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Design of a Variable Duty Cycle Maximum Power Point Tracking Algorithm for Solar Energy Conversion

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***Abstract*— The necessity of renewable energy source is increasing because of present energy crisis in the world. Photovoltaic energy is one of the very promising renewable energy resources which grew rapidly in the past few years. But the main obstacle of photovoltaic array is that with the change of operating of PV array, output voltage where maximum power can be gained also changes. To extract maximum power point impedance matching is necessary whatever load is connected to the solar panel. A maximum power point needs to be introduced to track the maximum power point. Literature review illustrates that there are many algorithms available for MPPT but most of them can work either below or above 50% duty cycle. This paper represents an algorithm which can operate over the full duty cycle. The design is based on simple buck-boost converter. MATLAB/Simulink is used to simulate design which is based on buck-boost converter. After that the controller part and the buck-boost converter is implemented.**

***Index Terms*—MPPT Algorithm, Buck-Boost Converter, PI Controller, PV array**

I. Introduction

Traditional fossil fuel is expected to run out within few years, considering that the world started to move on sustainable energy source like solar, wind, fuel cell. Tide, earth crust heat etc. the most efficient and cost effective resource is the sun energy which can be harnessed through PV array. Successful application of this resources depends on being able to utilize the voltage constantly where the power is maximum. To track the maximum power point, it needs to apply MPPT algorithm which will set the voltage automatically to get the maximum power.

There are many researchers have been conducted so far to optimize PV by using some methods, for instance: Constant voltage control, Perturb & Observe, Incremental Conductance, Fuzzy Logic and Neural Network. Perturb & Observe methods or also well known as Perturbation Methods is widely used but one drawback of this method is its disturbance increases along with the power and after the power of PV reaches the peak, the power will decrease and the disturbance becomes bigger [1]. Another drawback of its method is it introduce an oscillation on maximum power point area and not suitable to implement at an environment which suffer from rapid changes of temperature and irradiant [2]. Other alternative of MPPT methods are Fuzzy Control and Neural Network [3][4][5]. Fuzzy control has been used to control Boost converter in an electric car which is powered by solar energy [3]. Fuzzy control and Neural Network deteriorate from the complexity of fuzzy rules design process and also depend on learning process [3][4][5]. A DC to DC converter is needed for implementing MPPT. The DC-DC converter delivers the maximum power from PV module to load by adjusting the duty cycle and able to distribute a maximum power when load is changes [6]. Some common DC-DC converter topologies for implementing MPPT are Buck converter, Boost converter, Cuk converter, Full bridge converter and Buck Boost converter. In this paper an algorithm is proposed which will operate at any duty cycle. The performance of the proposed method outperformed the PO method when it implemented at Buck-Boost converter. A PWM controller is developed to follow the maximum power point of a PV array regardless the temperature, irradiance and load. The overall design is very simple consist of a buck boost converter which made the design compact and cost effective.

The PV systems are principally classified according to their mode of operation as stand-alone or grid connected systems. The operation of the stand-alone PV systems is independent on the grid. Recently, there is an increasing interest in installing grid-connected PV systems to form distributed generation. This trend is attributed to economic and technical benefits of distributed generation in micro-grids. On the other hand, the dispersed grid-connected PV systems require efficient power conditioning converters. The power conditioning devices include DC/DC boost converter and voltage source inverter. Many controlling strategies have been developed [7-9] to control the power conditioning converters. In most PV systems, MPPT algorithms are utilized for full extraction of the available solar energy. The controller adopts the pulse width modulation (PWM) technique to change the converter duty cycles to obtain stable output power close to MPP of the PV array. Fig. 1 shows the block diagram of PV energy generation system.

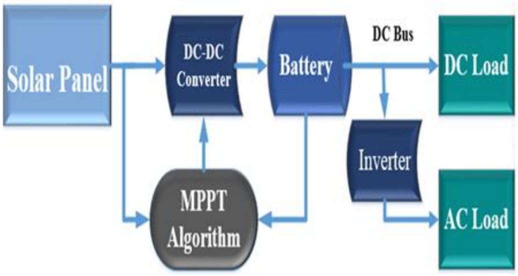

Fig. 1. Block diagram of PV energy generation system

II. PHOTOVOLTAIC MODEL

An ideal solar cell is modelled by a current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model. The resulting equivalent circuit of a solar cell is shown in fig. 2.

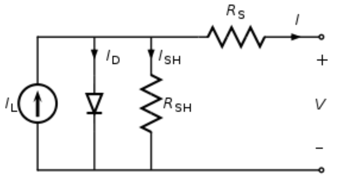

Fig. 2. Equivalent Circuit of a PV cell

A. Characteristic equation

From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor:

$$I = I_L - I_D - I_{SH} \quad \text{(i)}$$

Where

I = output current (amperes)

I_L = photo generated current (amperes)

I_D = diode current (amperes)

I_{SH} = shunt current (amperes)

The current through these elements is governed by the voltage across them:

$$V_j = V + IR_S \quad (2)$$

Where

V_j = voltage across both diode and resistor R_{SH} (volts)

V = voltage across the output terminals (volts)

I = output current (amperes)

R_S = series resistance (Ω).

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_0 \left\{ exp\left[\frac{qV_j}{nkT}\right] - 1 \right\} \quad (3)$$

Where

I_0 = reverse saturation current (amperes)

n = diode ideality factor (1 for an ideal diode)

q = elementary charge

k = Boltzmann's constant

T = absolute temperature

By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}} \quad (4)$$

Where, R_{SH} = shunt resistance (Ω).

Substituting these into equation (1) produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$$I = I_L - I_0 \left\{ exp\left[\frac{q(V+IR_S)}{nkT}\right] - 1 \right\} \quad (5)$$

In principle, given a particular operating voltage V the equation may be solved to determine the operating current I at that voltage. However, because the equation involves I on both sides in a transcendental function the equation has no general analytical solution. However, even without a solution it is physically instructive. Furthermore, it is easily solved using numerical methods.

Since the parameters I_0, n, R_S, and R_{SH} cannot be measured directly, the most common application of the characteristic equation is nonlinear regression to extract the values of these parameters on the basis of their combined effect on solar cell behavior.

B. Open-circuit voltage and short-circuit current

When the cell is operated at open circuit, $I = 0$ and the voltage across the output terminals is defined as the open-circuit voltage. Assuming the shunt resistance is high enough to neglect the final term of the characteristic equation, the open-circuit voltage V_{OC} is:

$$V_{OC} \approx \frac{kT}{q} ln\left(\frac{I_L}{I_0} + 1\right) \quad (6)$$

Similarly, when the cell is operated at short circuit, $V = 0$ and the current I through the terminals is defined as the short-circuit current. It can be shown that for a high-quality solar cell (low R_S and I_0, and high R_{SH}) the short-circuit current $I_{SC} \approx I_L$

C. EFFECT OF PHYSICAL SIZE

The values of I_0, R_S, and R_{SH} are dependent upon the physical size of the solar cell. In comparing otherwise identical cells, a cell with twice the surface area of another will, in principle, have double the I_0 because it has twice the junction area across which current can leak. It will also have half the R_S and R_{SH} because it has twice the cross-sectional area through which current can flow. For this reason, the characteristic equation is frequently written in terms of current density, or current produced per unit cell area:

$$J = J_L - J_0 \left\{ exp\left[\frac{q(V+Jr_S)}{nkT}\right] - 1 \right\} - \frac{V+Jr_S}{r_{SH}} \quad (7)$$

Where

J = current density (amperes/cm^2)

J_L = photogenerated current density (amperes/cm^2)

J_0 = reverse saturation current density (amperes/cm^2)

r_S = specific series resistance (Ω-cm^2)

r_{SH} = specific shunt resistance (Ω-cm^2)

This formulation has several advantages. One is that since cell characteristics are referenced to a common cross-sectional area they may be compared for cells of different physical dimensions. While this is of limited benefit in a manufacturing setting, where all cells tend to be the same size, it is useful in research and in comparing cells between manufacturers. Another advantage is that the density equation naturally scales the parameter values to similar orders of magnitude, which can make numerical extraction of them simpler and more accurate even with naive solution methods. There are practical limitations of this formulation. For instance, certain parasitic effects grow in importance as cell sizes shrink and can affect the extracted parameter values. Recombination and contamination of the junction tend to be greatest at the perimeter of the cell, so very small cells may exhibit higher values of J_0 or lower values of R_{SH} than larger cells that are otherwise identical. In such cases, comparisons between cells must be made cautiously and with these effects in mind. This approach should only be used for comparing solar cells with comparable layout. For instance, a comparison between primarily quadratic solar cells like typical crystalline silicon solar cells and narrow but long solar cells like typical thin film solar cells can lead to wrong assumptions caused by the different kinds of current paths and therefore the influence of for instance a distributed series resistance r_S.

III. PROPOSED MPPT ALGORITHM

Maximum Power Point Tracking (MPPT) is an algorithm that is added in charge controllers for extracting maximum available power from PV panel. PV panel can produce maximum power in which point is called 'Maximum Power Point'. Maximum Power Point Tracking is digital electronic tracking [10]. The charge controller takes data from the output of the panels, and compares it to the battery voltage. It then figures out what is the optimum power that the panel can put out to charge the battery. It takes this and converts it to best voltage to get maximum AMPS into the battery. Most modern MPPT's are around 93-97% efficient in the conversion. Typically, 20 to 45% power gain in winter and 10-15% in summer. Actual gain can vary widely depending weather, temperature, battery state of charge, and other factors. Literature review suggests that many MPPT algorithms are already available. Proposed MPPT algorithm is constant voltage based algorithm. Fig. 3 is the flow chart of proposed constant voltage based algorithm. According to proposed flow chart 1st step is to set the no. of load voltage of PV panel. Then it is multiplied with no. of cell and also with that result with 0.82 as V_{mpp} is 82% of V_{oc}. After that this result is compared with the voltage of Buck-Boost converter. Then this two voltage is subtracted to find error. If the Error becomes zero, previous duty is kept unchanged and given to IGBT. If Error is found not equal to zero, then subtracting voltage is passed through a PI controller (Arduino UNO). This controller compare the duty with SAW Tooth voltage and generate a new duty which required. And that voltage will give to the IGBT and do the same process again. With this algorithm the operating voltage V is perturbed with every MPPT cycle. As soon as the MPP is reached, V will oscillate around the ideal operating voltage. This causes a power loss which depends on the step width of a single perturbation i.e. the larger the step is, the larger the oscillations around voltage of maximum power is and vice versa [11].

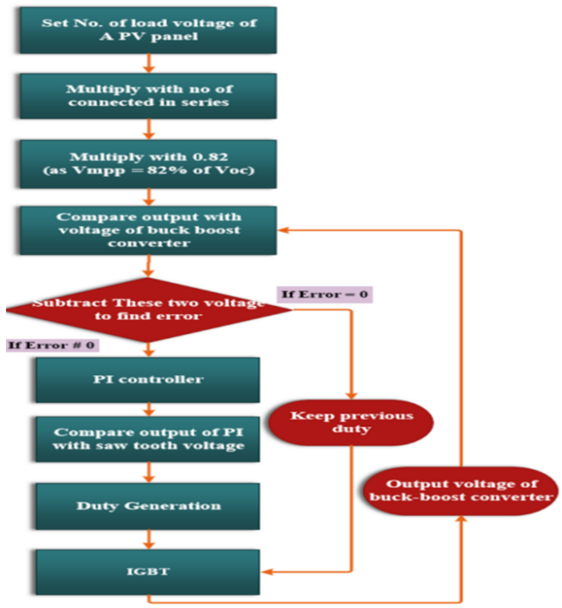

Fig. 3. Flow chart of proposed MPPT

If the step width is large, the MPPT algorithm will be responding quickly to sudden changes in operating conditions with the tradeoff of increased losses under stable or slowly changing conditions. If the step width is very small the losses under stable or slowly changing conditions will be reduced, but the system will be only able to respond very slowly to rapid changes in temperature and solar irradiance. The value of ideal step width is system dependent and needs to be experimentally determined.

IV. BUCK-BOOST CONVERTER

A Buck-Boost converter is a type of switched mode power supply that combines the principles of the Buck Converter and the Boost converter in a single circuit. It provides a regulated DC output voltage from either an AC or a DC input. The Buck converter produces a DC output in a range from 0V to just less than the input voltage. The boost converter will produce an output voltage ranging from the same voltage as the input, to a level much higher than the input.

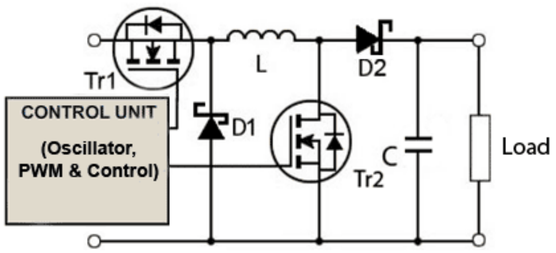

Fig. 4. Basic Buck-Boost Converter

By combining these two regulator designs it is possible to have a regulator circuit that can cope with a wide range of input voltages both higher and lower than that needed by the circuit. Both buck and boost converters use very similar components. They just need to be re-arranged, depending on the level of the input voltage. The common components of the buck and boost circuits are combined. A control unit is added, which senses the level of input voltage, then selects the appropriate circuit action.

A. Operation as a Buck Converter:

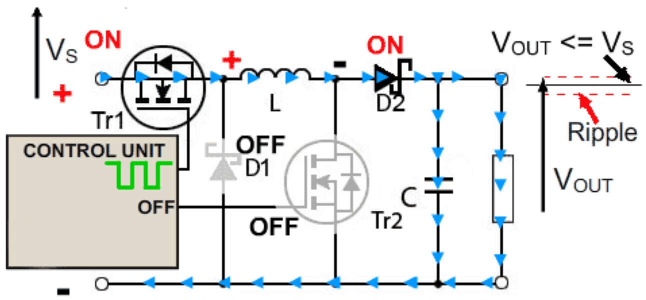

Fig. 5. Operation as a Buck Converter Tr1 ON Period

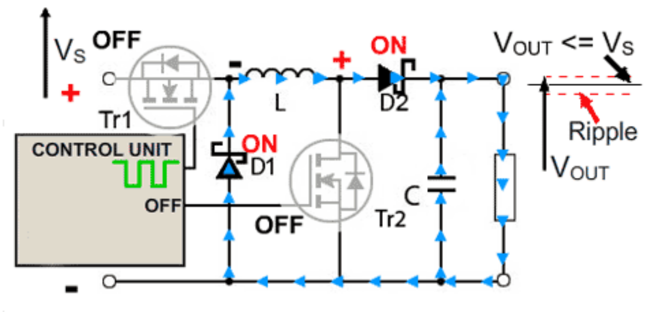

Fig. 6. Operation as a Buck Converter Tr1 OFF Period

When the circuit operates as a Buck Converter Tr2 is turned OFF, and Tr1 is switched ON and OFF by a high frequency square wave from the control unit. When the gate of Tr1 is high, current flows though L, charging its magnetic field, charging C and supplying the load. The Schottky diode D1 is turned OFF due to the positive voltage on its cathode. The current flow during the buck operation of the circuit when the control unit switches Tr1 off. The initial source of current is now the inductor L. Its magnetic field is collapsing, the back e.m.f. generated by the collapsing field reverses the polarity of the voltage across L, which turns on D1 and current flows through D2 and the load. As the current due to the discharge of L decreases, the charge accumulated in C during the on period of Tr1 now also adds to the current flowing through the load, keeping V_{out} reasonably constant during the off period. This helps keep the ripple amplitude to a minimum and V_{out} close to the value of V_S.

B. Operation as a Boost Converter:

In Boost Converter mode, Tr1 is turned ON continually and the high frequency square wave applied to Tr2 gate. During the ON periods when Tr2 is conducting, the input current flows through the inductor L and via Tr2, directly back to the supply negative terminal charging up the magnetic field around L.

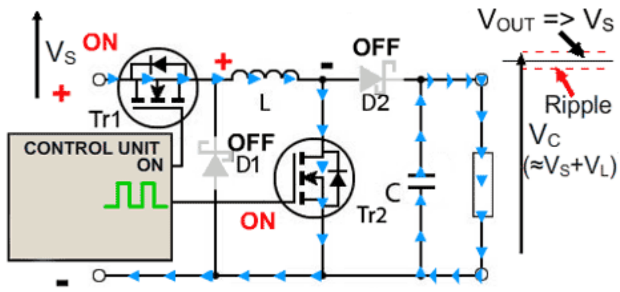

Fig. 7. Operation as a Boost Converter Tr2 ON Period

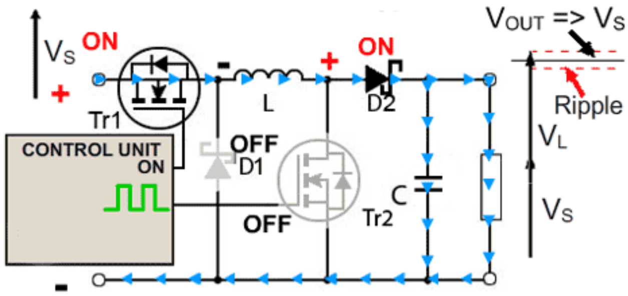

Fig. 8. Operation as a Boost Converter Tr2 OFF Period

D2 cannot conduct as its anode is being held at ground potential by the heavily conducting Tr2. For the duration of the on period, the load is being supplied entirely by the charge on the capacitor C, built up on previous oscillator cycles. The gradual discharge of C during the on period accounts for the amount of high frequency ripple on the output voltage, which is at a potential of approximately $V_S + V_L$ [12].

B.The Off Period: At the start of the OFF period of Tr2, L is charged and C is partially discharged. The inductor L now generates a back e.m.f. and its value that depends on the rate of change of current as Tr2 switches OFF and ON the amount of inductance the coil possesses; therefore the back e.m.f can be any voltage over a wide range, depending on the design of the circuit. Particularly that the polarity of the voltage across L has now reversed, and so adds to the input voltage VS giving an output voltage that is at least equal to or greater than the input voltage. D2 is now forward biased and so the circuit current supplies the load current, and at the same time re-charges the capacitor to VS + VL ready for the next ON period of Tr2 [12].

C. *Circuit Variations:* There are a number of variations of this basic Buck-Boost circuit, some designs working at lower frequencies or at high voltages may use bipolar transistors instead of MOSFETs; at low frequencies the higher speed switching of MOSFETs is less of an advantage. Also, in high voltage designs, silicon diodes may be used in preference to Schottky types due to the silicon diode's higher reverse voltage capabilities. Another variation is to use synchronous switching where, instead of using diodes that simply respond to the voltage polarity across them, four synchronized (by the control unit) MOSFETs do all the switching. Advantages of Buck Boost Converter over Other Converters: Main advantage of buck boost converter is, it can be operated with the range of 0 to 100% duty cycle.

V. SIMULATION AND ANALYSIS

All the simulation for the PV array, Buck-Boost converter and PI controller has been done using MATLAB/Simulink.

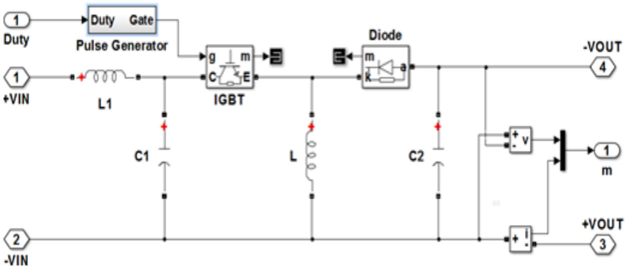

Fig. 9. Buck-Boost Converter

Fig. 10 and Fig. 11 are the simulated solar system with developed MPPT algorithm which consist of PV array, PI controller, Buck-Boost converter and simulated solar system without using MPPT algorithm.

Constant load to 60Ω, solar irradiance to 1000 W/m^2 and temperature to 25°C has been kept for curve analysis. Fig. 12 represents the simulated output result of PV array Voltage without MPPT and with MPPT. Output curve of PV array Voltage without using MPPT is a straight line at an average 60 V, where in the Fig. 13 the output voltage curve of PV arrays using MPPT increased linearly for a certain time and then saturated at 140 V. Comparing both the figures it can easily be said that the out voltage for solar system with MPPT is much higher than the solar system without MPPT.

Fig. 14 is the output current curve of the simulated solar PV panel without using MPPT and Fig. 15 is the output current curve of the simulated solar PV panel. Here in Fig. 14 the line on the graph shows the output of PV array current value without using MPPT is 1.3A. In Fig. 15 It becomes 2.4A when the system is using MPPT algorithm. So performance is better when system using developed MPPT algorithm.

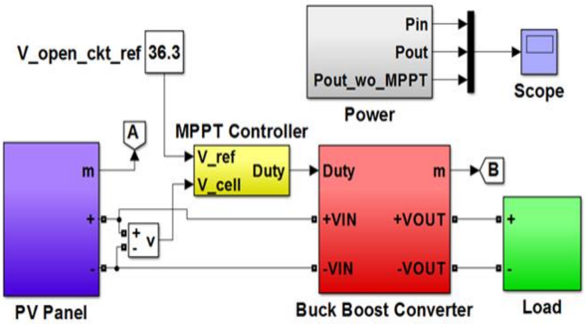

Fig. 10. PV array using MPPT

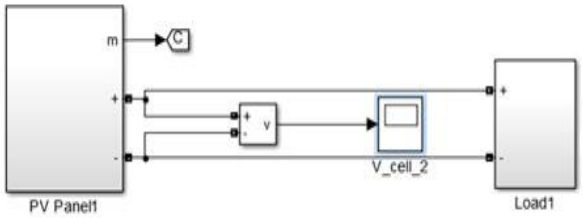

Fig. 11. PV array without using MPPT

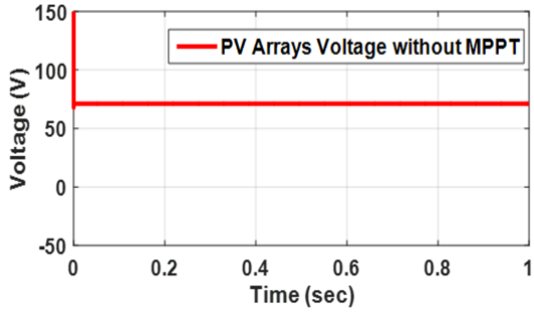

Fig. 12. PV array voltage without MPPT

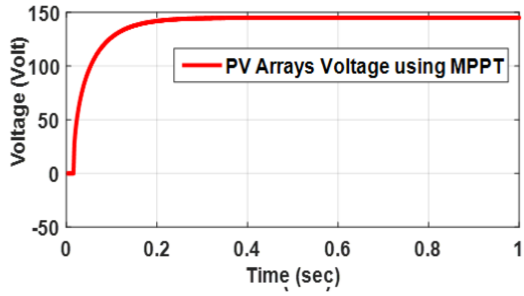

Fig. 13. PV array voltage using MPPT

Fig. 16 is output power curve for both the system using MPPT and without using MPPT. Where the power output for without using MPPT is around 80W and the power output for the solar system using MPPT is about 430W. The difference of these two output power is approximately 350W. From the obtained result, it is seen that using the developed MPPT algorithm the power obtained from solar cell has been increased by 14 times.

Fig. 17 shows that with the increment of solar irradiance, the output power from PV system using MPPT algorithm also increases.

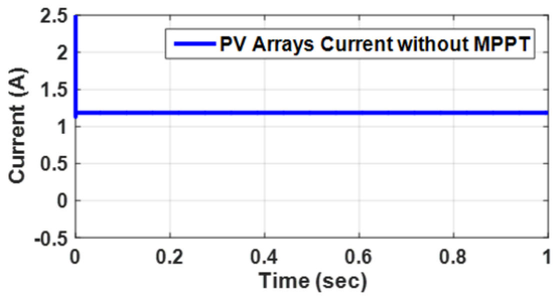

Fig. 14. PV array current without using MPPT

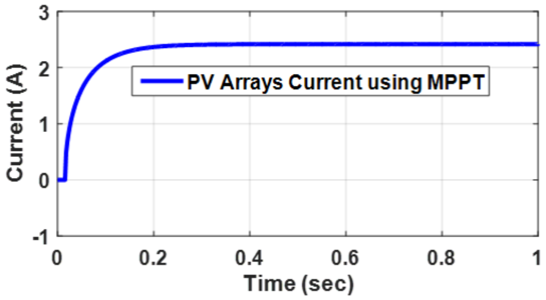

Fig. 15. PV array current using MPPT

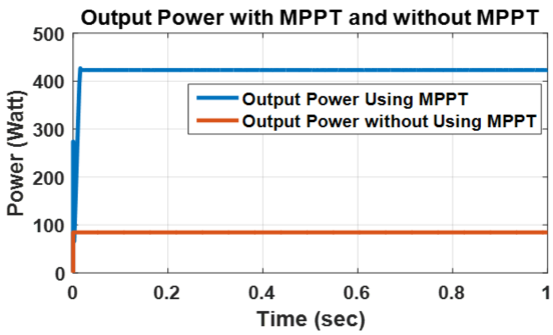

Fig. 16. Output power with MPPT and without MPPT

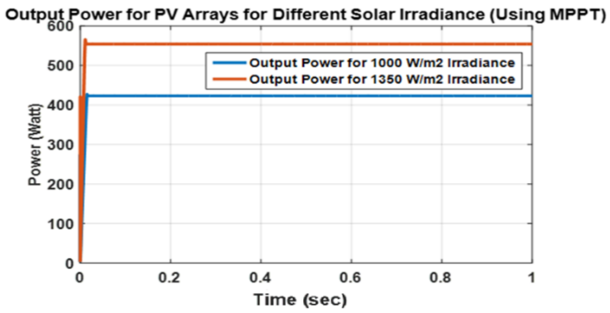

Fig. 17. Output power of PV array with various irradiances using MPPT

The output power while solar irradiance is 1000W/m^2 is around 425W and while irradiance is 1350W/m^2 is around 550W, which is 125W higher.

VI. HARDWARE IMPLEMENTATION

The proposed MPPT algorithm is implemented in an Arduino Uno microcontroller. A gate driver is connected to the output pin of this microcontroller. The gate driver is used to generate gate pulse through a non-inverting comparator for IGBT switch used in buck-boost converter. This pulse will decide whether the buck-boost converter operates either buck mode or boost mode. If the duty cycle or gate pulse becomes less than 50% then it will operate in buck mode, otherwise boost mode. Fig. 18 and 19 represents the buck-boost converter and the gate driver circuit respectively.


Fig. 18. Buck-Boost converter


Fig. 19. Gate driver circuit

The generated duty cycle from the Arduino Uno microcontroller is shown in Fig. 20

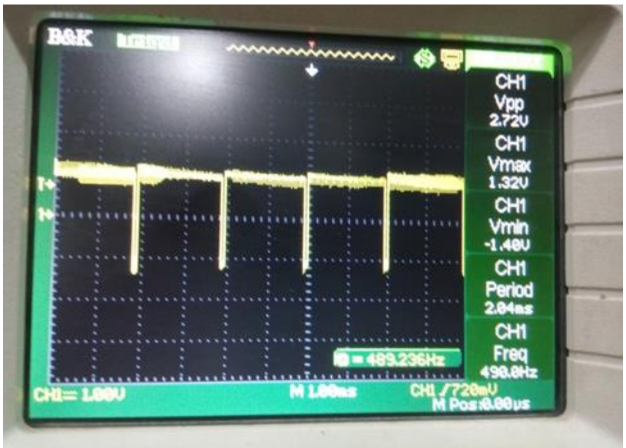

Fig. 20. Generated duty cycle from the microcontroller

The gate driver circuit was constructed and tested. The result of the implemented gate driver circuit is shown in Fig. 21.

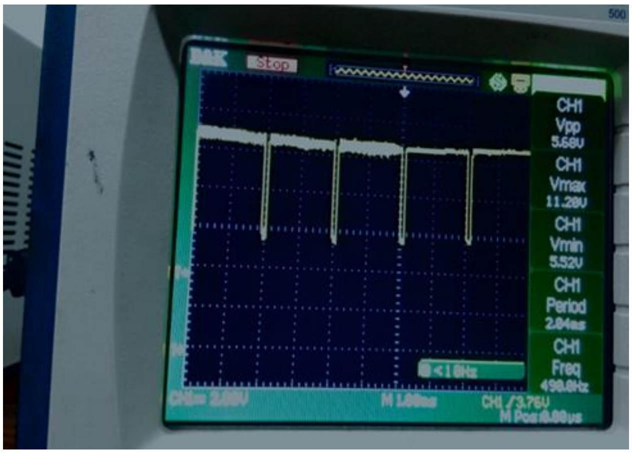

Fig. 21. Output of the Gate Driver Circuit

VII. FUTURE WORK

This system successfully uses the simple P&O algorithm to reach the MPP. The additional resources (labor) needed to implement the more complex incremental conductance algorithm. So, implementing the incremental conductance algorithm is a good choice in continuing this project.

The application of PV array normally faces the shading problem of solar light, this will lead to inconsistent power generation and low system efficiency. Future research can investigate to solve the partial shaded problem in photovoltaic power generation.

In future, this approach can be applied for tracking the Maximum Power Point without using any type of controller. Hence, reducing the cost and increasing the efficiency of the system.

Soft computing methods, such as the fuzzy or neural network can be combined with the Adaptive hysteresis current controller for fine tuning of the hysteresis band calculation for DC-AC inverter control.

VIII. DISCUSSION & CONCLUSION

The PV Array has been mathematically modelled. The programs implemented in the MPPT for PV application using P&O technique achieve the maximum power point. It has been shown that for the particular irradiance levels the maximum power is achieved. The same is carried out if there is a variation in temperature. It is a simple MPPT setup resulting in a highly efficient system. The main contribution of this thesis is tracking the maximum power point using a closed loop system consisting of some power electronic devices such as boost converter, rectifier and PV module as input device. Instead of using semiconductor devices live diodes IGBT's will be used

The various waveforms were obtained by using the plot mechanism in MATLAB. There is a small loss of power from the solar panel side to the boost converter output side. This can attribute to the switching losses and the losses in the inductor and capacitor of the boost converter. This can be seen from the plots of the respective power curves.

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