DEVELOPMENT OF HYBRID MPPT ALGORITHM UNDER PARTIAL SHADING CONDITIONS FOR LOW POWER APPLICATIONS

B.Raja Mohamed Rabi, K.Kanimozhi

Dept. of Mechanical Engineering, ULTRA College of Engg.& Technology for Women
Madurai, India, rabime2002@yahoo.co.in
Dept.of Electrical & Electronics Engg.,ULTRA College of Engg. & Technology for Women,Madurai,India,
kanilalith2003@gmail.com

ABSTRACT: *Partial shading is a condition at which efficiency and stability of photovoltaic (PV) system are affected. During partial shading conditions multiple peaks rise in the PV characteristic curve. Conventional Maximum power point tracking (MPPT) techniques are unable to track the maximum power due to global maximum power point (GMPP) occurring during partial shading conditions conventional techniques as the power generated decreases. Therefore a Hybrid MPPT algorithm is proposed in this paper to speed up the power tracking efficiency of PV systems under partial shading conditions. The algorithm adjusts the duty cycle for regulating the input voltage at the Maximum power point (MPP) and to provide impedance matching ie. Input impedance of converter equal to equivalent solar impedance of PV system at MPP for the maximum power transfer. As Cuk converters have low switching losses and the highest efficiency it is selected as a power conditioning circuit. The influence of algorithm parameters on system behavior is investigated and the various advantages and drawbacks of the technique are identified for different weather conditions.Simulation results are validated by experimental results obtained using Solartech SPMO85P PV modules connected to the RL load through the Hybrid MPPT controller.*
Key words: Photovoltaic System, Partial shading condition,Cuk converter,GMPP,MPPT,Hybrid MPPT
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1. Introduction

Solar power, an abundantly available renewable energy source is an alternative for dwindling fossil fuels.The energy conversion technologies of PV system suffer from serious drawbacks such as uncertainty in weather,installation cost and per unit generation cost[1] .

Although a reliable and fast MPPT algorithm can be designed by using the approaches [2], its efficiency is strongly affected by various disturbances.

Solar irradiation,temperature, configuration and shading are major constraints affecting the performance of a PV system. The shading on the PV panel, for instances, due to a passing cloud or neighboring buildings causes not only energy loss in the conversion, but also further non-linearity on the I-V characteristics[3].

The effect of changing cell temperature and solar irradiance on the choice and design of different topologies of DC–DC converter commonly used in PV systems is discussed in [4].

Unexpected shading effects due to dusts, clouds, leaves, branches of trees and buildings, causing shading on cells or part of modules or panels. Hence the P-V characteristics of the PV array will contain one global maximum corresponding to maximum power accompanied by many local maxima corresponding to much lower power [5].

MPP fluctuates with changes in climatic conditions and MPPT controller tunes the converter duty cycle to track the new MPP. The choice of converter must be optimal so that the duty cycle is adjusted to track the MPP under different atmospheric conditions[6].

In [7] a method dependent on conventional P&O method have been implemented and it has been showed that dynamic performance is affected by choice of frequency and amplitude of perturbation.Hence MPPT tracking performance is degraded during partial shaded conditions and overall system efficiency is reduced.

The control algorithm proposed for locating GMPP in [8] is complex in hardware realizations and dynamic performance is also poor. At local MPP occurring during partial shading conditions, the conventional MPPT algorithm fails to track maximum power and it may converge at multiple points resulting in a reduced PV output and efficiency.

To overcome the above mentioned drawbacks Adaptive Sliding mode controlled based MPPT controller was introduced for improving dynamic performance [9].Here also conventional P&O method was implemented and was not suitable for variable irradiation conditions.

Taking the above factors into consideration a hybrid MPPT algorithm suitable for partial shading and variable irradiation conditions is proposed to track GMPP for standalone PV system.

In this paper practical implementation of a PV system with Cuk DC-DC converter and Hybrid MPPT tracker to improve the PV system performance under partial shading conditions is discussed. This work is divided into the following sections: In section 2 PV system specifications and working of Hybrid MPPT controller is discussed. In section 3 and 4 Cuk converter state space analysis

and experimental validation is done. Finally a conclusion is drafted in section 5.

2. Materials and Methods

A Standalone PV systems is a direct coupled system where the DC output of PV array is directly connected to a load through a DC–DC converter and MPPT controller. DC–DC converter is selected based on the level of voltage required. The MPPT algorithm harvests maximum available power from the PV module. Maximum power changes with solar irradiation (G) and temperature (T).
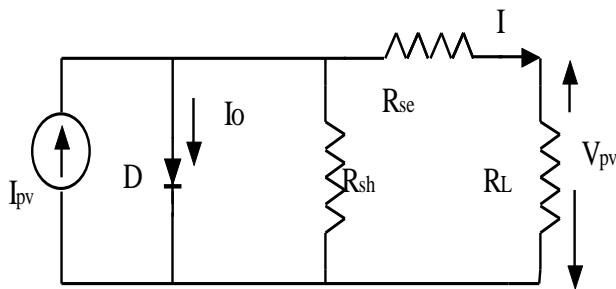

Fig. 1. Mathematical model of PV cell with one diode

2.1 PV System Modeling

The mathematical model of PV cell is shown in Fig.1 The characteristics of PV cell are a combination of current source and diode. Series and shunt resistors are added for the losses. The current source I–V characteristics are considered separately and the diode I–V characteristics are determined separately. Here these two elements are in parallel connection so by adding currents the PV array characteristics are achieved.
The equation of the mathematical model is

$$I_{pv} = I_{ph} - I_o \left(e^{\frac{(V_{pv} + R_{se}I_{pv})}{V_T}} - 1 \right) - V_{pv} + \frac{R_{se}I_{pv}}{R_{sh}}$$

(1)

where I_{PV}, V_{PV} denote PV cell output current and voltage, I_o is dark saturation current . R_{se}, R_{sh} denote series and shunt resistance and $V_T = nKT/q$ is thermal voltage. Here n denotes emission coefficient factor of PV cell, K is Boltzmann constant and T is cell temperature.

The specifications for a PV array formed with 36 PV cells connected in series and parallel is shown in Table 1.Each PV cell has an open circuit voltage V_{oc}= 22.2 V and short circuit current I_{sc} = 5.45 . A solar panel is constructed from the combination of such modules. A solar array is formed with maximum power of 85.2 W at V_{MPP} = 25.2 V and I_{MPP}=9.1 A.

Table1: PV Panel specifications

Description	Parameter	Nominal Value
Maximum Power	P_{max}	85.2 W
Short circuit current	I_{sc}	5.45 A
Voltage at MPP	V_{MPP}	25.2V
Current at MPP	I_{MPP}	9.1A
Open circuit voltage	V_{oc}	22.2 V
Solar irradiance	G	1000 W/m^2
Ambient temperature	T	25°C

2.2 Development of Hybrid MPPT algorithm for Partial shading effect

The PV array has nonlinear characteristics. Hence MPP tracking is made possible using Perturb and Observe (P&O) technique that senses the PV voltage, current and changes in load resistance. During changes in climatic conditions and partial shading effect P&O algorithm introduces oscillations around MPP and hence performance is poor.
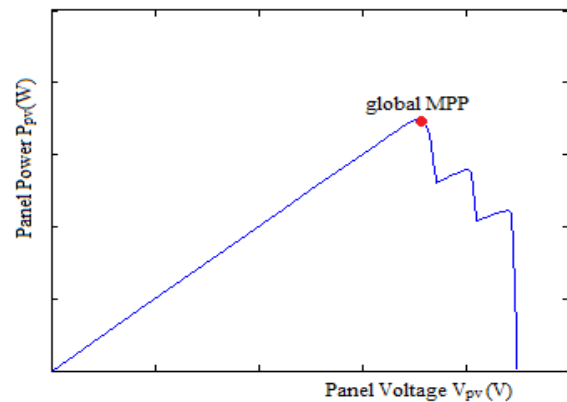

Fig.2. Power Vs.Voltage characteristics of partially shaded PV system

The power voltage (P-V) curve of the partially shaded array is shown in Fig.2. The figure shows the occurrence of multiple local maxima on the P-Vcharacteristics of solar PV system.Out of these local maxima only one will be global maximum power point.Implementation of conventional MPPT methods results in convergence at local maximum power points and in turn the PV sytem efficiency reduces .

During partial shading conditions global and local maximum power points are produced. Analysis of MATLAB simulation results in [9] has proved that the conventional MPPT techniques are ineffective in locating the absolute maximum in the P-V graph. Once the local maximum is reached, P&O methods fluctuate around that point.

To overcome the issue, an innovative MPPT solution has been developed based on Improved P&O[10],Incrementald based on Improved P&O [10],Incremental Conductance and Fractional Open-Circuit Voltage(FOCV) based MPPT techniques. The FOCV based MPPT technique utilizes the linear relationship between maximum power point voltage (V_{MPP})and open circuit voltage (V_{oc})

$$V_{MPP} = k_1 V_{OC} \qquad (2)$$

k_1 is proportionally constant $(0.71 - 0.78)$.

$$V_{MPP} = V_{MPP-1} + \Delta d \ \frac{\Delta P(k)}{\Delta V(k)} \qquad (3)$$

$$V_{MPP} = V_{MPP-1} - \Delta d \ \frac{\Delta P(k)}{\Delta V(k)} \qquad (4)$$

where Δd is constant with a value of 10%.

Therefore, to enhance the performance of the conventional P&O algorithm due to climatic changes under constant load (R_L), load value (R_L) has to be computed in every perturbation step to ensure changes in load and the changes in power as a result of irradiation changes.The load changes (ΔR_L) are also considered in the algorithm under constant weather conditions.

Fig.3 shows the flow chart for the Hybrid MPPT algorithm . The steps in hybrid MPPT method are:
1. In Hybrid MPPT algorithm operating point is positioned to lie within a band at which it is easier to locate MPP.It later moves the tracking path to regular tracking algorithm. MPP band of occurrence is identified by a data based value of control parameter n given by,

$$n = \ln \frac{I_{PV}}{V_{PV}} - V_{PV} \qquad (5)$$

The entire range of possible irradiation and temperature variations are considered to determine n_{min} and n_{max} values.This aids in fast MPP tracking.
2. PV system short circuit current alters with a sudden decrease or increase of irradiance. Therefore the MPP is determined by FOCV technique when the current difference sensed is higher than the specified threshold . V_{MPP} and V_{OC} for the PV system at various irradiance and temperature levels are observed to calculate k_1.Otherwise,

difference in the availability of power is calculated.
3. Variable perturbation size concept has been introduced to improve both tracking speed and algorithm accuracy. A smaller perturbation size is produced if the operating point is closer to the desirable point, else a larger perturbation is produced for operation point located far from the absolute MPP. Hence a reduction of the energy lost due to the fluctuation of the tracker near MPP is achieved.
4. During perturbation K suppose that, the solar irradiance is increased under fixed load R_L MPP shifts from a lower point to upper point in the I-V curve. Hence voltage perturbation increases.
5. Increase in PV power and voltage under constant load from lower to upper I-V and P-V curves will result in positive change in power $\Delta P > 0$ where $\Delta P = P(k) - P(k - 1)$ and positive change in voltage $\Delta V > 0$ where $\Delta V = V(k) - V(k - 1)$.This results in decrementing voltage perturbation to obtain a new MPP.
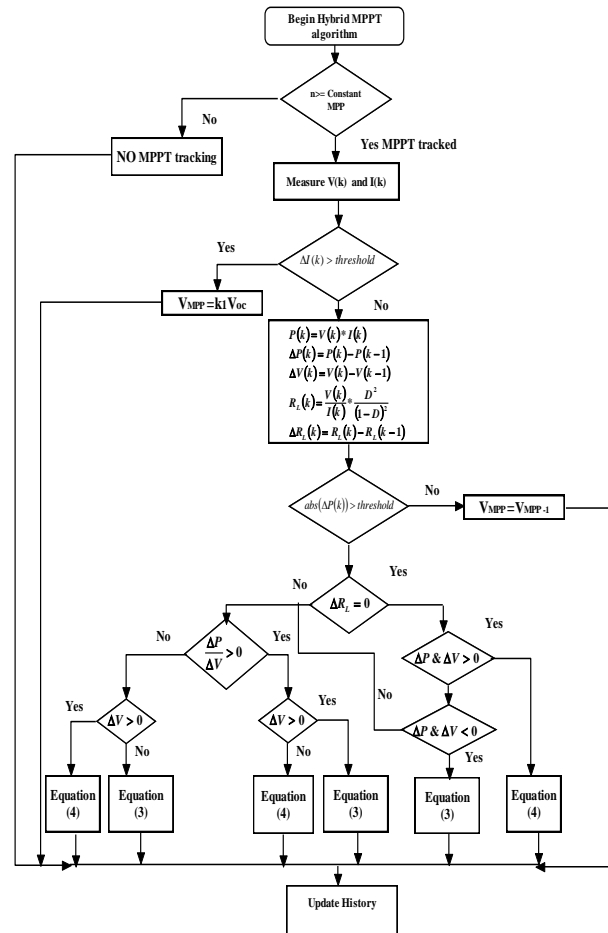

Fig.3. Hybrid MPPT algorithm

6. Decrease in solar irradiance during next instant of perturbation K+1 of P&O algorithm reduces the voltage level and moves the MPP from upper point to lower point in the I-V curve.The transferring of operating point will also decrease the PV power under fixed load with negative change in power $\Delta P < 0$, and negative change in voltage $\Delta V < 0$, Both negative change in power ($\Delta P < 0$) and voltage ($\Delta V < 0$) under constant load ($\Delta R_L = 0$) will orient algorithm to increment voltage perturbation to reach MPP.

7. The conventional P&O algorithm tracks MPP of PV system with the best performance when load varies under constant weather conditions.

Therefore, the load resistance (R_L) will orient the algorithm to recognize the cause of power variation which is either from weather or load. A Hybrid MPPT algorithm is designed by sensing combination of both weather and load change techniques and FOCV technique. These steps continue till MPP is reached. Thus the voltage at which MPP is reached is tracked.

3. Implementation of Hybrid Mppt Algorithm

The schematic of the Cuk converter based on boost buck topology is presented in Fig.4, where V_{in} is the input voltage source, Vo is output voltage, input inductor L_1, controllable switch S, energy transfer capacitor C_1, diode D_1, filter inductor L_2, filter capacitor C_2, and load resistance R_L. A continuous current produced at both the input and the output of the converter due to an inductor in series with both the input and the output of the switch is an important advantage of the Cuk converter topology. Unlike the Buck-Boost converter has a discontinuous input current, which adversely affects on the tracking efficiency of the MPP
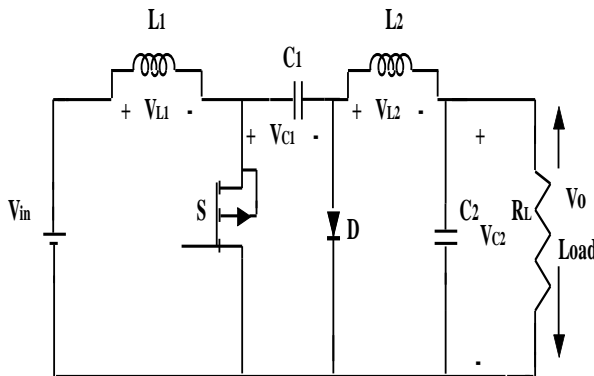

Fig.4. Cuk converter Schematic circuit

The three basic components in MPPT design are: a switch-mode DC-DC converter, a control circuit, and tracking algorithm. The heart of the MPPT hardware is a DC-DC converter.The converter aids the MPPT controller in regulating the input voltage at the MPP and to provide impedance matching for the maximum power transfer.

During load variations the one point at which the PV module provides its MPP is when R_L equal to the resistance at MPP(R_{opt}) $R_L = R_{opt}$. It is difficult to select a fixed load matching this value.Even if this is achieved this point alters under changed climatic conditions. When a DC-DC converter is interfaced between the PV system and the load, the MPP depends on the impedance (R_i), which depends on two parameters: R_L and duty cycle (D).
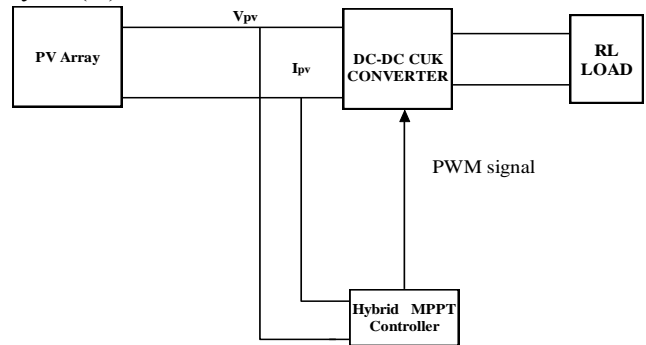

Fig.5. Block diagram representation of implementation Hybrid MPPT controller

Thus, for variable loads impedance matching is done by adjusting the duty cycle at any atmospheric condition.As the duty cycle of the PWM control signal changes, the load impedance varies and matches the MPP of the source power so as to transfer the maximum power to load. Implementation of Hybrid MPPT algorithm using the Cuk converter is shown Fig.5

3.1 Cuk Converter State Space Analysis
Switch S ON $0 < t < DT$:

During this time interval the input inductor L_1 stores energy from the source. The energy storage capacitor C_1 in the right hand of mesh transfers stored energy, over S, to the load R, and energy storing elements L_2 and C_2. Diode D_1 is reverse biased due to the polarity of voltage charged on the capacitor and therefore switched off.
Switch S OFF $DT < t < T$

Inductor L_1 and diode D charges the energy storage capacitor C_1 in the left hand mesh. D common to both meshes is forward biased . In the right hand mesh L_2 and C_2 transfer their stored energies, left from the previous time interval during the steady-state operation, to the load R_L over D again.

When a Cuk converter works in CCM it has high efficiency.The dynamic characteristics of the converter depends on the selection of circuit elements.The working of DC-DC converter in CCM is determined by the minimum value of inductance L_1 . C_{min} is the minimum value of capacitance to reduce the ripple voltage. Consider Cuk converter works in CCM mode.

In the state space, with the state variables x_1,x_2,x_3 and x_4 represented by currents i_{L1}, i_{L2} and voltages V_{C1} , V_{C2} the model of Cuk converter can be expressed as follows with γ as switching state.Using state space averaging technique

$$\frac{d}{dt}\begin{bmatrix} i_{L1} \\ i_{L2} \\ V_{C1} \\ V_{C2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{L_1} & 0 \\ 0 & 0 & 0 & -\frac{1}{C_2} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{C_2 R_L} \end{bmatrix}\begin{bmatrix} i_{L1} \\ i_{L2} \\ V_{C1} \\ V_{C2} \end{bmatrix}$$

$$+\begin{bmatrix} \frac{2V_{in}}{L_1} \\ \frac{-V_{C1}}{L_2} \\ \frac{-(i_{L2}+i_{L1})}{C_1}0 \\ 0 \end{bmatrix}\gamma + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix}V_{in} \qquad (6)$$

$$\dot{X} = AX + B\gamma + C \qquad (7)$$

The inductor value, required to operate the converter in the CCM is calculated such that the peak inductor current at maximum output power does not exceed the power switch current rating.

Taking into account that the ripple of the PV output current must be less than 2% of its mean value, the output capacitor value is calculated. Calculation of input capacitor value is done to determine the desired peak-to-peak output voltage ripple .

The converter switching frequency and the inductor value are the factors deciding the converter efficiency, cost, power capability and weight. If the switching frequency is chosen higher , the inductor core size reduces , but the power switch losses are increased.

Also, by using a large value, the peak-to-peak current ripple is smaller, requiring lower current rating power switches, but the converter size is increased substantially because a larger inductor core is required. The value of L_1 and L_2 decreases with the increase in frequency .The value of C_1 and C_2 decreases with the increase in frequency. The values of circuit parameters are chosen as follows.

Switching frequency is selected 25 KHz frequency for design as more switching losses occurs with higher frequency.The switching frequency has to be chosen lower to maintain high efficiency .

Table 2 :Cuk Converter parameters

Description	Parameter	Nominal Value
Primary Inductor	$L_1=(1-D)R_L/2Df$	15μH
Primary Capacitor	$C_1=DV_o/V_rR_Lf$	22 μF
Secondary Inductor	$L_2==(1-D)R_L/2f$	15 μH
Secondary Capcitor	$C_2=(1-D)V_o/8V_rL_2f^2$	44 μF
MOSFET	S	MUR3060
Diode	D	IRFP460
Load	R	2 to 100 Ω
	L	5 to 100 mH
Switching frequency	f	25KHZ
PV module	4 nos in series	340 W

Switching frequency f=25KHz, D=50%, $\frac{\Delta V_o}{V_o} = 0.1V$ $\Delta V_{C1} = 1V$ the circuit parameters are calculated and tabulated in table 2.

4. Results and Discussion

In this section MATLAB simulation results for PV array interfaced by the Cuk converter to Hybrid MPPT controller and load is presented.The specification of solar panel used is given in table 1 .The efficiency of Hybrid MPPT algorithm is verified by comparing simulation results with conventional P&O algorithm.The experimental set up is checked for different power schemes 2 PV panel in series and 4 PV panel in series.

4.1 Simulation results for two partially shaded series connected PV modules

The simulated system is composed of series connected PV module each with with 85 W power rating, Hybrid MPPT controller, DC/DC Cuk converter and RL load . The simulations were performed on a Cuk converter circuit with values shown in Table 2 .Simulation results are obtained

for irradiation changes and changes in load to validate the performance of Hybrid MPPT algorithm.
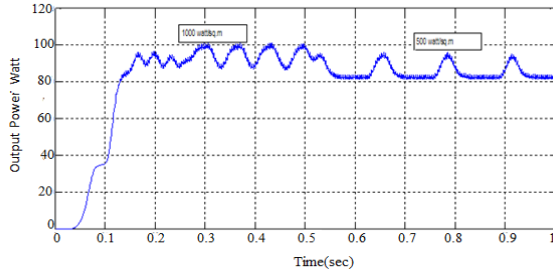

Fig.6. Output power for Cuk converter - P&O MPPT controller for step irradiation
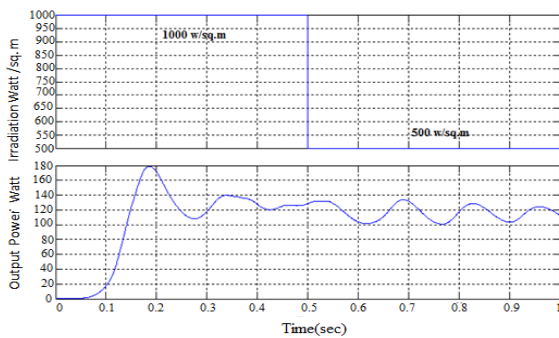

Fig.7. Output power for cuk converter - Hybrid MPPT controller for step irradiation

Two Solartech SPM085P solar models, each with a power of 85 watts are used for simulation. The partial shading condition is checked by stepping the solar irradiance level from high to low level. The initial level is set at G=1000 W/m². At t=0.5sec, the irradiance is suddenly stepped down to G=500 W/m². The temperature is kept constant at 25⁰C for all irradiance levels.

Comparison of simulation results of maximum power extracted with the conventional P&O MPPT controller are shown in Fig.6 and Fig.7.Fig.6 shows that convergence occurs in P&O based MPPT controller after 300 ms the power profile changes from 100 W to 90 W. Peak power of 180 W is extracted using the Hybrid MPPT controller and the change in power profile is from 140 W to 130 W. Moreover, the converter's input power follows the radiation change almost immediately. The converter's input power shoots up in 15ms. It can be seen that, the Hybrid MPPT algorithm is more accurate, powerful and responsive than conventional P&O based MPPT controller.The I-V curves simulated without shading and simulated with shading for P&O MPPT controller and hybrid MPPT controller are respectively shown in Fig. 8 and 9. The IV curves for Hybrid MPPT controller shows that global and local MPPs are easily detected.
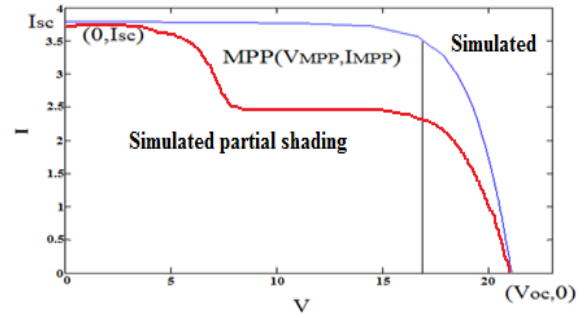

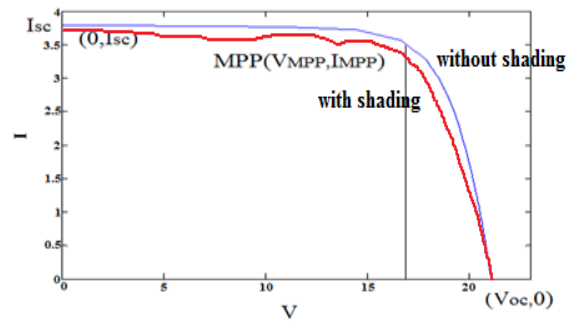**Fig.8** Simulated IV curve with and without shading with P&O MPPT controller

Fig.9 Simulated IV curve with and without shading with Hybrid MPPT controller

4.2 Experimental Validation

The experimental set up to test the performance of the proposed MPPT algorithms is shown in Fig. 10 . The circuit consists of four PV panels(two in case of low power and four in case of high power applications), a DC/DC converter,microcontroller kit, voltage sensor and current sensor as well as other peripherals for ensuring the robustness of the system.

Periodical sampling of the panel's voltage and current is done by voltage and current sensors. Signal conditioning is done to improve the quality of the signal. Conditioned signals are fed into the microcontroller through the analog to digital (A/D) channels.

Hybrid MPPT controller is implemented practically by using a microcontroller that is programmed to execute the Hybrid MPPT algorithm. The programming is done to sense the panel voltage (V_{PV}) and current (I_{PV}) .Hence the single operating point (I_{MPP},V_{MPP}) at which maximum power output is produced is determined .
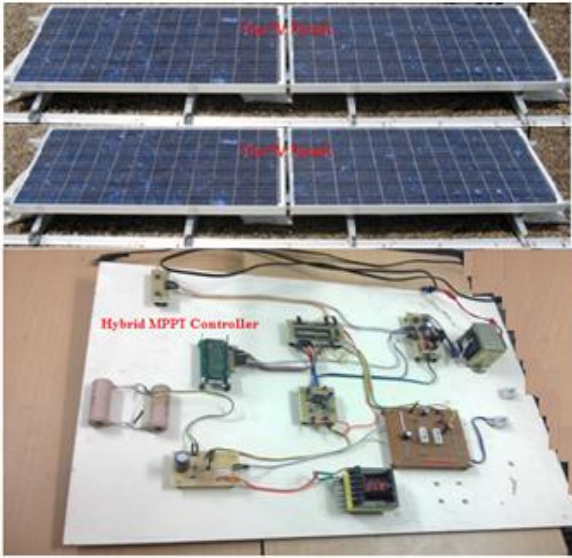
Fig.10 Prototype model of Cuk converter with Hybrid MPPT controller

The algorithm is written using C# programming language on an interface known as Micro C. The program built generates a ".hex" file which is burned onto the microcontroller by means of a lock burner.

A PWM signal to control the Cuk DC/DC converter is the output of the microcontroller. Fig.11 depicts the configuration of partial shading for four PV panels connected in series. Experimental verification was done for Irradiances $G_1=1000W/m^2$ and $G_2=500W/m^2$.

The single diode electrical equivalent model is used for modeling of PV module for partially shaded configuration. In a PV array the cells configured in series will render constant current where as the shaded cells will operate with a reverse bias resulting reverse power polarity leads to net power drop and thereby reducing the net power conversion efficiency.

Partially shaded module is shown in Fig. 11. When the panel is partially shaded the bypass diode makes way for the current and the shaded region will act as a reverse biased circuit .

The modeling equations of the partially shaded panel are given,

$$I_{PV} > I_{ph} \tag{8}$$

$$I_{PV} = \min\left(I_{PV1}, I_{PV2}\right) \tag{9}$$

$$V_{PV} = \Sigma V_{PV} \tag{10}$$

During partial shading, each panel gets exposed to different irradiation and therefore each panel has its own peak power.
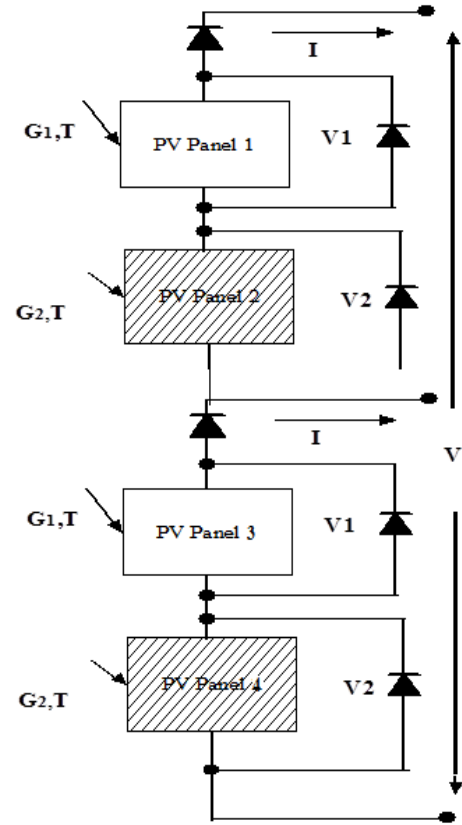

Fig.11 Partial shading configuration

In the system considered PV module of 170 W was blacked out to create partial shading effect. The corresponding output voltage and current waveform for change in irradiation from 500 Wm^2 to 1000 W/m^2 is shown in Fig. 12 .The system takes approximately 130 ms to reach MPP The experimental results validates the simulation results and only the steady state oscillation is invisible in simulation. It is due to the fact that dP/dV is much less.
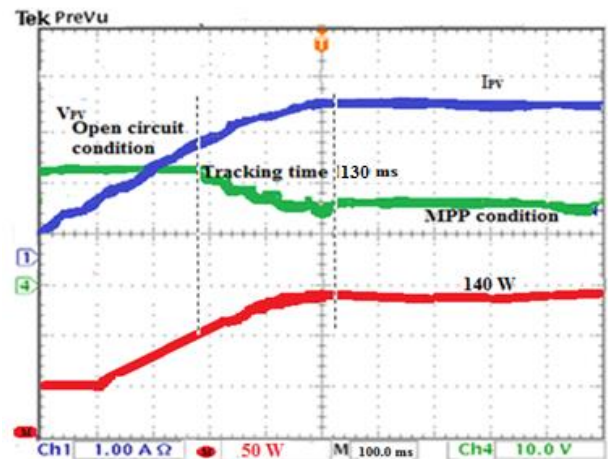

Fig. 12. PV voltage profile for step irradiation for 170 W system

Fig.12 proves that the three level perturbation is obtained for a step change in irradiation. The voltage changes from open circuit voltage at first level , power tracking occurs at second level of and finally steady state condition is reached at third level . The steady sate is reached after 250 ms with a constant output power of 140 W.

Fig. 13 shows the results of voltage and current under changing solar irradiation levels from 500 W/m² to 1000 W/m² to create a partial shading effect by hiding two PV module for 340 W system. Here an ouput power of 320 W is obtained in 130 ms.Hence the designed MPPT algorithm is also suitable for different power applications.
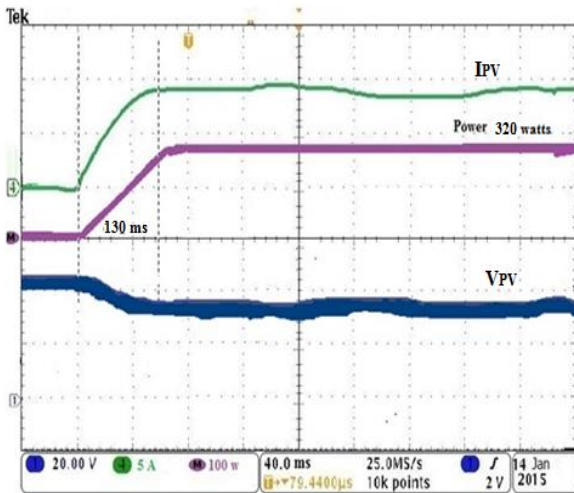

Fig. 13. PV voltage profile for step irradiation for 340 W system

The comparison results of conventional P&O controller Improved P&O[10] and Hybrid MPPT controller shown in Table 3 validates the efficiency of Hybrid MPPT controller.

Table 3: Comparison between MPPT controllers

Methodology	Step irradiation (1000 W/m² to 500 W/m²)	
	Output Power profile (watts)	Tracking time (ms)
Conventional P&O Controller	100 to 90 W	300
Improved P& O Controller (170 W)	130 to 80 W	250
Hybrid MPPT Controller (170 W)	140 to 85 W	130
Hybrid MPPT Controller (340 W)	320 to 170 W	130

The effectiveness of the proposed algorithm is validated by an improvement in the transient response.The system settles faster with an improved tracking time of 130 ms. The MPPT tracking efficiency of PV system with Cuk converter is 93.8%. The efficiency obtained validates the advantage of proposed Hybrid MPPT controller during partially shaded condition.

5. Conclusion and Future Work

This work aimed to propose a fast and stable MPPT technique for tracking maximum power under partial shading conditions.The Hybrid MPPT algorithm was simulated using Cuk converter in MATLAB Simulink and experimental prototype was developed using a simple PIC16F877A microcontroller.The Hybrid MPPT algorithm improves steady state stability, dynamic response and tracks the maximum power of 150 Watts and 320 W with a tracking efficiency of 93.8% .In future the work will be extended for higher power ratings.The duty cycle of the main switch of the Cuk converter is 34.9%. Duty ratio control using Hybrid MPPT algorithm offers better energy utilization efficiency and better stability characteristics at a slower transient response and improved performance at rapidly changing irradiance.In discussing the results of the simulation and experiment, a conventional cuk converter could be a good choice for a standalone PV system that requires operating in low irradiation conditions. The advantage of the proposed technique over conventional techniques are high efficiency , speed, stability and affordable cost.We are currently working on PV array system layout optimization techniques to further minimize shading effect.

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