Adaptive Incremental-Conductance MPPT based Solar PV system for Electric Vehicles.

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***Abstract*—** *Solar power being a renewable energy resource has tremendous potential of usage in the imminent future. As the solar energy harvest is dependent on irradiance, temperature and other climatic conditions, it is imperative that a Photovoltaic (PV) system should operate at a Maximum Power Point (MPP) in order to extract maximum power from the system. During sudden variations in irradiance, most of the Maximum Power Point Tracking (MPPT) controllers take long settling time at MPP point. This paper discusses an effective strategy to maximize solar energy harvest and to minimize disturbance error with a heuristic method for faster dynamic response and lower device stress than conventional designs, for solar electric vehicle (SEV) applications. Study has been done using MATLAB/Simulink for a standalone solar power system controlled with Incremental Conductance (IncCon) MPPT algorithm and heuristic techniques. The IncCon MPPT algorithm provides the fast-dynamic response and well-regulated PV output voltages. Heuristic methods with gathered data for various conditions and multiple locations guarantee a better performance and faster settling time. The number of parameters needed to be monitored in this method is significantly lower than other algorithms, making the implementation more streamlined and cost effective. Simulation of proposed heuristic method for rapid changes in irradiation was found to provide faster settling time and achieved maximum output compared to traditional IncCon algorithm. Experimental results are also provided to confirm the observed scenario.*

Keywords *- Solar PV System, Maximum Power Point Tracking, Incremental Conductance, Heuristic Technique, Electric vehicles.*

I. INTRODUCTION

The world's energy demand is increasing rapidly with the growth of population and the change in people's lifestyles. Limited reserves of fossil fuels, global warming and energy policies have urged developed countries to seek renewable energy [1]. Moreover, the main purpose of the evolution of smart grid from the current power grid is to increase the energy efficiency, reliability and sustainability. Solar energy is a promising renewable energy due to its various advantages such as limitlessness, zero pollution and noise and good reliability, thus gaining increased attention from governments and researchers in various countries.

EVs provide a clean, energy efficient and noise-free means for commuting when compared with gasoline vehicles. Indian government has ambitious plans for the mass scale shift to Electric Vehicles (EVs) by 2030 so that all vehicles on Indian roads by then—personal and commercial—will be powered by electricity. Solar power generation technologies are expected to become an attractive power source for automotive applications because of their cleanness, high efficiency, and high reliability [2]. Nowadays solar power is considered as the best solution for electric vehicle drives and other loads that demand DC supply. Although PV systems exhibit good power capability during steady-state operation, the dynamic response of PV during transient and instantaneous peak power demands is relatively slow and has low photoelectric conversion efficiency at 12%–22%. Implementing the Maximum Power Point Tracking (MPPT) technology to extract the highest amount of power from PV systems is one of the most practical methods to address this problem.

In recent years, many MPPT control methods have been proposed [3]-[12]. Among these methods, the most commonly used approaches are Perturb and Observe (P&O) and Incremental Conductance (IncCon). A traditional P&O algorithm is simple and easy to develop. It works by imposing a fixed step perturbation on a reference voltage or current, measuring the output power of the PV system, and comparing the values before and after perturbation to determine the direction of the perturbation for the next step. If PV power increases, then the direction of the perturbation is the same as that in the last step, otherwise, the direction is reversed. Despite the simple structure of the P&O algorithm, the fluctuation among the MPP is inevitable. In the selection of the tracking step, it is difficult to take account of both tracking precision and response speed. In some instances, the P&O algorithm generates an erroneous direction when a sudden change in irradiance occurs. In contrast, the IncCon method is used to determine the perturbation of the control parameter by comparing incremental conductance with instantaneous conductance [6]-[8]. However, the IncCon method has the same limitation as the P&O algorithm.

To overcome these drawbacks and improve the accuracy of the PV system, an MPPT method combining both the model-based and heuristic techniques was proposed [9] –[11]. The main disadvantages of such techniques are their slow tracking speed and poor performance in the rapidly changing irradiance. In this paper, an enhanced heuristic method is proposed to eliminate the aforementioned disadvantages and claiming the advantages of faster settling time. This technique is simple, easy to implement and employs nominal data provided by manufacturer to create an approximating function for the MPPT controller.

II. SYSTEM DESCRIPTION

Fig.1 illustrates the block diagram of a standalone DC Solar power system with the proposed MPPT controller. A Modified IncCon MPPT controller is designed to extract MPP from PV panels. To implement the MPPT technique effectively and to change the unregulated DC voltage from PV panel to the desired regulated DC voltage, a high efficiency Buck Boost converter is connected between the PV source and DC load.

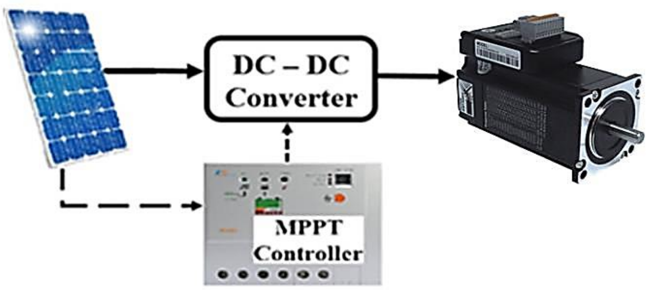


Fig.1: Block diagram of a Standalone DC Solar power system.

a. PV Model

A PV array consists of several photovoltaic cells in series and parallel connections. Typically a solar cell can be modeled by a current source and an inverted diode connected in parallel to it. Series resistance is due to hindrance in the path of flow of electrons from n to p-junction and parallel resistance is due to the leakage current [12], [13].

In Fig. 2(a), PV cell is modeled as a current source (I_{PH}) along with a diode and series resistance (R_S). The shunt resistance (R_{SH}) being very high value, has a negligible effect and can be neglected.

The output current from the photovoltaic array is

$$I = I_{PH} - I_d \quad (1)$$

$$I_d = I_o\,(e^{qVd/kT} - 1) \quad (2)$$

Where I_o is the reverse saturation current of the diode, q is the electron charge, V_d is the voltage across the diode, k is Boltzmann constant (1.38 * 10^{-19} J/K) and T is the junction temperature in Kelvin (K).

From eqn.1 and eqn.2,

$$I = I_{PH} - I_o\,(e^{qVd/kT} - 1) \quad (3)$$

Using suitable approximations,

$$I = I_{PH} - I_o\,(e^{q((V+IRs)/nkT)} - 1) \quad (4)$$

Where, I is the PV cell current, V is the PV cell voltage and n is the diode ideality factor.

When the voltage and the current are multiplied we get the P-V characteristics as shown in Fig. 2(b). The point indicated as MPP is the point at which the panel power output is maximum .

b. Buck-Boost Converter:

A Buck-Boost converter topology used here is represented in Fig 2(c). The design equations for the converter are depicted below from eqn. 5 to 15.[14] – [16]

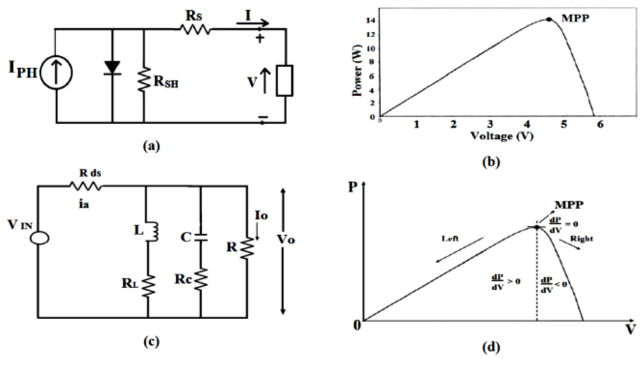


Fig.2 (a) Single diode model of a PV cell, (b)P-V characteristics curve of PV cell. (c) The Equivalent circuit of Buck Boost converter, (d) Basic idea of IncCon method on P-V Curve.

Duration of the on state (T_{ON}) = $D * T_S$ (5)

Duration of the off state (T_{OFF}) = $(1 - D) * T_S$ (6)

The rate of increase of inductor current during on condition is given by;

$$\Delta I_L = (V_O(1-D)/L) * \Delta T \quad (7)$$

For steady state operation the average inductor current is zero.

$$(\Delta I_L)_{OPEN} + (\Delta I_L)_{CLOSED} = 0 \quad (8)$$

$$V_o = \left[-(V_{IN} - V_{DS}) * \frac{D}{1-D} - V_D - \frac{I_L * R_L}{1-D}\right] \quad (9)$$

$$I_o = \frac{1}{T_S}\left(\frac{I_{PK}}{2} * (1-D) * T_S\right) \quad (10)$$

$$I_{DS} = I_L * R_{DS(on)} \quad (11)$$

$$V_L = (V_{IN} - V_{DS} - I_L * R_L) \quad (12)$$

The value of minimum inductance can be determined from this equation.

$$L_{min} \geq \frac{V_O * T_S}{(2 * I_{O(CIRT)})} * \frac{V_{L(max)}}{(V_O - V_{L_{max}})} \quad (13)$$

The practical value of inductance is chosen to be $L = L_{min} * 1.25$.

Taking into consideration the value of the resistance, the value of the output voltage is given.

$$V_O = V_{IN} * \frac{D}{1-D} * \frac{1}{1 + \frac{R_L}{R * (1-D)^2}} \quad (14)$$

Output capacitance:

$$C = \frac{I_{O_{Max}} * D_{max}}{f_s * \Delta V_O} \quad (15)$$

$I_{O(max)}$ is the maximum output current and D_{max} is the maximum duty cycle.

c. Maximum Power Point Tracking (MPPT) Technique

A typical solar panel converts only 14 to 22 percent of the incident solar irradiation into electrical energy. MPPT technique is used to improve the efficiency of the solar panel . Though PV solar module does not fit into a linear model, the concept of Maximum Power Transfer theorem (ie) the power output of a circuit is highest when the thevenin's impedance of the circuit (source impedance) matches with the conjugate of load impedance, can be used to develop the tracking algorithm of solar power. There are different techniques used to track the Maximum Power Point (MPP). Few of the most popular techniques are P&O, IncCon, Parasitic Capacitance, Voltage and Current based Peak Power Tracking .

d. Incremental Conductance (IncCon) MPPT Algorithm

In IncCon method, the array terminal voltage is always adjusted according to the MPP voltage. It is based on the incremental and instantaneous conductance of the PV module .
Fig. 2 (d) shows that the slope of the P-V array power curve is zero at the MPP, positive on the left of the MPP and negative on the right side of the MPP.
The basic equations of this method [4] are as follows.

$$dI/dV = -I/V \text{ at } MPP \quad (16)$$

$$dI/dV > -I/V \text{ left of } MPP \quad (17)$$

$$dI/dV < -I/V \text{ right of } MPP \quad (18)$$

where I and V are PV array output current and voltage respectively. This method exploits the assumption of the ratio of change in output conductance is equal to the instantaneous negative output conductance .

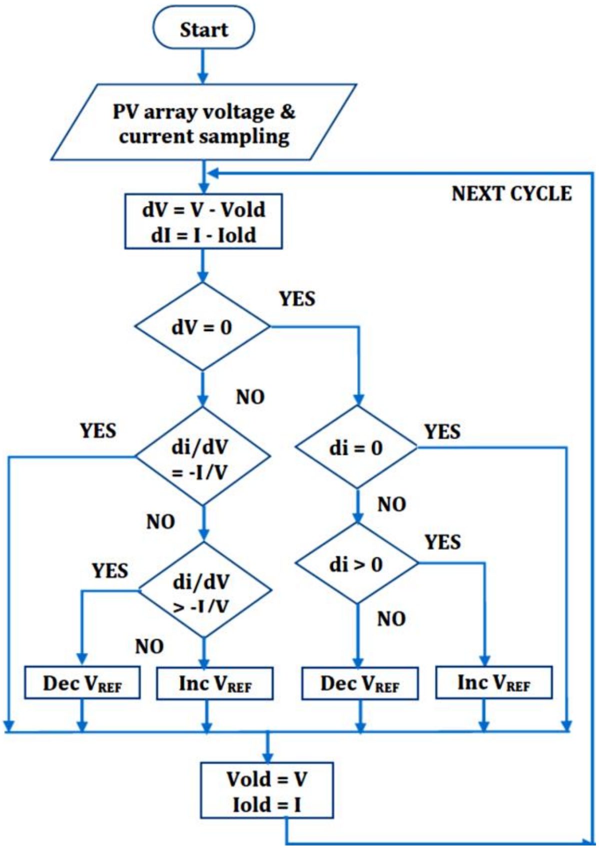


Fig.3: Flow chart of Incremental Conductance(IncCon) algorithm.

We have, $P = V I$ (19)

Applying the chain rule for the derivative of products yields to

$$\partial P/\partial V = [\partial(VI)]/\partial V \quad (20)$$

At MPP, as $\partial P/\partial V = 0$

The above equation could be written in terms of array voltage V and array current I as

$$\partial I/\partial V = - I/V \quad (21)$$

The MPPT controller gives the correcting PWM signal of the DC– DC Buck-Boost converter until the condition $(\partial I/\partial V) + (I/V) = 0$ is satisfied. The flow chart of IncCon MPPT technique is shown in Fig.3.

e. Heuristic Technique for Optimization

While there are general guidelines of what is likely to make a good solution, the prior knowledge can be incorporated in the choice of the initial solutions or in the search process (guided search). The inclusion of prior knowledge might significantly reduce the search space and increase the convergence speed. A new solution can be generated by modifying the current solution (neighborhood search) based on past experience or results . In this paper, the PV insolation data of yesteryear was used as starting point in the iterations. The look up table was used to have a database of insolation and its corresponding Vpv and Ipv from the PV model from the simulation as shown in Fig. 4.

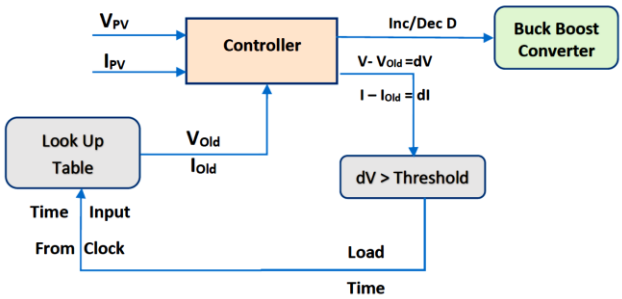


Fig 4: Concept of Heuristic IncCon MPPT Method

The starting point of iterations from the lookup table makes the tracking faster thereby reducing the number of iterations and hence the time for settling to final output. The deviation between previous and current values when varies more than a threshold value, initiates loading of current time in to the look up table for new set of values, the controller tracks the MPP and adjusts the duty cycle corresponding to the current insolation.

Heuristic Techniques like Extremum seeking control and adaptive extremum seeking control [17] approaches track the MPP by establishing a feedback system that is able to produce an oscillatory behavior around the equilibrium point. In this paper we have introduced a concept of look up table for the choice of initial solutions, and implemented with 3D Lookup table in MatLab simulation.

III. SIMULATION AND EXPERIMENTAL CIRCUIT

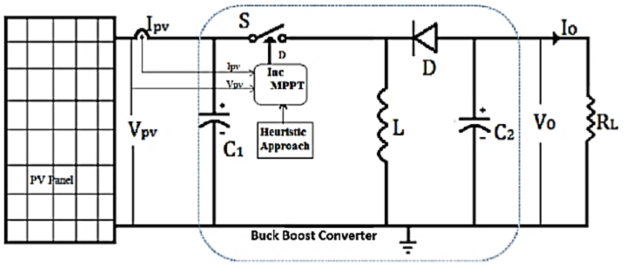


Fig.5: Simulation circuit of Proposed PV – Heuristic IncCon MPPT Model.

The entire PV system has been modeled using Power System Block set under MATLAB™/Simulink™ as shown in Fig.5. Here, the PV module is built in Simulink with the following parameters: Isc, Voc, Im and Vm at standard conditions are 6.15A, 21.6V, 5.59A and 17.5V respectively. It is assumed that all PV cells are under the same irradiance and temperature condition, therefore only voltage and current sensors are needed, which make the measuring circuits simple and cost of the hardware low. A Buck-Boost converter has been modeled in the simulation. From the design calculations the inductor has been chosen to be 47µH and the capacitance is taken to be 2000µF for a ripple free current. The detailed circuit parameter of the Buck-Boost converter is given in Table 1.

The IncCon MPPT algorithm is embedded as a function block in the circuit and the desired outputs were obtained from the respective scopes. The V_{PV} and I_{PV} are the PV voltage and current.

Specification	**Rating**
Power rating (Po)	150 W
Input voltage (Vi)	25 V
Output voltage (Vo)	45 V for boost mode; 24 V for buck mode
Switching frequency (f_S)	100 kHz
Load resistance (R_L)	100 Ω
MOSFET power switch (S)	IRFP250
output diodes (D)	MUR3060
capacitor (C_1 and C_2)	2000 µF

Table 1 Circuit parameters of the Buck-Boost Converter

For applying heuristic method for one day data, the real-time implementation of such approximating function is based on a reduced three-dimensional lookup table procedure that minimizes the computational complexity of the proposed technique.

Fig.6 shows the control scheme and experimental hardware setup of the proposed PV-Buck- Boost system. The control scheme was implemented using 16 bit dsPIC30F4011controller, due its advantages over its predecessors [18],[19]. PV source was constructed using FS-4100-2 (150W) model, polycrystalline type PV module. The PV voltage and other test point signals of hardware were measured using DSO.

To verify the feasibility and performance of the proposed heuristic method, simulations were conducted in MATLAB and the same was verified with dSPACE control desk module, after due testing hardware circuit was developed with dsPIC development board.

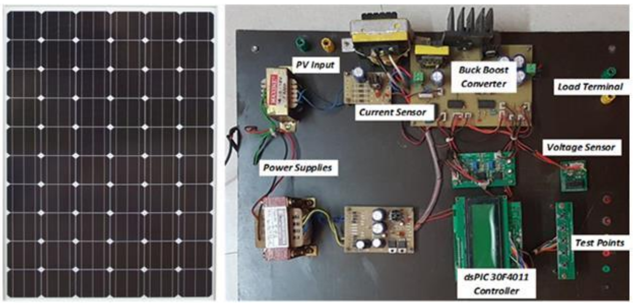


Fig.6 Experimental Setup

IV. DISCUSSIONS ON SIMULATION AND EXPERIMENTAL RESULTS

To investigate the effectiveness of the proposed heuristic IncCon MPPT algorithm, the performance characteristics at steady state and transient conditions were analyzed for different constant and rapidly changing irradiations and load changes.

Table 2 shows the simulation results on the performance of the system under various irradiance levels, by conducting it without MPPT and with MPPT controller.

Insolation Step (G) (W/m^2)	PV peak power without MPPT (W)	PV peak power with proposed MPPT (W)
400	11	25
700	28	51
1000	49	83.2

Table 2: PV power without and with proposed MPPT Controller. (R_L = 100 Ω)

It was observed that, without MPPT, when the irradiance was changed from 400 to 1000, the output has reached a maximum power of 49W. When the simulation was repeated with proposed MPPT method, the output was found to vary from 25W to a max of 83W, thus showing an increase of nearly double the value than its previous simulation results.

(a) Testing under step variation of insolation (G) with fixed T & R_L conditions.

The simulation is carried out for a temperature of 35° C. The insolation (G) is taken for a step rise in insolation from 400 to 500 W/m^2 at 1.25ms. The load resistance is fixed at 100Ω and the power output was measured. Fig 7 (a) and (b) show the output power obtained in simulation and experimental circuit. The output power of the MPPT PV system for step change in input started from 24W and increased to 32W within 0.05ms in simulation. The same was proved in the experimental result as shown in Fig. 7 (b). where the change in output power from 19 to 30.5 watts happened within 0.15ms. Both simulation and experimental results prove that the transient response for the step change in G, shows no significant overshoot during transition and the output settled smoothly to steady state without oscillations.

(b) Testing under sudden change in Load Resistance (R_L) from 100 Ω to 75 Ω.

The transient responses of the proposed PV system for a step change in load with fixed irradiation have been investigated. Fig. 8 (a) to (d) show the output voltage and current obtained in simulation and experimental results. Fig. 8(a) shows that during simulation, when the load R_L had changed from 100Ω to 75Ω, the PV voltage got modified and drops down from 75V and quickly settled to 64V in steady state. The same was observed in experimental setup as shown in Fig 8(b). Fig 8(c) and (d) show the transient response of output current under the step change in load resistance.

(c) Simulations under fixed T with one-day Insolation data and variable load conditions with Heuristic Approach.

The simulation is carried out for a temperature of 35° C. The insolation (G) is taken as one-day irradiation data from CWET for the date of 1st January, 2016 to reflect real time conditions, and varying the load resistance from 10Ω, 25 Ω, 100 Ω, 500 Ω and 1000 Ω. The insolation for one-day data is mapped in 2.4 milliseconds as shown in Fig.9. The output power obtained, with and without proposed MPPT for all those R_L values is shown in Fig. 10(a) and (b). It is observed that there is a drastic decrease in output power with increase in resistance when the system is operated without MPPT whereas with proposed MPPT the system's output peak power mostly remains same. It is also observed that without MPPT, when the resistance is increased from 10Ω, 25Ω, 100 Ω, 500Ω and 1000 Ω in steps, the peak power reduces from 55.2W, 50.1W, 27.5W, 8.2W and 4.3W respectively. When repeating the same for system with heuristic IncCon MPPT, the peak output power was varying from 85.8 to 88.6W showing that the output is stabilized for any change in load.

From Fig 11, the energy ratios obtained are 1: 1.61: 1.74, taking energy obtained without MPPT as reference value. It is observed an increase of about 75% more energy through the proposed modified IncCon MPPT which is again 7.7% above the energy obtained with conventional IncCon MPPT Method.

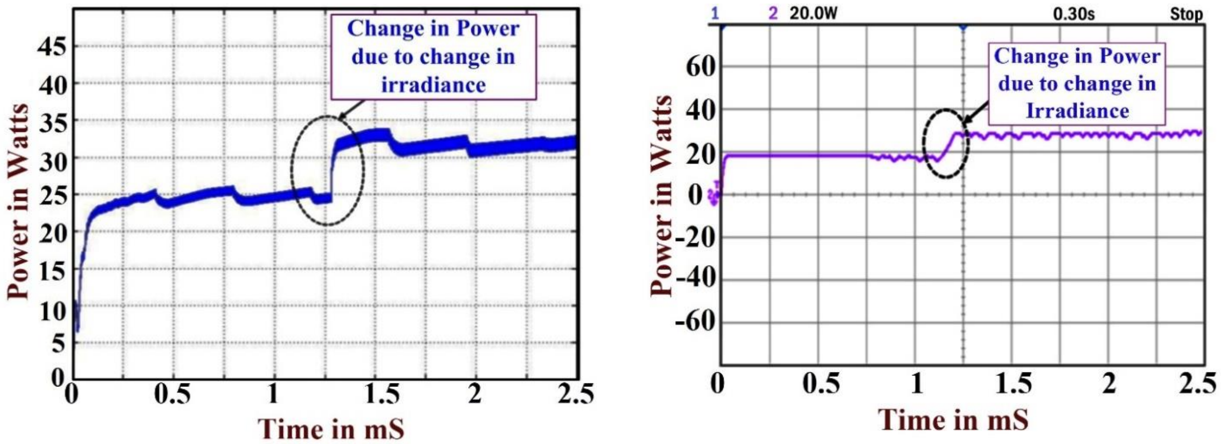
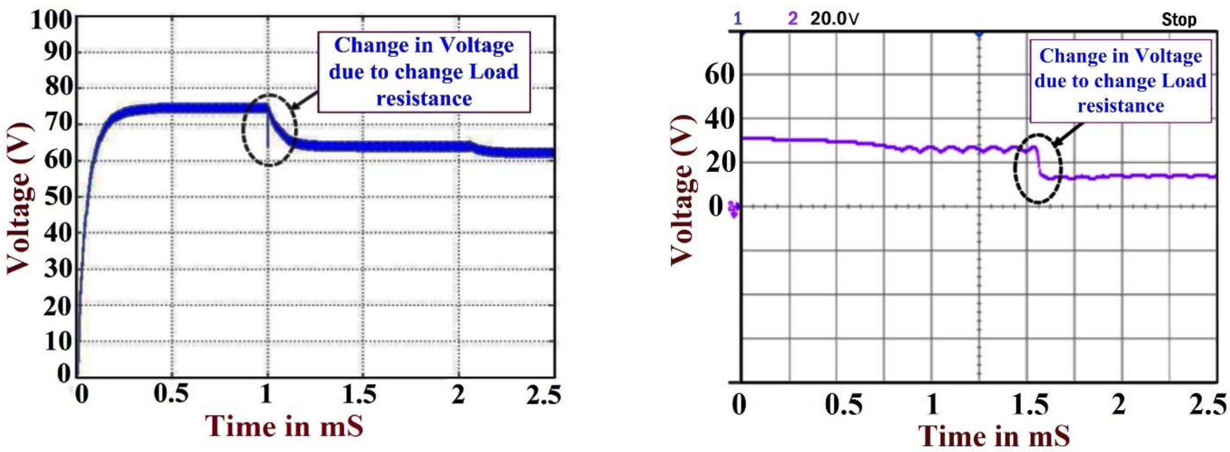


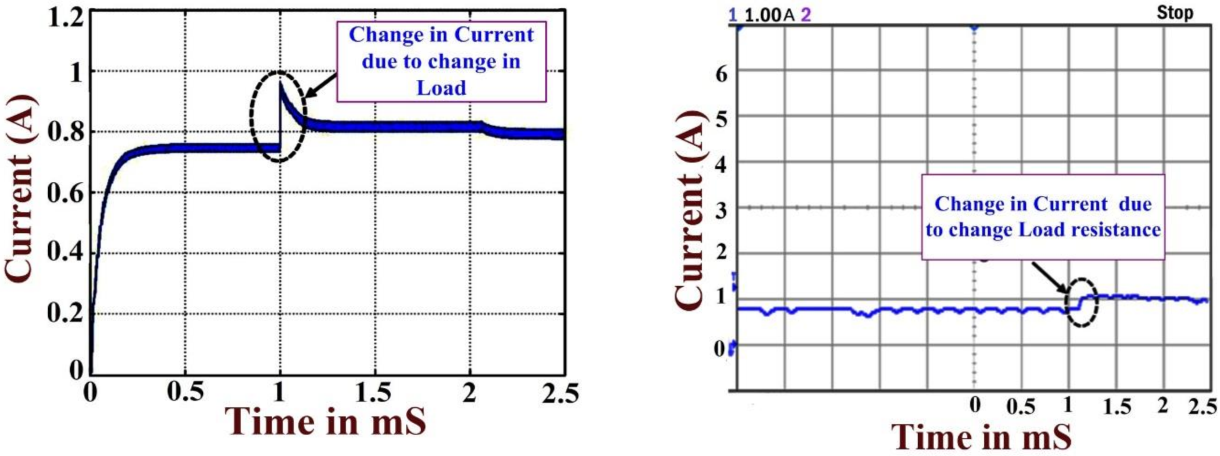
Fig. 7 : PV Power with proposed MPPT for irradiation change at R_L = 100 Ω (a) Simulation output (b) Experimental output .



(a)

(b)

Fig. 8 : Load voltage and load current for a sudden change in load resistance (a) Simulation result of load voltage (b) Experimental output of load voltage



(c) (d)

Fig. 8 : (c) Simulation output of load current (d) Experimental output of load current.

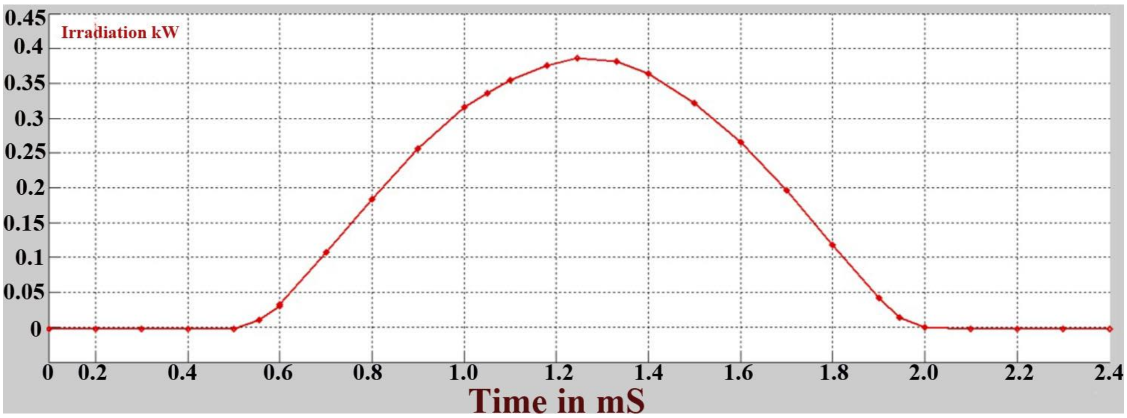
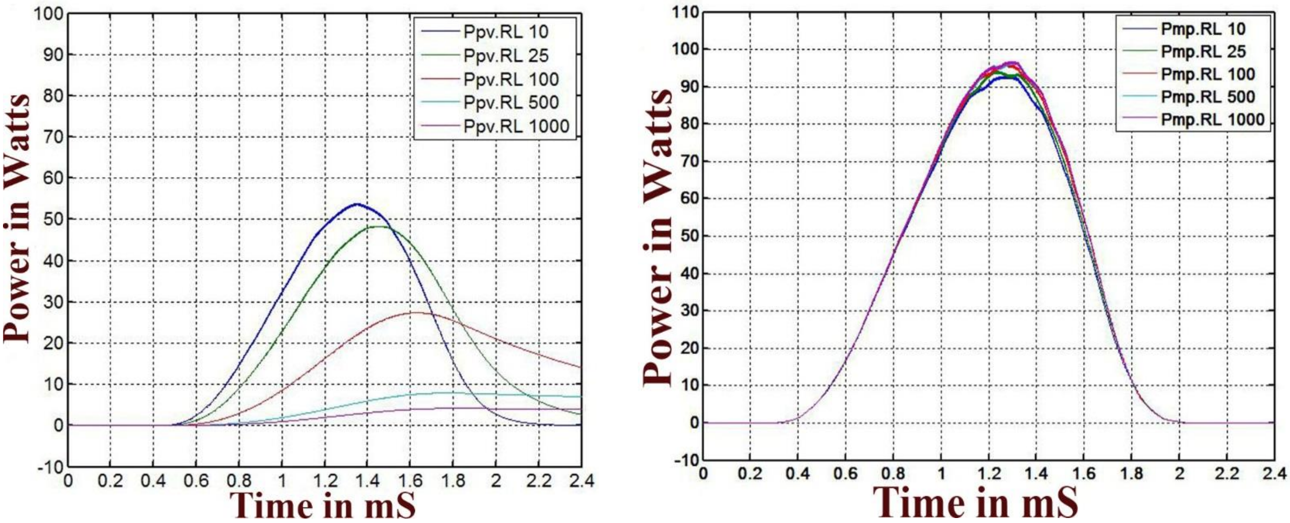


Fig.9: One Day Insolation Data



(a) (b)

Fig.10: PV Power for one day Insolation data with R_L = 10 Ω, 25Ω, 100 Ω, 500 Ω and 1000 Ω (a) Without MPPT (b) With MPPT

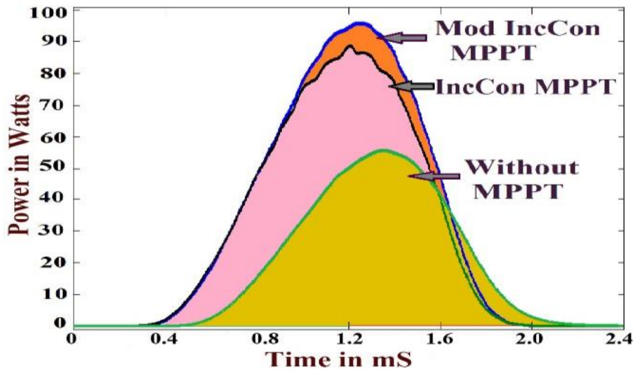


Fig. 11: Energy curve when operated without MPPT, with conventional IncCon MPPT and with heuristic based IncCon MPPT for a fixed load of $R_L = 100\Omega$.

Table 3 lists the PV power and energy obtained with comparison results between plain PV system, IncCon MPPTand using the proposed IncCon MPPT with heuristic approach. It is observed that there is much more increase in output power with the proposed system. It is clear that on comparison between PV without MPPT, IncCon MPPT and the proposed IncCon MPPT with heuristic technique, the proposed system is more efficient in tracking for low as well as high irradiations and the peak power was found to be 95.6W. There is a difference of 7W between IncCon MPPT and the proposed IncCon MPPT with heuristic approach.

	Without MPPT PV System	**With Conventional IncCon MPPT PV System**	**With proposed heuristic IncCon MPPT PV System**
Peak Power (Watts)	55.2	88.6	95.6
Energy (Watt-ms)	4.3527	7.0005	7.5924

Table 3. PV power and total energy obtained without MPPT, with conventional IncCon MPPT and with heuristic based IncCon MPPT for one-day insolation data

V. SUMMARY AND CONCLUSION

In this paper, a modified Incremental Conductance (IncCon) algorithm using heuristic approach is proposed. This method computes the maximum power and directly controls the extracted power from the PV. It requires only measurements of PV voltage and current and thus making the system less complicated and cost effective. The paper began by demonstrating the lower efficiency and slow tracking speed of the IncCon method. Then, it is proved that the proposed model uses the distinguished features of the heuristic method applied over the IncCon algorithm and hence provides high accuracy and tracking speed. The effectiveness of the proposed system was checked using MATLAB and also verified using a prototype. By using this MPPT method, the output power was found to increase by 28%, and the energy developed over one day insolation showed a 7.7% increase over traditional IncCon MPPT. The inclusion of prior knowledge in the heuristic approach has significantly reduced the search space and increased the convergence speed, and offers advantages like reduced settling time, good tracking efficiency, high response and greater control for the extracted power.

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