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An Adaptive resistance perturbation based MPPT algorithm for Photovoltaic applications

MAHESWARAN GUNASEKARAN[1,3], (Student Member, IEEE), VIJAYAKUMAR KRISHNASAMY[1],(Senior member, IEEE), SIVAKUMAR SELVAM[2],(Member, IEEE) DHAFER J ALMAKHLES[2],(Member, IEEE), and NORMA ANGLANI[3],(Senior Member, IEEE)

[1]SRM Institute of Science and Technology, Tamilnadu, India
[2]Renewable Energy Laboratory, Prince Sultan University, Riyath, Saudi Arabia
[3]Department of Electrical, Computer and Biomedical Engineering, University of Pavia, Italy

Corresponding author: Vijayakumar Krishnasamy (e-mail: kvijay_srm@rediffmail.com).

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ABSTRACT This paper proposes a Resistance perturbation based maximum power point tracking (MPPT) with an adaptive control limit algorithm to extract the maximum power from solar photovoltaic (PV) array. This algorithm consists of two main functions, namely 1) resistance perturbation & observation (RP&O) and 2) adaptive resistance control (ARC) limit. The RP&O operates the PV array at maximum power point (MPP), and the ARC limit continuously monitors the resistance of the PV R_{pv} to determine the operating limit of MPP. The ultimate aim of proposing this algorithm is to reduce the oscillations and improve MPP's tracking performance for sudden variation in temperature and irradiance conditions. Furthermore, it does not require an expensive pyranometer or temperature sensor to track the MPP of the PV array. This paper also compares the proposed and conventional MPPT algorithm's performance. Its validation results in both MATLAB/Simulink and experimental studies are presented under constant and sudden changes in irradiance conditions.

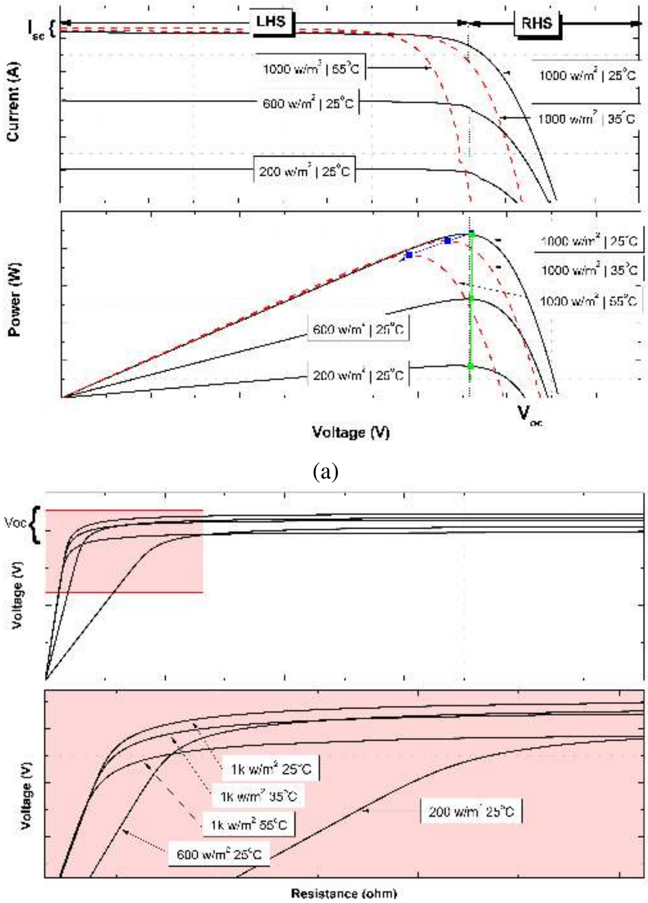
INDEX TERMS Adaptive Resistance Control (ARC) limit, Irradiance, Maximum Power Point Tracking (MPPT), Power Oscillations, Resistance Perturbation & Observation (RP&O).

I. INTRODUCTION

NOWADAYS most of the countries are focusing on power generation from the non conventional energy sources instead of conventional energy sources to reduce the environmental impacts [1]. The availability of energy sources like wind, hydro and solar photovoltaic, etc are abundant in nature. Among all these energy sources, solar photovoltaic (PV) is the most promising non-conventional energy sources, due to its less maintenance and pollution free to the environment. Though there are many advantages in considering power generation from PV, it has a few drawbacks in real-time such as non-linear V-I characteristics, constant power generation, efficiency and large space requirement. Power generated from the solar PV is not constant throughout a day because of continuously varying weather conditions and also it is available only in day time. Due to its intermittent in nature, power generated from PV is maximum at only one point for the given irradiance (W/m^2) and temperature (^{o}C).). It is named as a maximum power point (MPP) of PV, where it's operating voltage (V_{mp}) and current (I_{mp}) of the MPP related to irradiance and temperature is shown in Fig. 1a. Therefore, designing a maximum power point tracking algorithm plays a major role in solar PV system. In [2,3] the authors discussed a wide range of MPPT algorithms .They are categorized in terms of parameter estimation, usage of sensors, computation time, controller complexity, variable step size perturbation, tracking speed and their implementation cost. The key ideas behind all developed MPPT algorithms are to track the MPP faster and more accurate in varying irradiance condition with low power oscillations.

Though there were many developed algorithms in the literature, main focus has been given to incremental conductance (INC), P&O and hill climbing (HC) algorithms [4-6]. The main control parameter considered for all these three algorithms are voltage, current and duty cycle of the converter. The P&O algorithm focuses on perturbating the voltage of PV panel, while hill climbing focuses on perturbating the duty cycle “d “of the boost converter. Generally in the conventional P&O based MPPT algorithm, the voltage and power of PV system are measured instantaneously, and then the voltage is adjusted as increment or decrement to reach the MPP for appropriate direction with its fixed step size. The main drawback of the conventional P&O algorithm is its tracking direction, step size and oscillation around MPP in sudden variation in irradiance condition and it requires a PI controller to tune the control parameter. In order to overcome these issues, a modified Perturbation and observation based MPPT algorithm is proposed in [7]. In this algorithm the threshold value is introduced to fix the boundary of MPP. Thus, the changes in power are compared with threshold value, once the error is higher, then it seems the irradiance variation is assumed to be high and it is low for low error. Based on this error, the voltage is forced to follow a boundary of MPP with less oscillation. In [8], the author focused on perturbation of current instead of voltage to make the adaptive perturbation size and implemented with sudden change in variation, but it requires two additional sensors for measurement of irradiance, and short circuit current to determine the perturbation size. Hence the cost of implementation is high. In [9], the MPP is tracked by relating the switching frequency with irradiance, this variation determines the duty cycle of DC-DC converter. But its tracking speed is not in considerable limit. In order to limit the tracking speed, the self and enhanced adaptive control method is proposed in [10]. In this method, the perturbation is based on voltage instead of current. The control is executed by incremental PID controller, but it has a moderate oscillation compared to [11].

The fuzzy logic based modified P&O mppt algorithm has been proposed in [12].here the duty cycle is controlled by the adaptive step size method. Though the modified fuzzy based mppt algorithm track the mpp ,but the efficiency is less than 99%. In [11], authors developed a flexible power point algorithm, which sets the power reference based on the demand. It will work based on the power reference and maximum power limit. Even though PV produces a maximum power by this algorithm but, it was not fully utilized by the grid because a part of the power is limited. Hence it is not economical for PV MPPT methods. The single voltage sensor based algorithm was developed in [13] to limit the steady state oscillation, but it does not have better performance in sudden change in irradiance and transient state of PV system. The same approach was introduced by a modification of 80% open circuit voltage ($0.8V_{oc}$) to reduce the tracking time of oscillation around the MPP in [14]. In order to increase the Tracking efficiency of the mppt, the author [15] was used the relation between the load line and the I-V curve of the pv to track the mpp. The trigonometric based mathematical method is used to achieve the fast response with low steady oscillation. Though the tracking efficiency is improved but tracking speed and accuracy is still challenging to track the new mpp, at sudden varying irradiance condition.



(a)

(b)

FIGURE 1: (a) Typical IV and PV Characteristics and (b) RV characteristics of Solar PV array at different irradiance and temperatures

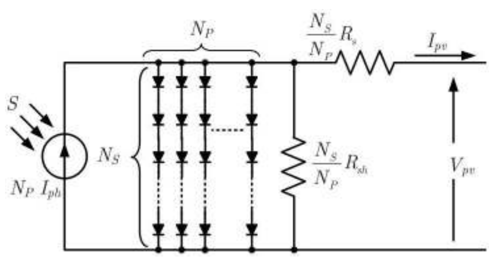


FIGURE 2: Equivalent circuit of typical Series-Parallel connected PV Cells

Some researchers focused on mathematical based theorem for mppt algorithms [16-22]. In [16], the authors modified a conventional INC algorithm by applying a residual theorem; here the fluctuation around the MPP have been minimized to apply a minimum residue values of algorithm by setting a proper gain value of controller. Even-though it has some advantages compared with conventional algorithm, it has moderate performance for sudden change in climatic conditions. To overcome this issue, the authors developed a

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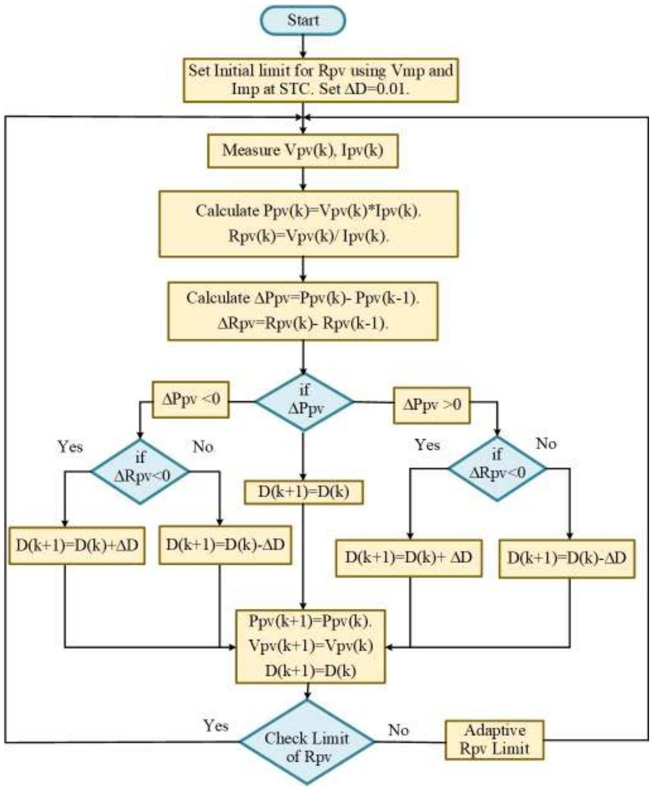
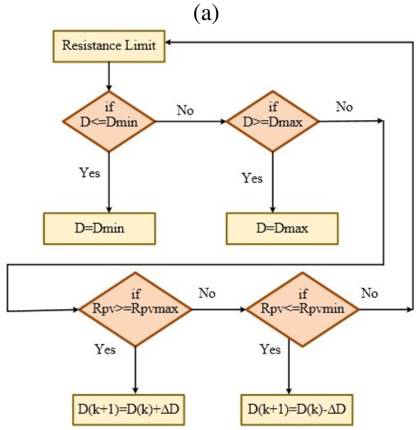


(a)



(b)

FIGURE 3: (a) Flowchart of the proposed MPPT algorithm, (b) Adaptive Rpv Limit

learning based INC method and maximize M-kalman filter based P&O algorithm in [16,17]. Its computation time is higher in comparison to the conventional algorithm. Likewise some of the soft computing based algorithms are developed in [19-22]. In these methods, the oscillation around MPP is reduced, but the computation time increases because of learning based adaptive step size perturbation. Motivated by the above discussion and in order to overcome the issues, this paper proposes a novel resistance perturbation based adaptive resistance control limit MPPT algorithm. Instead of voltage and current perturbation based MPPT reported in [23, 24],

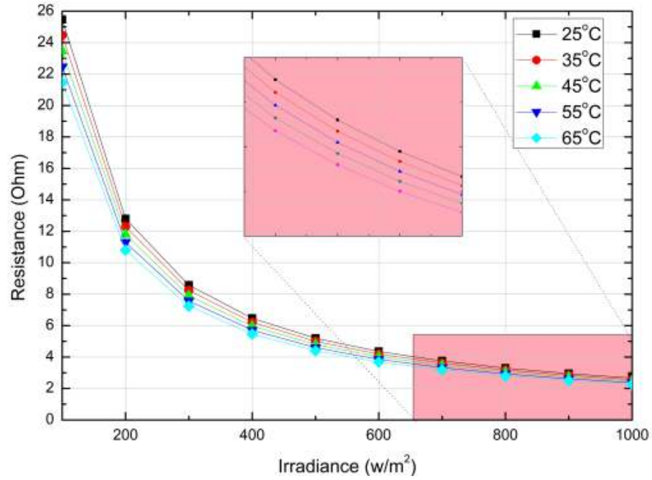


FIGURE 4: Estimated PV MPP Resistance at different Irradiance and Temperature

the proposed algorithm is developed based on the resistance perturbation by modifying conventional P&O algorithm and it is developed to reduced PV Power oscillations. It also brings the operating point of PV to quickly track the new MPP under sudden changes in irradiance without using a sensor for measuring an irradiance and short circuit current etc. In the proposed algorithm, the operating point of MPP is determined by perturbating the resistance of PV to operate in MPP boundary. The R-V characteristics of PV is shown in Fig. 1b.

To overcome a sudden varying weather condition, an ARC limit is introduced in this algorithm. The ARC sets the operating limit of PV nearer to the MPP by perturbing the PV resistance. It is designed to operate in right hand side (RHS) of PV curve, rather than both direction of PV curve. It does not require the measurement of any parameters regarding the short circuit current (I_{sc}), open circuit voltage (V_{oc}), irradiance (Irr) to operate the algorithm. Furthermore, it does not require PI based controllers hence it does not require a soft computing based tuning algorithms to tune the gain value of the controller. Its ease of implementation significantly reduces the hardware complexity. There by it overcomes the major disadvantages of conventional MPPT algorithms.

This paper is organized as follows. In section II mathematical model of PV module and Proposed MPPT algorithm is discussed. In section III the realization of boost converter is designed. The simulation and hardware studies are carried out in Section IV and V. Finally, the section VI concludes the proposed MPPT algorithm.

II. PROPOSED MPPT ALGORITHM

A. MATHEMATICAL MODEL OF PV MODULE

Fig. 2 shows the equivalent circuit of typical Series-Parallel connected PV cells. It is basically a p-n junction semiconductor device to generate a current through a photovoltaic effect. As discussed earlier, PV characteristics are non-linear in nature as represented in Fig. 1. Based on the theory of semiconductors, the basic mathematical equation that describes the ideal PV module characteristics [21-22] is given by,

$$I_{pv} = N_p I_{ph} - N_p I_d (e^{\frac{q(\frac{V_{pv}}{N_s} + \frac{I_{pv} R_s}{N_p})}{AkT}} - 1) - \frac{N_p \frac{V_{pv}}{N_s} + I_{pv} R_s}{R_{sh}} \quad (1)$$

where I_{pv}, I_{ph}, I_d is the PV terminal current, photo current generated due to solar light intensity, and diode reverse saturation current in Amperes respectively, V_{pv} is the PV terminal voltage in volts, R_s and R_{sh} is the series and shunt resistance in Ω respectively, q is the electron charge (1.609x10^{-19} C), A is the diode ideality constant, T is the PV module temperature in degree Kelvin, k is Boltz-mann's constant (1.38x10^{-23} J/K), N_s and N_p are the number of series and parallel connected PV cells, respectively.

B. RESISTANCE PERTURBATION BASED MPPT ALGORITHM

The main goal of the proposed algorithm is to track the operating point of PV near to MPP under both steady state and sudden varying climatic conditions with reduced power oscillations. This algorithm has two main functions.

1) **Resistance P&O (RP&O):** The basic idea behind this algorithm is modified from conventional P&O algorithm. Instead of current and voltage, the resistance perturbation is introduced (as PV resistance is directly proportional to PV voltage) to improve the tracking performance of the MPPT algorithm as shown in the Fig. 3.
2) **Adaptive Resistance Control limit (ARC):** This ARC limit is developed based on the perturbation of resistance. The function of this limit is to operate the resistance of PV nearer to the MPP and force the PV side DC-DC boost converter to operate in the RHS of I-V curve as shown in Fig. 1. This limit is activated only during sudden changes in irradiance or resistance of PV as shown in Fig. 3 (b).

The basic idea behind this algorithm for resistance perturbation instead of voltage or current perturbation is explained as follows: $P_{pv}(k), V_{pv}(k), I_{pv}(k)$, and $R_{pv}(k)$ are power, voltage, current, and resistance of the PV panel at k^{th} iteration. ΔR_{pv} and ΔP_{pv} are the change in PV resistance and power respectively.

Initially, the proposed algorithm starts with Resistance perturbation by measuring the changes in the PV power (ΔP_{pv}) and PV Resistance (ΔR_{pv}). Upon observing this variation, an appropriate perturbation in control signal to the DC-DC boost converter is introduced to set the new PV operating point of PV. Based on this new operating point, the direction of PV operating point can be tracked. Due to operating limit enforcement in the proposed algorithm, the PV operating point of PV quickly jumps to the MPP as compared to other

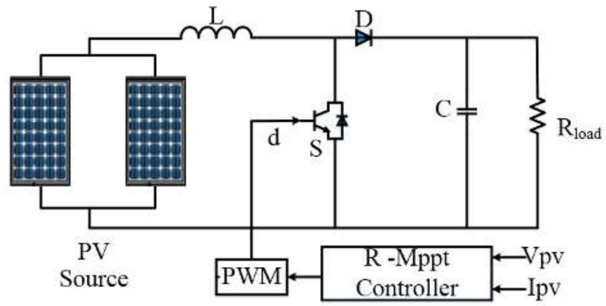


FIGURE 5: PV with Boost Converter

MPPT algorithms. Most of the proposed algorithms in the literature [18-23] operate the PV in left hand side (LHS) of MPP region. Because in the LHS of IV characteristics of PV as shown in Fig. 1a, the PV current variation is low but the PV voltage variation is high. In the proposed algorithm, the PV operates in RHS of MPP region of I-V characteristics. Hence, the voltage variation in RHS is small but current variation is high. In the proposed algorithm, the voltage variation is low by using RP&O and current variation is also low by using ARC. However, the PV should not reach beyond the short circuit current (I_{sc}) at LHS and open circuit voltage (V_{oc}) at the RHS as shown in Fig. 1a. Thus, the MPP region of proposed algorithm is as expressed below.

$$\begin{aligned} V_{mp} \le V_{pv} \le V_{oc} \\ R_{min} \le R_{pv} \le R_{max} \end{aligned} \quad (2)$$

whereas R_{min} and R_{max} are the minimum and maximum PV resistance predicted at 1000 W/m^2 @ maximum operating temperature (say 55^oC) and 100 W/m^2 @ minimum operating temperature (say 25^{o}C) respectively. Hence it can operate in minimum irradiance to maximum irradiance at corresponding MPP resistance (R_{mpp}) without calculating any other parameter like I_{sc}, V_{oc} and Irr of the PV panel like [13-24]. Whenever the irradiance of PV changes, the value of R_{pv} also changes, thereby its violating the min-max limit. At this instant ARC of proposed algorithm gets activated and forces the PV to operate in RHS of the MPP region through the duty cycle control of DC-DC converter. This enforcement makes the operating point of PV to quickly jump to the MPP region by reducing the power oscillations in tracking MPP. The proposed algorithm continuously repeats the process to limit the steady state oscillation and improves the performance in sudden changes in irradiance and hence the V_{pv}, I_{pv}, P_{pv}, and R_{pv} will be operate at MPP in all climatic conditions.

C. SET THE OPERATING POINT CONTROL LIMITS TO RHS

The ARC continuously monitors the R_{pv} in such a way that the R_{pv} lies within the limits as given in (2). The PV current expressed in (1) can be reduced to (3) by neglecting the

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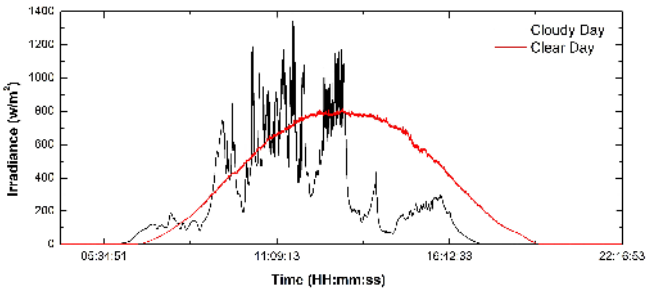

FIGURE 6: 24hrs Irradiance Data

diode saturation current and current flow in the internal PV resistance.

$$I_{pv} \cong N_p I_{pv} \cong N_p(I_{pv,n} + k_i \Delta T)\frac{G}{G_n} \quad (3)$$

where $I_{pv,n}$ is the light generated PV current, k_i, ΔT, G, G_n are the temperature coefficient of PV current (% / ^oC, change in PV panel temperature (deg Kelvin), given irradiance (W/m^2) and irradiance at standard testing conditions (STC) (1000 W/m^2), respectively. In almost all the cases, the light generated PV current $I_{pv,n}$ is approximately equal to the short circuit current (I_{sc}) of PV panel. Therefore, (3) can be modified as,

$$I_{pv} \cong N_p(I_{sc} + k_i \Delta T)\frac{G}{G_n} \quad (4)$$

Using (4), with the knowledge of I_{sc}, k_i, T and G the value of PV current at specified temperature and irradiance can be predetermined. Since the PV voltage (V_{pv}) variation in RHS of I-V curve is very low. The variation of PV voltage (V_{pv}) can be predicted for given temperature and irradiance by the following approximated expression with the knowledge of V_{mp} at STC.

$$V_{pv} \cong N_s V_{mp}(1 - \frac{1.25K_v \Delta T}{100} - 0.05V_{mp}\frac{G_n - G}{1000}) \quad (5)$$

whereas V_{mp} and k_v are the PV voltage at MPP and temperature coefficient of voltage (%/^oC) respectively. Using (4) and (5), the initial PV resistance limit for ARC can be estimated as

$$R_{pv} = \frac{V_{pv}}{I_{pv}}$$
$$R_{pv} \cong \frac{N_s V_{mp}(1 - \frac{1.25K_v \Delta T}{100} - 0.05V_{mp}\frac{G_n - G}{1000})}{N_p(I_{sc} + k_i \Delta T)\frac{G}{G_n}} \quad (6)$$

Using (6), the minimum and maximum limit of R_{pv} can be estimated. If the PV panel temperature increases for the given irradiance, the R_{mp} at corresponding temperature reduces. Similarly, the irradiance of solar decreases for a given temperature, then the R_{mp} at the corresponding irradiance increases. Using (6), the initial limit for R_{pv} can be estimated in such way that the proposed algorithm operates the PV panel at the RHS of I-V curve. Minimum resistance for the limit can be estimated at 1000 W/m^2 with assumed maximum operating temperature of 55^{o}C, R_{pv},min value will be,

$$R_{pv,min} \cong \frac{N_s V_{mp}(1 - \frac{1.25K_v \Delta T}{100} - 0.05V_{mp}\frac{G_n - 1000}{1000})}{N_p(I_{sc} + k_i \Delta T)\frac{1000}{G_n}} \quad (7)$$

where as ΔT=(55+273.15)-(25+273.15). Similarly, the maximum resistance for the limit can be estimated at assumed irradiance change upto 100W/m^2 with assumed maximum operating temperature of 25^{o}C, $R_{pv,max}$ value will be,

$$R_{pv,max} \cong \frac{N_s V_{mp}(1 - \frac{1.25K_v \Delta T}{100} - 0.05V_{mp}\frac{G_n - 100}{1000})}{N_p(I_{sc} + k_i \Delta T)\frac{100}{G_n}} \quad (8)$$

From (7) and (8), the minimum and maximum PV resistance operating limit can be estimated. Fig. 4 shows the estimated R_{mp} values at different operating temperature and irradiance for the PV panel specification given in Table 1. These predicted values of R_{mp} match with the actual PV data with maximum error of 2.5%

III. PROPOSED MPPT ALGORITHM REALIZATION USING BOOST CONVERTER

Fig. 5 shows the schematic of the boost converter to realized the proposed MPPT algorithm, which enables the load to consume maximum power available from the PV by matching the PV and load resistance by duty ratio control. The duty ratio (d) can be determined by evaluating the input and output relation of boost converter. Consider the ideal lossless boost converter. The output voltage can be expressed as,

$$V_o = \frac{V_{in}}{1-d}$$
$$I_o = I_{in}(1-d) \quad (9)$$

Where V_{in}, V_o, I_{in} and I_o are the PV voltage (V_{pv}), Boost converter output voltage, PV current (I_{pv}) and Boost converter output current respectively. Using (9), the load resistance of the boost converter and the operating duty cycle for the given load can be determined as,

$$R_o = \frac{V_o}{I_o} = \frac{R_{in}}{(1-d)^2} \quad (10)$$

Where, $R_{in} = \frac{V_{in}}{I_{in}}$. Using (10), the operating duty ratio of boost converter for the given load can be expressed as,

$$d = 1 - \sqrt{\frac{R_{in}}{R_o}} \quad (11)$$

Since, R_{in} is the solar PV resistance R_{pv}, then (11) can be rewritten as,

$$d = 1 - \sqrt{\frac{R_{pv}}{R_o}} \quad (12)$$

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From the equation (12), it is clear that the duty cycle also depend on the PV resistance (R_{pv}) and the load resistance (R_o). The inductor and capacitor values of the boost converter are designed based on [25]. Considering the boost converter operating in continuous current conduction mode, then for inductor with 1% current ripple(ΔIpv) at switching frequency (f_s) = 10 kHz as,

$$L = \frac{V_{pv} d}{2 \Delta I_{pv} f_s} \tag{13}$$

For capacitor 1% voltage ripple (ΔVo) at switching frequency (f_s)= 10 kHz as,

$$C = \frac{I_o d}{2 \Delta V_o f_s} \tag{14}$$

For a resistive loading of R=25Ω, the load current I_o, load voltage V_o and the nominal duty cycle d for the PV panel specification given in Table 1 is,

$$\begin{aligned} I_o &= \sqrt{\frac{P_o}{R}} = 4A \\ V_o &= \sqrt{P_o R} = 100V \\ d_{nom} &= 1 - \sqrt{\frac{R_{mp}}{R}} = 0.6 \end{aligned} \tag{15}$$

For the load current I_o in (15), the value of L and C from (13) and (14) is 12mH and 120μF respectively. The available value of capacitance in the market for the output voltage determined from (15) is 270μF at 160V.

TABLE 1: PV Panel Specifications at STC

Parameters	Values
Maximum Power P_{mp}	200W
Open Circuit Voltage V_{oc}	47.8V
Short Circuit Voltage I_{sc}	5.4A
Voltage at maximum power V_{mp}	40V
Current at maximum power I_{mp}	5A
Voltage temperature coefficient k_v	-0.29841%/^{o}C
Current temperature coefficient k_i	0.046%/^{o}C

TABLE 2: Boost Converter Nominal Values

Parameters	Values
Input Voltage V_{pv}	40V
Input Current I_{pv}	10A
Output Voltage V_o	100V
Output Current I_o	4A
Load resistance R	25 Ω
Duty ratio d	0.6
Inductor L	12mH
Capacitor C	270μF
Switching Frequency f_s	10KHz

IV. SIMULATION STUDIES

The performance of the proposed MPPT algorithm is validated through simulation using MATLAB/Simulink under different operating conditions. Boost converter is designed for the nominal values mentioned in the Table 2 and it is operated with the proposed RP&O MPPT algorithm for the PV panel mentioned in the Table 1. The solar PV system considered for the simulations studies are described in the Table 1. In simulation studies, the proposed MPPT algorithm is tested for 400 W by connecting two PV modules in parallel. The PV array is simulated here in two different cases say (i) Sudden change in irradiance while operating at 25^{o}C temperature and (ii) Sudden change in irradiance while operating at 55^{o}C. Fig. 6 shows the 24 hrs real time irradiance data of a typical clear and cloudy day recorded using pyranometer by Gantner Instruments. Before starting the simulation, as per the proposed MPPT algorithm, the operating limits are calculated. Fig. 4 shows the predicted values of R_{mp} for the PV string configuration given in Table 1 ranges from 1000W/m^2 to 100W/m^2 at 25^{o}C to 55^{o}C. Using (7 & 8), the minimum and maximum estimated value of PV resistance for the proposed PV configuration is calculated.

The tracking curve of MPP for the proposed MPPT algorithm with sudden increase in irradiance from 600 to 850W/m^2 and sudden decrease from 850 to 600 $W/m^2$is shown in the Fig 7(a)-(b). Fig 8 shows the irradiance pattern to test the proposed MPPT and conventional P & O algorithm operated under 25^{o}C and 55^{o}C respectively. At the time t=(0-0.5)s the irradiance is 600 W/m^2, the operating point of MPP for conventional P&O algorithm and proposed algorithm is at point A. At the time t=0.5s, the irradiance of the PV array is suddenly increased from 600 W/m^2 to 850 W/m^2, then the MPP point for conventional algorithm is moved from A and it reaches the point C through A-D-E-C, where as it starts from point A and reaches point C through A-B-C for proposed algorithm as shown in Fig. 7a. At the time t=1s, the irradiance of the PV array decreases from 850 to 600W/m^2.In order to track the sudden changes in irradiance of PV the MPP point is further moved from point C-A as C-H-G-I-A for conventional P&O algorithm, whereas it reaches the MPP point C-A as C-F-A for the proposed MPPT algorithm as shown in Fig. 7b. Table 3 tabulates the tracking path of proposed and conventional MPPT algorithm.

The operating limits in the proposed MPPT algorithm for simulation studies can be estimated from (7) & (8). $R_{pv,min}$=3.54Ω (1000 W/m^2 at 55^{o}C) and $R_{pv,max}$=9.7Ω (400 W/m^2 at 25^{o}C) which corresponds to the duty cycle limits of D_{min}=0.19 and D_{max}=0.52. These are the adaptive limits for the proposed MPPT algorithm for the given PV configuration.

From Fig. 9(a), initially the irradiance of the panel is at 600 W/m^2 with MPP voltage and current of 39.9 V and 6A. At time 0.05s, it was suddenly increased to 850 W/m^2. At 850W/m^2, the V_{pv}=39.83 V, I_{pv}=8.54 A, R_{pv}=4.66Ω and Ppv=340.14 W. During the sudden change in irradiance, the

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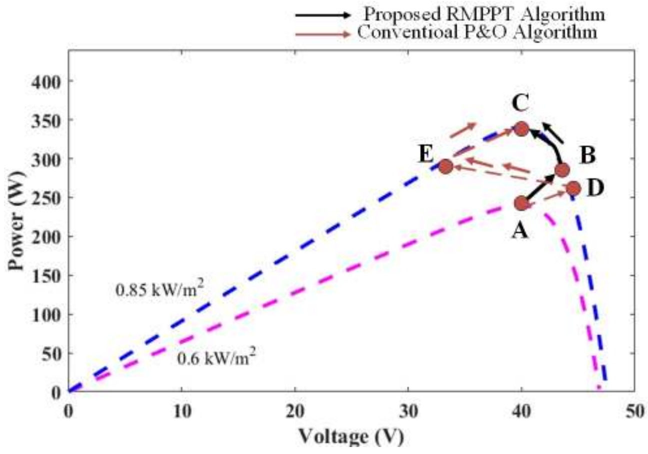
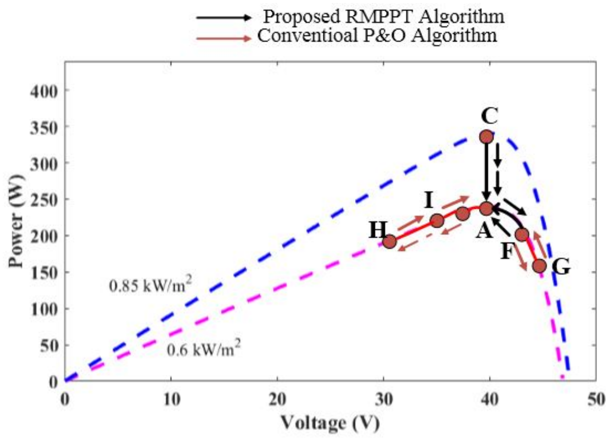


(a)



(b)

FIGURE 7: a) Tracking curve for sudden increase in irradiance b) Tracking curve for sudden decrease in irradiance.

TABLE 3: Comparison of Tracking performance for Conventional and Proposed MPPT algorithm

Cases	Conventional P & O algorithm		Proposed MPPT algorithm	
	600 to 850 w/m^2	850 to 600 w/m^2	600 to 850 w/m^2	850 to 600 w/m^2
Tracking Direction	A-D-E-C	C-H-G-I-A	A-B-C	C-F-A
Tracking path	LHS-RHS		RHS	
Tracking Time (cycles)	11	9	5	4

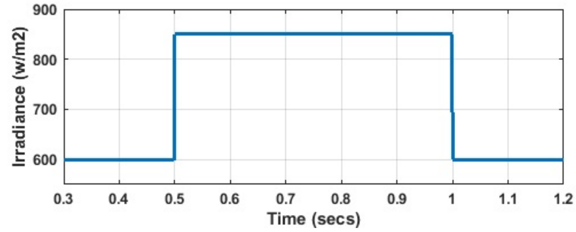


FIGURE 8: Irradiance (W/m^2) pattern used for the simulation studies

TABLE 4: Steady State performance parameters variations

Parameter	Variation***							
	P & O				Proposed			
	25^oC		55^oC		25^oC		55^oC	
	S	E	S	E	S	E	S	E
ΔV_{pv}(V)	3.22	4	2.446	6	0.39	0.4	0.1	0.1
ΔI_{pv}(A)	0.83	1	0.69	0.8	0.09	0.08	0.02	0.1
ΔP_{pv}(W)	10.29	15	5.81	20	0.15	3.3	0.009	3.8
$\Delta R_{pv}(\Omega)$	0.88	**	0.64	**	0.10	**	0.02	**

* S - Simulation; E - Experiment
** Not observed
*** Oscillations are observed at Standard Test Conditions

PV resistance will move out of the operating limits (i.e it try to move on left side of PV curve to set new operating point of MPP). At this point, the ARC gets activated and limits the duty ratio of boost converter; thereby the operating point of the PV is moved near to the MPP region in right side of MPP as shown in tracking curve Fig. 7a. At time t=1s, the irradiance is suddenly decreased from 850 to 600 W/m^2. At 600 W/m^2 the Ppv and R_{pv} will be around 239.8W and 6.6Ω. Due to sudden decrease in irradiance, operating resistance of the PV in the proposed algorithm may go beyond the MPP due to the sudden decrease in PV current. But the ARC limit in the proposed algorithm limits the operation of converter beyond the MPP using duty cycle limit and bring it to MPP quickly by reducing the oscillations as shown in tracking curve Fig. 7b. Similarly for the PV is operating at 55^{o}C at 600 W/m^2, the values of Voltage, Current, resistance and Power are V_{pv}=35.3 V, I_{pv}=6.1 A,R_{pv}=5.78Ω and P_{pv}=215.33 W and at 850 W/m^2 the values are V_{pv}=35.35 V, I_{pv}=8.5 A,R=4.15Ω and P_{pv}=300.47 W. The performance of voltage, current, resistance and power for varying irradiance at 25^{o}C and 55^{o}C is shown in Fig 9 & 10.

From the Fig 7 (a & b), for sudden increase and decrease in irradiance, the new operating MPP tracked by the conventional P&O algorithm take long path and results in more oscillation around MPP, whereas the proposed MPPT algorithm quickly shifts to the new operating MPP based on the ARC limit. It is worth to mention that from the simulation studies, the tracking curve and the simulation results depicts the proposed MPPT algorithm gives better tracking performance and less oscillation around MPP by setting ARC limit. When compared to the conventional P&O algorithm, the steady state performance parameters variations are described in Table 4.

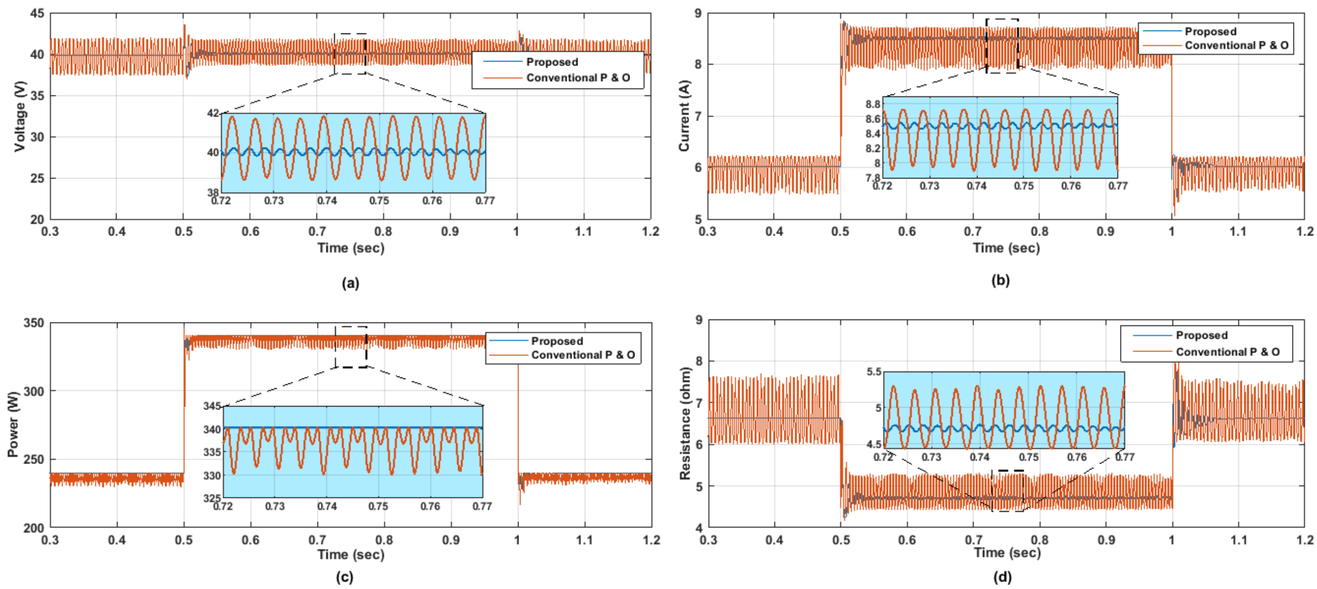


FIGURE 9: Simulation Results of Proposed and Conventional P & O MPPT algorithm operated under 25^{o}C (a) PV Voltage (V) (b) PV current (A) (c) PV Power (W) (d) PV terminal resistance (Ω)

From the Table 4, the ripple voltage, current, power and resistance of proposed MPPT algorithm is low when compared with conventional P&O algorithm and Table 5 shows the comparison of proposed MPPT algorithm with other MPPT algorithm.

V. EXPERIMENTAL STUDIES

The proposed algorithm was realized using the boost converter and TI TMS320F28379D microcontroller. The proposed MPPT algorithm was implemented in the TI microcontroller, and the PV voltage and current measurements were done with the help of Taraz USM-3IV Voltage and Current sensing module. The nominal parameters of the boost converter for experimental studies are given in Table 2. A Half-Bridge configuration using MOSFET was used as a Boost converter in this experimental study. This Silicon Carbide (SiC) based MOSFET (SCT3080KL) rated at 1200V 31A and is driven by ACPL-332J smart gate driver IC. Chroma Solar PV emulator and DC Load simulator were used as Solar PV sources and Load, respectively, for this experimental study. The proposed MPPT algorithm was validated for PV panel specifications given in Table 1 considering two panels (400 W in total) connected in parallel. Fig. 13, 14 & 15 shows the proposed MPPT algorithm's experimental results under different irradiance and panel temperature in two cases.

For the given PV panel specifications, the operating limits in the proposed MPPT algorithm can be estimated from (7) & (8) as $R_{pv,min}$=3.39 Ω (1000 w/m^2 at 65^oC) and $R_{pv,max}$=9.7 Ω (400 w/m^2 at 25^oC), which corresponds to duty cycle limit of D_{min}=0.18 and D_{max}=0.52. Here the performance of the proposed MPPT algorithm is validated for three different scenarios, and it is also compared with the conventional MPPT algorithm. The startup behaviour of proposed MPPT algorithm and conventional P & O algorithm is shown in Fig. 12 (a & b). This startup behaviour is tested at STC.

The second and third case is validated for sudden changes in irradiance condition with two different varying temperature conditions at 25^oC and 55^oC. Second case: In this case, the PV panel is operated at a sudden increase and sudden decrease in irradiance condition at 25 ^oC. Initially, the PV panel is operated in 850 w/m^2 at this instant, the P_{pv}=316.43 W, V_{pv}=38.22 V, I_{pv}=8.28 A. While the irradiance suddenly decreases from 850 w/m^2 to 600 w/m^2, there is a sudden change in the PV power. At 600 w/m^2, the V_{pv}=38.12 V, I_{pv}=5.84 A , P_{pv}=222.75 W. Due to a sudden decrease in irradiance, the operating resistance of the PV in the proposed algorithm may go beyond the MPP due to the sudden decrease in PV current. But the ARC limit in the proposed algorithm limits the operation of the converter beyond the MPP using the duty cycle limit and bring it to MPP quickly by reducing the oscillations. Likewise the irradiance is suddenly increased from the 600 w/m^2 to 850 w/m^2; at 850W/m^2, the P_{pv}=316.43, V_{pv}=38.22, I_{pv}=8.28. Because of the sudden increase in irradiance, the PV current will get increased. Hence the resistance of the PV will get reduced. In this condition, the ARC operates the PV effectively to reach the new MPP with low oscillation compared with the conventional P&O MPPT algorithm. Fig. 13 (a & c) shows the performance of the proposed RMPPT algorithm with PV operates at the sudden decrease and increase in irradiance at 25^oC, and Fig. 13 (b & d) shows for conventional P&O based mppt algorithm. Similarly, the proposed MPPT algorithm

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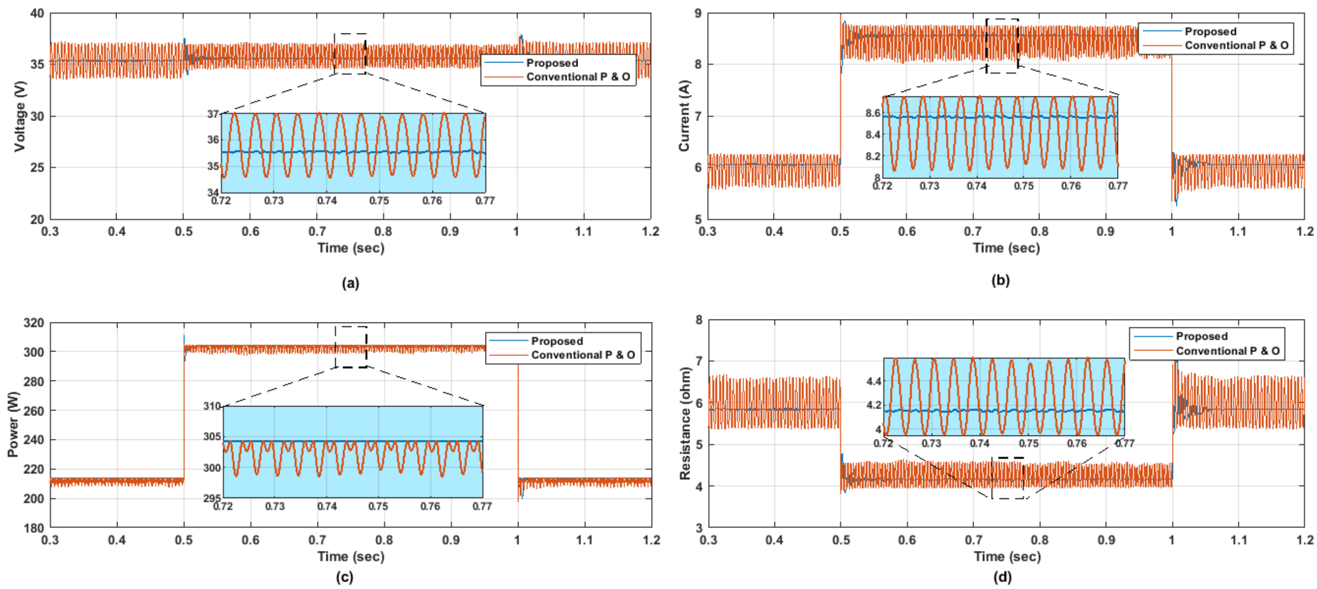


FIGURE 10: Simulation Results of Proposed and Conventional P & O MPPT algorithm operated under 55^{o}C (a) PV Voltage (V) (b) PV current (A) (c) PV Power (W) (d) PV terminal resistance (Ω)

TABLE 5: Comparison of proposed MPPT algorithm with other MPPT algorithms

Parameters	[26]	[27]	[28]	[30]	[29]	[31]	[32]	**Proposed**
Perturbation parameter	Voltage	Current	Voltage	Current	Voltage	Voltage	Voltage	**Resistance**
Direction of perturbation	LHS	LHS	LHS	Not specified*	Not specified*	LHS	LHS	**RHS**
scaling factor	No	Yes	Yes	Yes	Yes	Yes	Yes	**No**
PI controller	Required	Required	Required	Required	Required	Required	Required	**Not required**
Implementation complexity	Moderate	Moderate	Low	Moderate	Moderate	Moderate	Moderate	**Low**
Tracking speed (secs)	2	0.15	0.25	0.025	4.8	0.8	0.5	**0.052**
Tracking efficiency	98.65	98.45	99.84	95.4	98.56	99.2	99.34	**> 99%**
Adoptability to sudden changing irradiance	Low	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	**High**

* Not specific about the perturbation direction

was also tested under 55^oC panel temperature with the same irradiance pattern as third case, which is shown in Fig. 14 (a, b, c & d). Fig. 14 (a & c) shows the performance of the proposed RMPPT algorithm, and Fig. 14 (b & d) shows the performance for the conventional P&O mppt algorithm. By comparing the results of two operating temperatures from Fig. 13 & 14, the PV voltage at 25^oC has less variation than the PV voltage variation in 55^oC during tracking of MPP using the proposed MPPT algorithm. Clear response of proposed MPPT algorithm and Conventional P & O algorithm for the case 2 & 3 are shown in Fig. 15. From the experimental result, it is concluded that the proposed MPPT algorithm gives better performance results under different environmental conditions. From the experimental studies, it is clearly noted that the performance of the Resistance perturbation based MPPT Adaptive control limit have better performance when compared to the conventional algorithm. The proposed MPPT algorithm has more advantageous than the conventional P&O MPPT algorithm under sudden varying climatic conditions from the experimental and hardware results.

VI. CONCLUSION

The resistance perturbations based MPPT algorithm is proposed in this paper. It is developed to combine two features, namely, resistance perturbation to reduce the oscillation around the MPP, instead of current and voltage perturbation in conventional algorithms and another one is operating PV in right side of MPP rather than left side, to improve the tracking performance of the PV under sudden varying in irradiance and temperature. ARC limit is used to operate the PV in right side of MPP. Additionally, the proposed algorithm does not require extra sensors for the measurement of irradiance and temperature to operate the algorithm at MPP and PI controller to track the PV curve under different operating conditions. The performance of proposed MPPT algorithm was validated in both simulation and experimental studies. The results obtained from these studies for the proposed MPPT algorithm show less oscillations around the MPP, and improved tracking performance at both varying in temperature and irradiance as compared to the conventional MPPT algorithm. Future work of this paper considers the evaluation of proposed MPPT algorithm in grid connected PV systems.

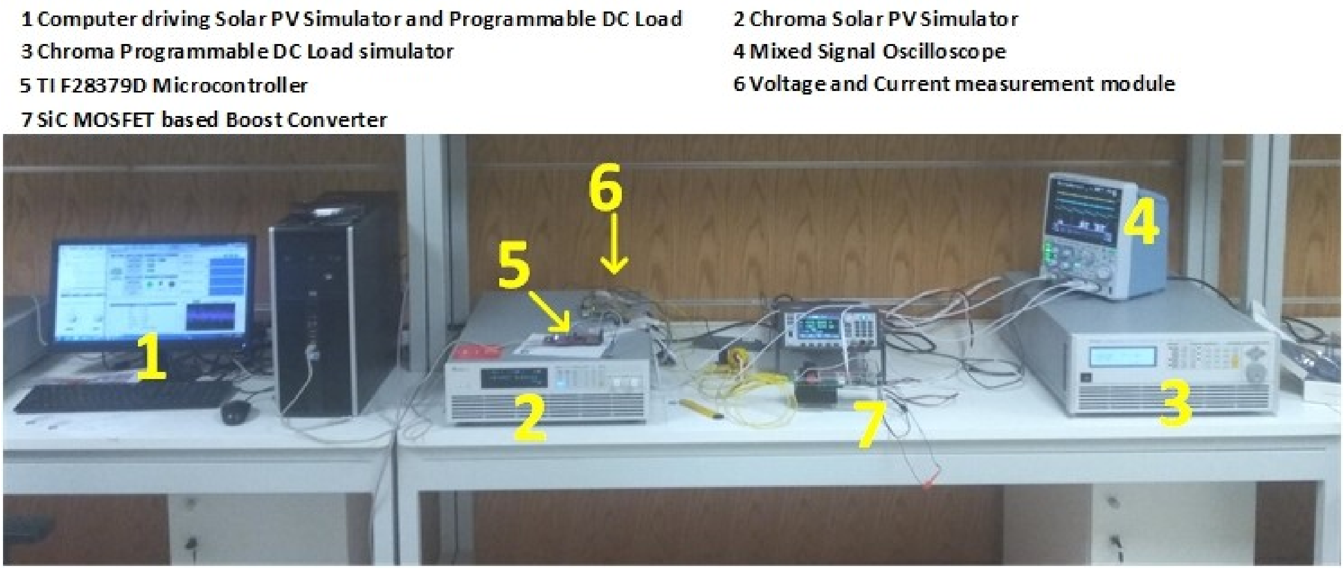
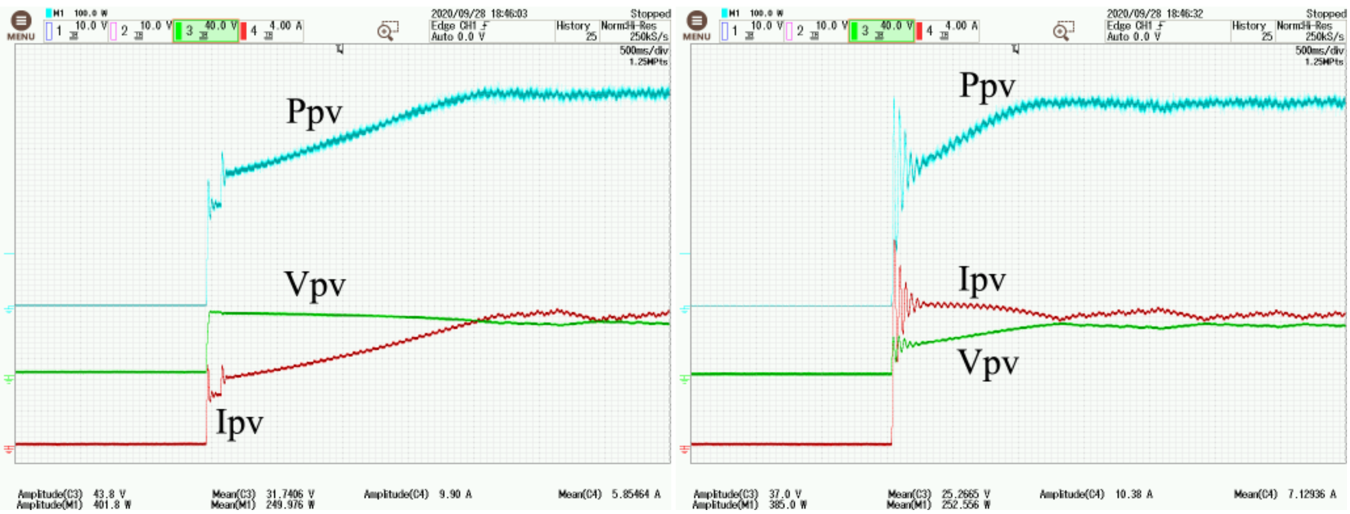


FIGURE 11: Experimental setup to validate the performance of proposed MPPT algorithm



(a) (b)

FIGURE 12: Startup behaviour (a) Proposed Algorithm, (b) Conventional P & O Algorithm

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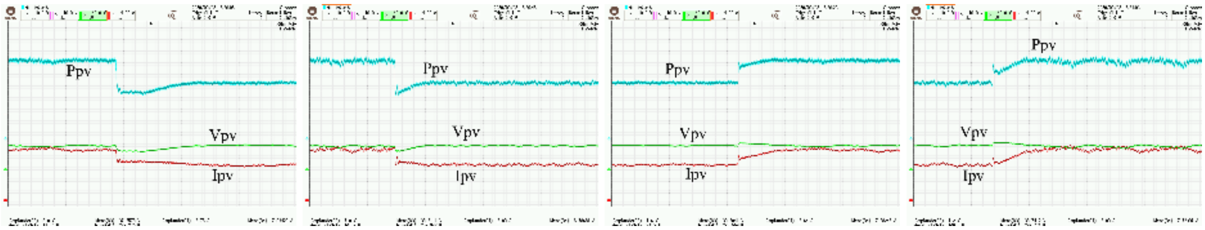
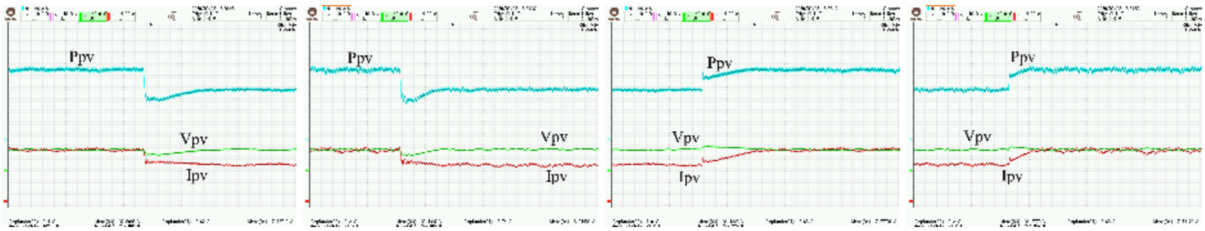


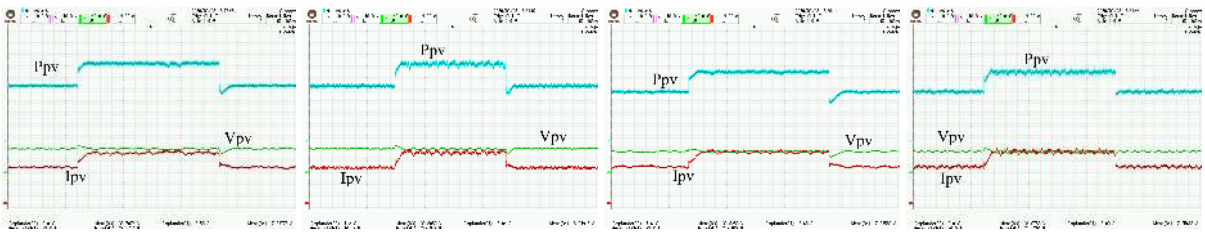
(a) (b) (c) (d)

FIGURE 13: Experimental results : Sudden change in Irradiance operating at 25^oC (a,c) Proposed MPPT algorithm, and (b,d) Conventional P & O algorithm



(a) (b) (c) (d)

FIGURE 14: Experimental results : Sudden change in Irradiance operating at 55^oC (a,c) Proposed MPPT algorithm, and (b,d) Conventional P & O algorithm



(a) (b) (c) (d)

FIGURE 15: Experimental results : performance of proposed MPPT algorithm (a,c) and conventional P & O algorithm (b,d) under different irradiance pattern operating at 25^oC and 55^oC respectively

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MAHESWARAN GUNASEKARAN (S'19) was born in Tamilnadu, India, in 1991.He received his bachelor'sdegree in Electrical and Electronics Engineering and Master's degree in Power Systemsfrom Anna University, Chennai in 2013 and 2015.Currently he is working towards his PH.D in SRM Institute of Science and Technology, India. He is the recipient of the CICOPS fellowship 2020, University of Pavia, Italy. His research interest includes Maximum powerpoint tracking algorithms for solar Photovoltaic systems, Energy managementand control strategy for Grid connected renewable energy sources, Operation and control of ac/dc microgrid. Flexible control and stabilityanalysis of PV penetration in both On-grid and Off-grid-tied inverters, Loadfrequency control for Restructured power system.

VIJAYAKUMAR KRISHNASAMY (SM'17) received the bachelor and post graduate degrees from Annamalai University and obtained the PhD degreefrom SRM Institute of Science and Technology.Currently he is working as a Professor and Headin the Department of Electrical and ElectronicsEngineering of SRM Institute of Science andTechnology. The research interests include Power system modelling, Power Electronics converters for Grid connected systems, Computational Intelligenceapplications in Power Systems, etc. He has published more than 130 papers in various reputed journals. He was awarded the Best Teacher awardin the department of EEE SRMIST for the academic year 2004 & 2006. He isa senior member of IEEE, Fellow member of IE(I), and member of variousprofessional bodies like IET, IEICE, ISTE and ISCA.

SIVAKUMAR SELVAM (M'20) was born in Tamilnadu, India, in 1991. He received his B.E. degree in Electrical and Electronics Engineering, and M.E. degree specialized in Power Electronics and Drives from Anna University, Chennai in 2013 and 2015 respectively. He is currently working as Research Assistant in Renewable Energy Laboratory, Prince Sultan University, Saudi Arabia. His research interest includes Grid interfaced Solar PV systems, Multilevel Inverters, DC-DC converters for Microgrid applications, and Digital Control of Power converters.

DHAFER J. ALMAKHLES (SM'20 – M'14) received the B.E. degree in electrical engineering from theKing Fahd University of Petroleum and Minerals,Dhahran, Saudi Arabia, in 2006, and the master'sdegree (Hons.) and Ph.D. degree from The Universityof Auckland, New Zealand, in 2011 and2016, respectively. Since 2016, he has been withPrince Sultan University, Saudi Arabia, where heis currently the Chairman of the Communicationsand Networks Engineering Department, and theDirector of the Science and Technology Unit and Intellectual PropertyOffice, Prince Sultan University. He is the leader of the Renewable EnergyResearch Team and Laboratory. His research interests include power electronics,control theory, unmanned aerial vehicles, renewable energy systems,and FPGA applications. He is a member of the IEEE Power Electronics andthe IEEE Control Society. He is a Reviewer Member of various internationaljournals and conferences, including the IEEE and IET.

NORMA ANGLANI (M'99 - S'93 – SM'18) received the Laurea (with Hons.) and Ph.D. degrees in ElectricalEngineering from the University of Pavia, Pavia, Italy, in 1993 and 1999, respectively. Sheis an IEEE member and a Chartered Engineersince 1995. After graduating she worked for a consulting company in the energy efficiency area. Later, she was a Postdoctoral Fellow with theEnergy Analysis Group and with the Energy EfficiencyStandards Group, Lawrence Berkeley NationalLaboratory, Berkeley, CA. She is now Assistant Professor with theDepartment of Electrical, Computer and Biomedical Eng., University of Pavia (I), where she currently teaches and does research in the field of energy management, energy planning, modelling, and efficient compressed air systems.She set up the Labac laboratory, a joint effort between academia andindustry. She has been responsible for several research contracts with publicand private bodies and has co-authored more than 70 scientific papers. She is IEEE Senior member since 2018 and IEEE-IAS WiE Liaison (2019/2020). In 2018, she got the National qualification as Associate Professor.