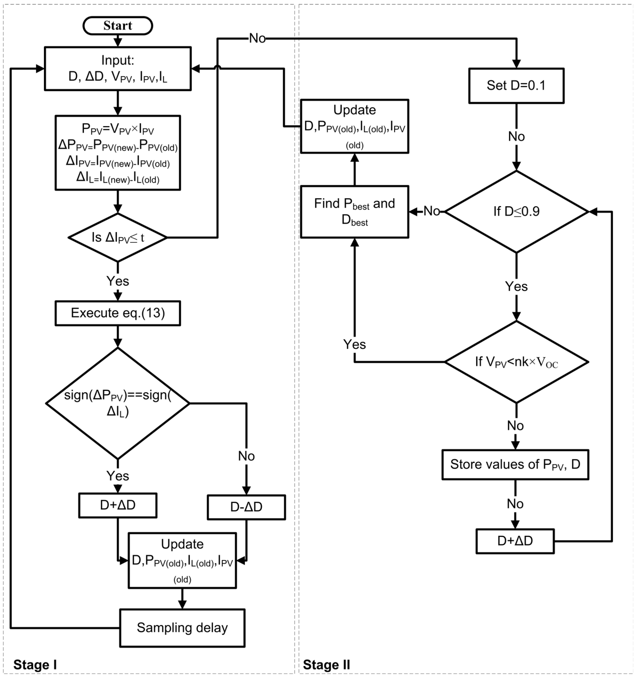

FIGURE 5. Proposed hybrid two stage iRCC algorithm.

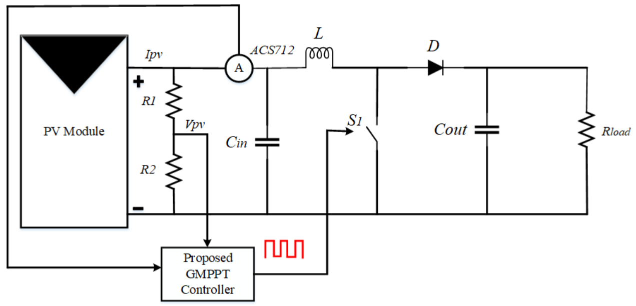

FIGURE 6. Block diagram of proposed algorithm.

either through voltage or current, however voltage based RCC method is considered more suitable for high frequency applications [27].

Fig.4 represents the conventional flowchart of ripple correlation control technique, in which the voltage and current are sensed and signum function is applied according to eq. (13) and, a corresponding increase or decrease in the duty cycle takes place until the maximum power point P_{MP} is reached. The conventional RCC MPPT is not able to work under partial shading conditions.

V. PROPOSED HYBRID TWO STAGE RCC ALGORITHM

The flowchart of the proposed two stage RCC algorithm is shown in Fig.5. The working of these two stages are explained below.

A. STAGE I | CONVENTIONAL RCC

Stage I is a conventional RCC which initiates the algorithm. The array voltage, current and inductor current are first detected and the power is calculated. This stage also calculates the change in power and current by comparing the stored and instantaneous values. Thereafter, eq. (13) is executed and based on it their difference is checked. If the resultant entities are equal then an increment is applied else a decrement is applied to the duty cycle. This stage works only in steady weather conditions. Any abrupt change in current indicates a partial shading condition which is sensed through a threshold limit ‘t’. This limit can be arbitrarily set according to the PV panels and the environmental conditions of the area. If the change in PV current exceeds this limit the stage I shifts the control to stage II.

B. STAGE II | PARTIAL SHADING DETECTION

Stage II is a process to identify the global maxima in a partially shaded PV array through duty cycle sweeping method. So initially, the duty ratio is modulated from D=0.1 till D=0.9 with modulation ratio equal to ΔD. It also limits the duty modulation region by using the concept of fractional open circuit voltage (FOCV) MPPT method, i.e., $V_{MP} = kV_{oc}$, where V_{oc} is the open circuit voltage of PV array at standard test condition (STC). The value of k comes from the manufacturer information of the panels with usual values ranging between 0.7-0.85 [37]. Throughout the process of duty modulation, the resultant power along with that particular duty ratio is stored as an array. After D reaches 0.9 the system moves to the array and fetch the best duty ratio corresponding to the best P_{PV}. Thereafter, it updates the values of duty cycle, power and current.

VI. CONCEPT VALIDATION

The proposed modification in the RCC MPPT is validated using computer aided simulations and an experimental prototype built in the lab. The general block diagram of the test bench is shown in Fig.6. The overall system consists of a PV array (2 × 2) with specifications provided in Table 1, a dc-dc boost converter, current and voltage sensors and a controller for compiling the MPPT algorithm. A voltage divider network is used to sense the PV voltage and a hall effect sensor is used to measure the current of the PV array. The proposed iRCC algorithm is simulated in the MATLAB/Simulink. To benchmark, the proposed iRCC is compared with the cRCC MPPT. Furthermore, the testing conditions are not only restricted to the fixed environmental conditions, but different partial shading conditions are also applied to verify the effectiveness of proposed RCC MPPT.

TABLE 1. Data Sheet of PV Module at STC 1000W/m^2, AM 1.5, 25°C.

Parameters	Specification	Values
P_{MP}	Maximum Power Point	40 W
V_{OC}	Open Circuit Voltage	21 V
I_{SC}	Short Circuit Current	2.57 A
V_{MP}	Voltage at MPP	17V
I_{MP}	Current at MPP	2.35A
N_s	No. of series connected cells	60

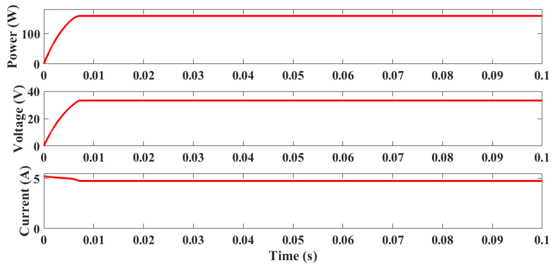

FIGURE 7. Power tracking of two stage algorithm under STC.

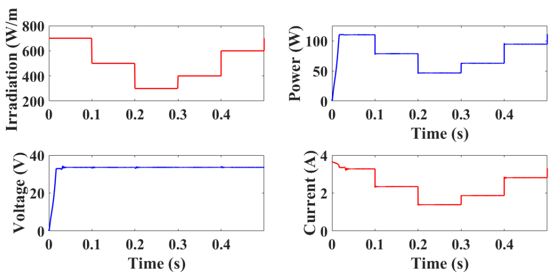

FIGURE 8. Power tracking of the two stage algorithm under variable irradiance.

A. SIMULATION

This arrangement is tested under standard testing condition (1000 $\frac{W}{m^2}$ and 25°C), variable irradiance condition and under two different partial shading scenarios listed in Table 2. The partial shading conditions are selected such that the GMPP occurs in first peak for the PSC-1 and on second peak for PSC-2.

TABLE 2. Partial shading scenarios.

Irradiance	G1(W/m^2)	G2(W/m^2)	G3(W/m^2)	G4(W/m^2)
Module	M_{11}	M_{12}	M_{21}	M_{22}
PSC-1	200	200	1000	1000
PSC-2	900	900	600	600

1) PERFORMANCE UNDER STANDARD TESTING CONDITION (STC)

Figure 7 shows that the key waveform obtained under the STC. The proposed system worked well under the STC.

2) PERFORMANCE UNDER VARIABLE IRRADIANCE CONDITION

Variable irradiance test is performed against step increase and decrease in irradiance at 25°C according to the pattern shown in Fig. 8. The irradiance is set initially at 700 $\frac{W}{m^2}$ till 0.1 s. After which a cloud is emulated by stepping the irradiance down to 500 $\frac{W}{m^2}$. At 0.2 s the cloud density increased such that the irradiance falls to 300 $\frac{W}{m^2}$ till time t=0.3 s. The subsequent increase in irradiance at 400 and 600 $\frac{W}{m^2}$ occurs at the same time interval of 0.1 s. The resultant graphs are also plotted within Fig. 8 and shows satisfactory performance.

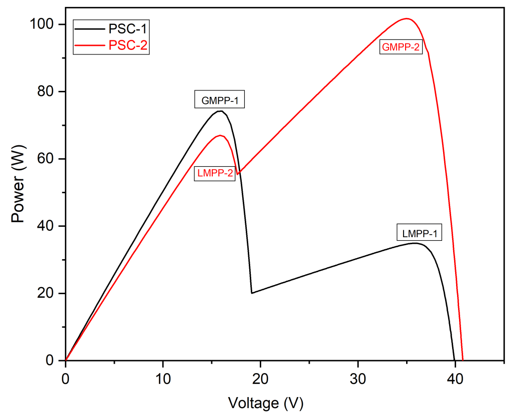

FIGURE 9. Resultant P-V curves under partial shading conditions 1 and 2.

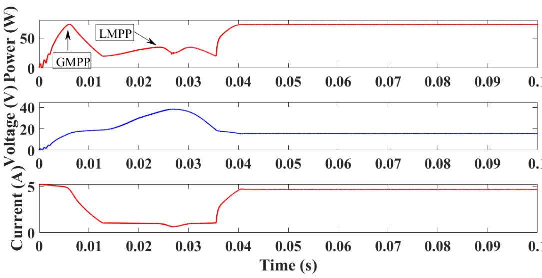

FIGURE 10. Power tracking of the proposed algorithm under PSC-1.

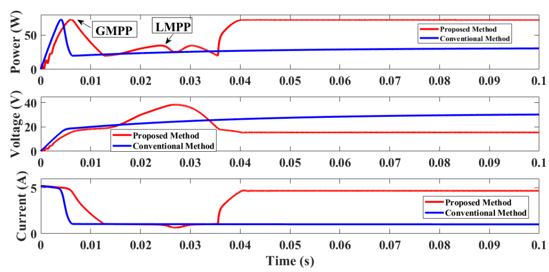

FIGURE 11. Comparison of the proposed and conventional method under PSC-1.

3) TEST UNDER PARTIAL SHADING CONDITION

This test is to identify the performance of proposed two stage algorithm in reaching the GMPP. The selected scheme of PV panels when subjected to the partial shading conditions listed in table 2 the resultant P-V curves exhibit two power peaks as as shown in Fig.9.

Figure 10 reveals that the proposed two stage algorithm is able to operate the system at GMPP owing to the use of partial shading detection stage inbuilt.

When PSC-2 is applied to the system, the algorithm first detects the peaks according to the proposed algorithm, and then operate the system at the GMPP as shown in corresponding power curve of the system shown in Fig.12. The performance gain of proposed hybrid two stage algorithm is summarized in Table 3.

TABLE 3. Comparison of the proposed and conventional method for PSC-1 and PSC-2.

Method	P_{max}(W)	Photovoltaic Power (W)	Tracking time (ms)	Tracking efficiency (in percent)
Proposed Method	72.91 for PSC-1	72.57	40	99.53
Conventional Method	72.91 for PSC-1	31.38	200	43.03
Proposed Method	101 for PSC-2	100.6	27.2	99.60
Conventional Method	101 for PSC-2	100.3	30.76	99.30

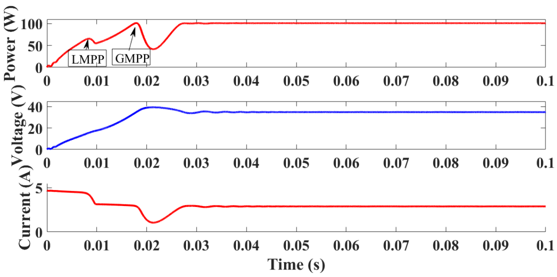

FIGURE 12. Power tracking of the proposed algorithm under PSC-2.

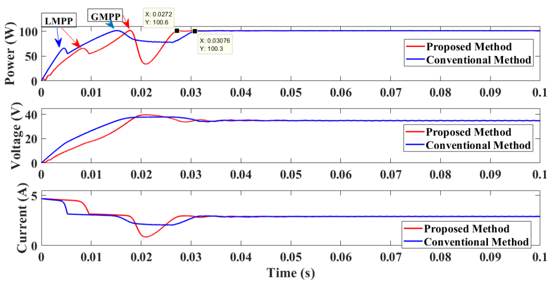

FIGURE 13. Comparison of the proposed and conventional method under PSC-2.

B. ANALYSIS AND PERFORMANCE COMPARISON OF RECOMMEND APPROACH

The proposed method provides the duty cycle using two sensors such as voltage and current, while conventional ones also use two. In the proposed and conventional method, only one diode and one mosfet are used. The degree of complexity of the conventional method is low compared to the proposed method. The proposed method reacts accurately to any type of partial shade. The reaction of the conventional method against partial shading is not accurate. Figure 11 shows when the irradiation took place so that its 1st peak is GMPP. From the Fig.11, the conventional method remains at the 2nd peak, regardless of whether it is not GMPP. In such a scenario, the conventional method remains with less power from the 2nd peak while the proposed method sticks to this peak, which is the GMPP. Fig.13 shows when a partial shading has occurred so that the 2nd peak is GMPP. In such a case, both the proposed and the conventional methods follow the peak which is the GMPP. In the same Fig.13 the tracking time of the conventional method is high. The tracking time of the proposed method is low. The settling time of the of the proposed method is high, whereas the conventional method have settling time low.

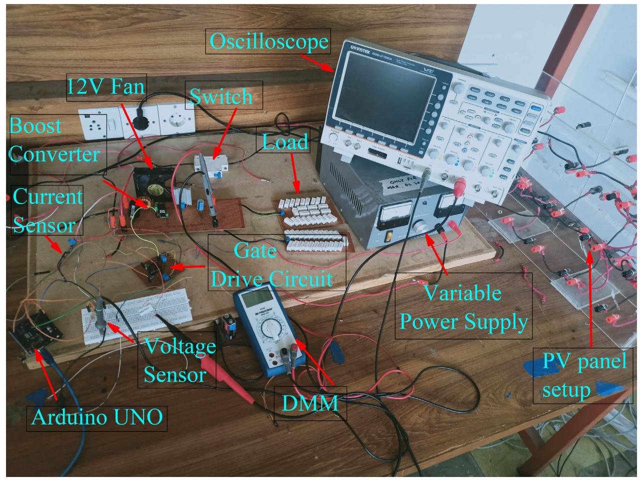

FIGURE 14. Experimental setup.

Table 3 shows the comparison of various parameters between the proposed method and the conventional method. In the partially shaded state PSC-1, the nominal power is 72.91 W, the power track according to the proposed method is 72.57 W. While the power track with the conventional method is 31.38 W. In the same case, the settling time of the proposed method is 40 ms, while it is 200 ms for the conventional method. In the next case of PSC-2, the nominal power is 101 W, the power track according to the proposed method is 100.6 W with a settling time of 27.2 ms. The power trace according to the conventional method in the PSC-2 is 100.3 W with a settling time of 30.7 ms. After analyzing the result of the both the method under different PSC's. The proposed method is suitable to track the rated power under any kind of the PSC's, whereas the conventional method fail under various condition of PSC's. The tracking speed of the proposed method under any case of PSC's is good enough than the conventional method. The efficiency of the proposed method under any PSC's is also better than the conventional method.

VII. EXPERIMENTAL VALIDATION

The proposed two stage hybrid algorithm is experimentally verified using a hardware prototype as shown in Fig.14. The values of the key components of this setup are tabulated in table 4. Although, the voltage is sensed using a voltage divider network, ACS712 20 A current sensor is used to sense the current. The output of these sensors interacts with a micro-controller which runs the proposed algorithm. The

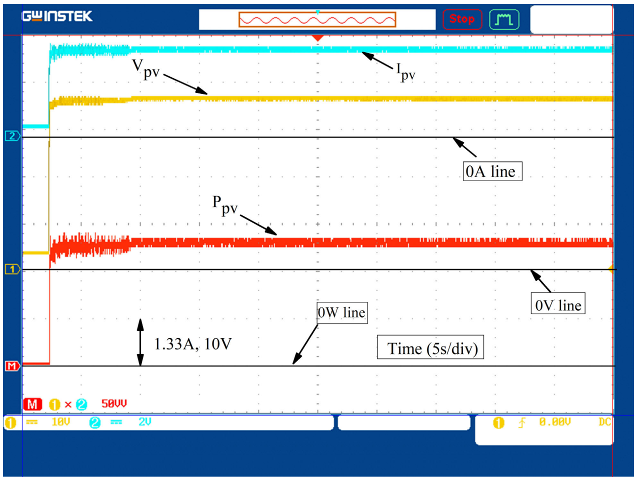

FIGURE 15. Experimental results for uniform irradiance condition.

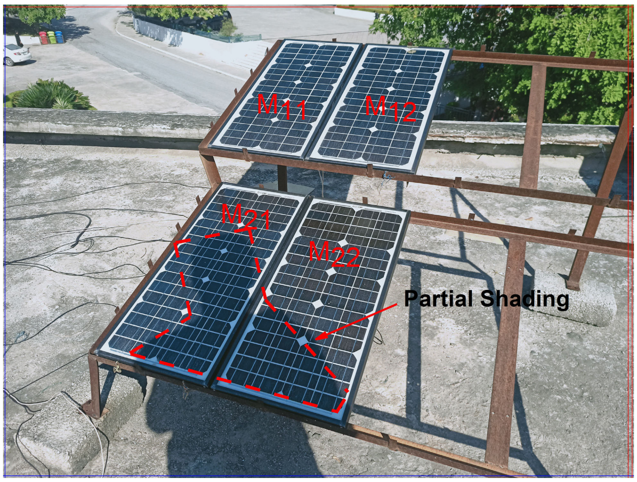

FIGURE 16. Partial shading condition 1 (PSC-1).

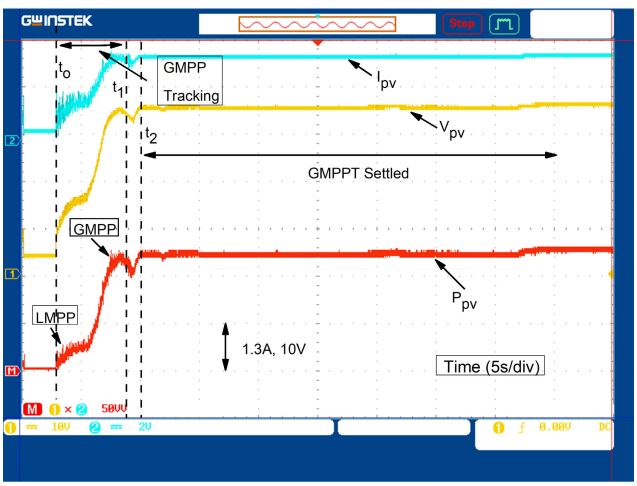

FIGURE 17. Performance of proposed algorithm | Partial shading condition 1.

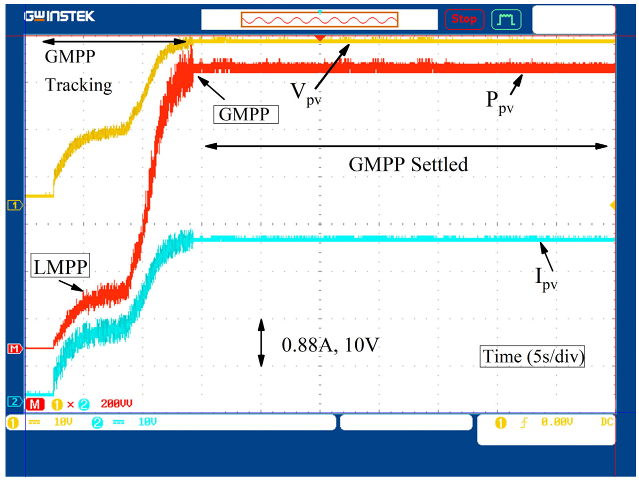

FIGURE 18. Performance of conventional algorithm | Partial shading condition 1.

FIGURE 19. Partial shading condition II.

proposed method provide the desired switching pulse to the gate driver circuit to tack the GMPPT. This experimental verification process includes the benchmark of the proposed hybrid algorithm with conventional RCC MPPT method.

Following the simulation test, the Fig. 15 shows the hardware results of the proposed algorithm when tested under uniform irradiance condition. Thereafter, the tests for partial shading are conducted. Figure 16 shows the realization of PSC-1 wherein, a human shadow is created over panel M_{21}

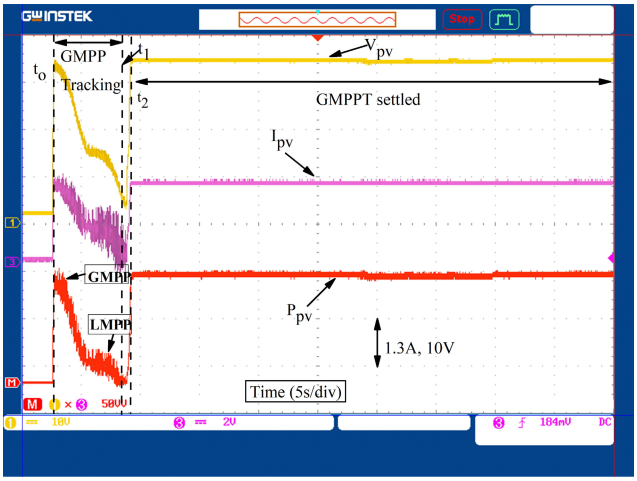

FIGURE 20. Performance of proposed algorithm | Partial shading condition 2. (PSC-2).

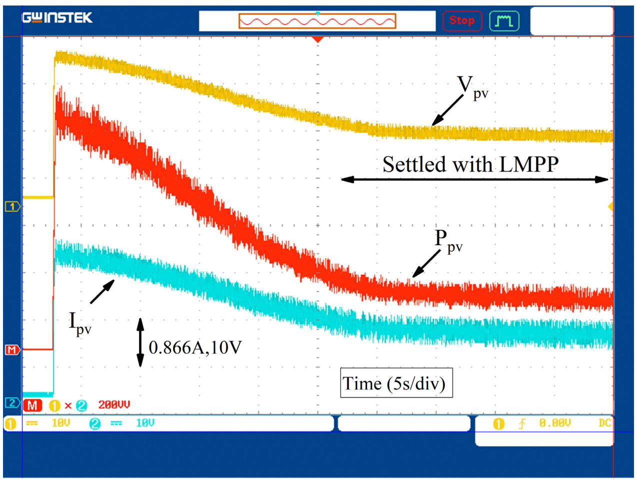

FIGURE 21. Performance of conventional algorithm | Partial shading condition 2.

TABLE 4. Detail of prototype components.

Components	Variable	Value
2X2 array		Table ??
Inductor	L	160 μH
Input Capacitor	C_{in}	1000 μF
Output Capacitor	C_{out}	47 μF
Load Resistance	R_L	63 Ω

andM_{22} while panel M_{11} and M_{12} have no shadow over them. This partial shading scenario creates a P-V curve such that the GMPP lies on the 2nd peak as evident from Fig. 17. For the same partial shading scenario, the performance of conventional RCC algorithm is elaborated in Fig.18.

Figure 19 shows the second scenario of partial shading that results in the generation of GMPP in the first peak. Here, panel M_{11} and M_{12} are under the man made shadow,whereas panel M_{21} and M_{22} have no shadow. Figure 20 shows the experimental graph for the proposed hybrid two stage algorithm. It is evident that from time t_0 to t_1 first it detects the global maxima using duty modulation stage and then from time t_1 to t_2 it initiates the second stage based on RCC to stick with the GMPP. On the other hand, for the same partial shading scenario, the performance of conventional RCC MPPT is shown in Fig.21. It is clear that despite having a change in weather condition, the conventional RCC MPPT algorithm operates at the second peak which is LMPP.

This experimental verification proves the effectiveness of the proposed method in contrast with the conventional RCC method.

VIII. CONCLUSION

In this work, an iRCC algorithm is proposed to achieve the global maximum power point. The proposed algorithm is able to work under partial shading condition as verified under different practical testing conditions. After analyzing the result we conclude that: The proposed iRCC method follows the GMPP with good tracking efficiency. Whereas the conventional cRCC may or may not track the GMPP depending upon the pattern of shading.

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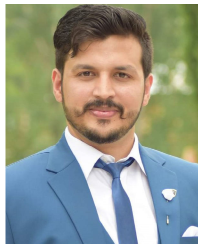

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