Synchronous Buck Converter with Perturb and Observe Maximum Power Point Tracking Implemented on a Low-Cost Arduino-microcontroller

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ABSTRACT

Maximum power point tracking (MPPT) is used in photovoltaic (PV) systems to enhance efficiency and maximize the output power of PV module, regardless the variation of temperature, irradiation, and the electrical characteristics of the load. A new MPPT system has been presented in this research, consisting of a synchronous DC-DC step-down Buck converter controlled by an Arduino microcontroller based unit. The MPPT process with Perturb and Observe method is performed with a DC-DC converter circuit to overcome the problem of voltage mismatch between the PV modules and the loads. The proposing system has high efficiency, lower cost and can be easily modified to handle more energy sources. The test results indicate that the use of the proposed MPPT control with the designed synchronous Buck converter increases the PV output power; hence increases the overall solar system efficiency. The synchronous Buck converter test results used in this design showed high converter efficiency up to 95% of the power produced from the solar module, leading to reduce power loss caused by the power transfer process from PV module to the loads.

Keywords: photovoltaic MPP system, P&O algorithm, DC-DC converter, Arduino microcontroller.

المحول التزامني الخافض مع تقنية التتبع والاضطراب لنقطة الطاقة العظمى تنفذ على متحكمة الاردوينو واطئة الكلفة

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الخلاصه

تقنية تتبع نقطة الطاقة العظمى تستخدم في النظام الفوتوفولتائي لكي تزيد من القدرة المستخرجة من اللوح الفوتوفولتائي بغض النظر عن تأثير درجة الحرارة وحالة الاشعاع الشمسي وخصائص الحمل الكهربائية. طور نظام جديد بتقنية تتبع نقطة الطاقة العظمى في اللوح الفوتوفولتائي يتكون من المحول التزامني الخافض للتيار الكهربائي المستمر والذي يتحكم به وحدات المتحكمة الصغيرة الاردوينو.ان تقنية تتبع نقطة الطاقة العظمى مع طريقة الاضطراب والتتبع قد طبقت مع دائرة المحول التزامني الخافض للتيار المستمر للتغلب على مشكلة عدم توافق الفولتية بين اللوح الفوتوفولتائي والحمل. النظام الناتج لديه كفاءة عالية، كلفة واطئة وممكن بسهولة تحويله لكي يتحمل مصادر فولتية او طاقة اعلى. النتائج العمليه بينت ان استخدام النظام المقترح يتحكم بتقنية تتبع نقطة الطاقة العظمى يزيد من كفاءة الطاقة المستخرجة من اللوح الفوتوفولتائي وبالتالي يزيد من كفاءة النظام الشمسي الكلية. ان نتائج اختبار المحول التزامني الخافض للتيار المستمر المستخدم في هذا التصميم اظهرت كفاءة تحويل عالية للطاقة الماخوذة من اللوح الفوتوفولتائي بنسبة اعلى من 95% وبالتالي قلل من خسائر الطاقه الناتجة من تحويل القدرة من اللوح الفوتوفولتائي الى الحمل.

1. INTRODUCTION

Nowadays the photovoltaic power systems are one of the fastest-growing renewable energy technologies, providing more secure power sources and pollution free electric supplies. Unfortunately, PV systems have its own problems, besides the high fabrication cost, the energy conversion efficiency not exceeds 30%.Because the output power of PV modules severely affected by irradiance levels. Another limitation is the electricity produced from PV system is expensive competed to the electricity from the utility grid. Therefore, the use of PV system and make it operate at maximum output power in any environmental conditions is desired, **Dinçer,** and **Meral, 2009**.

A typical PV solar system has a current-voltage (I-V) characteristic curves under constant uniform irradiance similar to that presented in **Fig.1**. The operation point of the system is at the intersection of the I-V curve and load line, there is one unique point at the knee of the curve known as maximum power point (MPP). At the MPP the PV system operates at the maximum power. When a PV system is directly connected to a load, the photovoltaic system operations point is not at MPP most of the time. The problem is overcome by using an MPPT technique that use algorithm maintains the PV system operating point at the MPP. Many MPPT methods have been proposed in the literature each has it is pros and cons and differed in complexity, cost, tracking speed, and another aspect. These methods use different solar panels characteristics and the location of the MPP, including perturb-and-observe method, open- and short-circuit method, incremental conductance algorithm, fuzzy logic and artificial neural network, **Hohm,** and **Ropp**, **2003**.

An MPPT system is used to extract the maximum power from the PV module. A prototype design has been developed, using one of the famous switch mode power converters named synchronous buck converter. Step-down DC-DC converter acts as an interface between the PV module and load to transfer the maximum power of the photovoltaic system to the load. Maximum power is transferred by changing the load impedance as seen by the source and matching it at the peak power of it when the duty cycle is varied. In order to maintain PV module's operating at its MPP, different MPPT methods are studied. In the literature, many MPPT methods are proposed such as the perturb and observe (P&O) method, incremental Conductance(IC) method, Fuzzy Logic Method etc., **Morales, 2010**. However, one algorithm, the perturb and observe (P&O) claimed by many methods and continue to be by far the most common MPPT method used in practice because it is simple structure and ease of implementation. This paper presents a practical implementation of P&O algorithms based on Arduino microcontroller for tracking of the maximum power generation from PV system under a rapid change in the radiation level. The proposed control system algorithm obtains the Data from the PV system through microcontroller's Analog and Digital ports to perform the pulse width modulation to the DC-DC converter. These techniques vary in many aspects like simplicity, speed of convergence, digital or analogical implementation, number of sensors required, cost, effectiveness range, and in other aspects

2. MATHEMATICAL MODELING OF PV MODULE

The main building block of the photovoltaic module is the PV cell, the PV cells connected in a series-parallel manner to form the PV module. The PV cell basically is a P-N junction semiconductor which represents the main electrical unit of solar power generation system. The PV receives energy from the sun and generate DC power when exposed to light.

The generated voltage and current for such PV modules depend generally on solar radiation and cell temperature. The equivalent circuit model of a simplified single-diode is as shown in **Fig. 2.**

The mathematical equation describing the I-V characteristics of a PV solar cells module is given by **Elbaset, et al., 2014.**

$$I_{PH} - I_D - \left(\frac{V_D}{R_P}\right) - I_{PV} = 0 \qquad (1)$$

$$V_{PV} = V_D - I_{PV}R_S \qquad (2)$$

I_{ph}: The generated current of solar cells module. This current varies with temperature according to the next equation:

$$I_{PH} = \left(I_{PV} + K_1(T - 298)\right) * \overline{H}_T/100 \qquad (3)$$

and the diode characteristic is:

$$I_D = I_O e^{(V_D/V_T)-1} \qquad (4)$$

$$V_T = \frac{A*KB*T}{q} \qquad (5)$$

$$I_{PV} = I_{PH} - I_O\left[\exp\left[\frac{(V_{PV}+I_{PV}*R_S)}{V_T}\right] - 1\right] - \frac{V_{PV}+I_{PV}*R_S}{R_P} \qquad (6)$$

Io: The reverse saturation current, Amp. This current changes with temperature variation as follows:

$$I_O = I_{OT} * \left[\frac{T}{T_T}\right]^3 * \exp\left[\frac{q*E_{go}}{KB*A\left(\frac{1}{T_T}-\frac{1}{T}\right)}\right] \qquad (7)$$

The solar cells output can be calculated by the following equation:

$$P_{PV,out} = V_{PV} * \left[I_{PH} - I_O\left[\exp\left[\frac{q*(V_{PV}+I_{PV}*R_S)}{A*KB*T}\right] - 1\right] - \frac{V_{PV}+I_{PV}*R_S}{R_P}\right] \qquad (8)$$

From the previous equations, it can be concluded that the power and output current of a PV module is mainly affected by solar radiation and the cell temperature. **Fig. 1** clarifies the I-V characteristics curve of a PV module and a resistive load Ropt. The resistance characteristic is a line of slope $1/R_{opt}$. At the intersection of the two curves, the operating point is located. In the curve AB region the module acts as a current source and in the CD region, it acts as a voltage source. Notice in the BC intermediate zone, the PV characteristic is nonlinear; this is the area where can find the MPP for which the PV module could provide its highest power for certain atmospheric conditions. R_{opt} represents the resistance at that point, **Elbaset, et al., 2014.**

3. DC-DC REGULATORS

In any solar system the maximum power point varies with the variation of atmospheric condition this means at each irradiance and temperature there is one optimum output voltage for the PV module to operate with. In order to make the PV panel operates at it is MPP and maintain optimal battery charging process, the DC-DC regulator is required to increase or decrease the output voltage of solar module to the desired battery level. These regulators are also known as switching regulators. Switch mode DC-DC converters are utilized to convert the unregulated DC input into controlled DC output at the desired voltage level. The heart of MPPT system hardware is DC-DC converter and without it, the maximum power could not be achieved, **Daib, 2012.**

A power switch, an inductor, a capacitor and a diode are the basic component of any DC converter that can be arranged to form a different type of DC-DC converters. MPPT system uses DC converter for regulating the PV terminal voltage at MPP and matching the load by providing maximum power transfer. The most efficient and fast way to permit a pulse width modulation to control the frequency and the switch duty cycle is MOSFET. The amount of transferred power from the input to output depends on duty cycle high. There is no need for any analog to digital signal conversion from the microcontroller to the MOSFETs because the signal remains digital from the source and this is one of PWM advantages, **Hiwale, et al., 2014.**

There are different types of the DC-DC converter such as Buck, Boost, Buck/Boost, Cuk and Single Ended Primary Inductor Converter (SEPIC).In Buck converter, the output voltage is lower than the input voltage, while Boost converter works on higher the output voltage since it has less the input voltage. The Buck/Boost and Cuk converters have the same characteristics that the output voltage is higher or lower the input voltage, and the polarity of the voltage between input and output are reversed. However, SEPIC converter cans low or high the input voltage by maintaining the polarity between input and output. The main type of DC-DC converter in this project is synchronous Buck converter, **Mwinyiwiwa, 2013.**

3.1 Synchronous Buck Converter Basics

The synchronous buck converter is used to reduce a voltage level from a higher voltage to a lower voltage. Today in industry Synchronous buck converters are very popular since it provides high-efficiency solutions for a wide range of applications especially in portable electronics. A synchronous buck converter supplies a regulated voltage that is lower or the same as input voltage and can minimize power loss by delivering high currents. As shown in **Fig. 3**, the synchronous buck converter is consisting of two power MOSFETs, an output inductor, and an output capacitor. This specific buck topology derives its name from the control method of the two power MOSFETs; the on / off control is synchronized in order to provide a regulated output voltage and to prevent the MOSFETs from turning on at the same time. **Klein, 2006.**

The high side MOSFET (Q_1) is connected directly to the circuit input voltage. When Q1 turns on, current is provided to the load through the high side MOSFET. During this time, the low side MOSFET (Q_2) is turned off and the inductor current increases, charging the LC filter. When Q_1 turns off, Q_2 turns on and current is delivered to the load through the low side MOSFET. At this time, the inductor current decreases, discharging the LC filter. Q_2 the low side MOSFET presents an additional function when both MOSFETs are off. It locks the voltage of switch node through the body diode to prevent VSW from going too far negative when the high side MOSFET first turns off, **Geetha,** and **Pramila, 2016.**

Fig.4 demonstrates the synchronous buck converter basic waveforms in continuous conduction mode. The peak to peak inductor current is the total change in inductor current. The switch mode output voltage is smoothed out by the LC output stage so as to supply a regulated DC voltage at the output. To prevent shoot−through the MOSFETs are synchronously controlled. Shoot−through occurs when both MOSFET the high side and low side are on at the same time, providing a direct short to ground. **Meekhun, et al., 2011.**

The high side MOSFET on−time determines the duty cycle of the circuit and is defined in Equation 1.

$$D = \frac{t_{ON,HS}}{t_{ON,HS}+t_{OFF,HS}} \cong \frac{V_{OUT}}{V_{IN}} \qquad (9)$$

The output voltage equals the input voltage when the duty cycle, D is equal to 1 then the high side MOSFET is on 100% of the time. The high side MOSFET is on 10% of the time when the duty cycle of 0.1, producing an output voltage that is nearly 10% of the input voltage.

3.2 Buck Converter Power Losses

The MOSFETs power, stage output, controller/driver, feedback loop, and the converter layout itself all that causes losses in buck converter power. In most buck converter designs the duty cycle is lower than 0.5 for, with a standard duty cycle of-0.1 to-0.2 in the calculating and server market. Platforms design is moving to frequencies of higher switching, delivering the skill to reduce the size of converter and form factors. At the same time, converters performance must be great and have higher efficiency. The performance output stage greatly influences the overall operation of the buck converter. For this reason, it is imperative to optimize the inductor and capacitor selection for the precise application, **Panda,** and **Aroul, 2006.**

4. MPPT CONTROL ALGORITHM

Maximum power point trackers (MPPTs) has an important role in control the output of the photovoltaic (PV) power systems because they maximize the PV system output power for a given set of conditions, and therefore maximize the efficiency of the solar module. Thus, an MPPT can minimize the total cost of PV system. Using an MPPT algorithm, MPPTs find and maintain operation of the system at the maximum power point. In this paper, P&O is used and described in the following subsection because this method requires less hardware complexity and low-cost implementations. MPPT operate at very high frequencies, usually in the 20-80 kHz range. The advantage of high-frequency circuits is that they can be designed with small components, **Hamzescu,** and **Oprea, 2013.**

4.1 Perturb and Observe (P&O) Technique

The perturb and observe algorithm is the most commonly used in MPPT systems because of simple structures and easy implementations. This technique is known as perturbation and observation algorithm because it is work by continuously changing the operating point of the PV panel and discovered the corresponding variation of the output power in order to determine the next variation to approach to the MPPT, **Hiwale, et al., 2014.**

The principal of P&O algorithm, the perturbation variable can be the reference value for the terminal voltage of PV panel, a terminal current of PV panel, or the duty cycle of the MPPT converter. In the other world, the operating voltage of the PV panel is perturbed by small incrementing determining result the change in power.

Fig. 5 shows a clarification of the PV panel output power against panel voltage at a specific irradiance and constant temperature, the spot indicated represents the MPP.

Let's say having two operating positions as point **A** (dP/dV > 0) and point **B** (dP/dV < 0) as pointed in **Fig.5**. If the voltage at point A is perturbed and (dP/dV > 0), it is clear that the operation point is on the left side of MPP. The P&O algorithm would then increase the PV module voltage to move the operation point towards the MPP. At point B if (dP/dV < 0) it is clear that the operating point is on the right side of the MPP. The P&O algorithm would then decrease the PV module voltage, **Hohm,** and **Ropp, 2003**.

Hence, the key function in the perturbation and observation algorithm is a determination of the perturbation direction. Here the PV terminal voltage used as a control variable, first of all, using the sensor to measuring the terminal voltage, V_{pv} and current, I_{pv}, then obtain the output power from V_{pv} and I_{pv} product. The algorithm detects if the module power increase with increasing the terminal voltage, then the reference voltage is increased by one step size otherwise, the algorithm will decrease reference voltage by one step size. If the PV output power decreases while the PV terminal voltage increase, the reference voltage is dropped by one step size perturbation, otherwise, the reference voltage is increased by one step size perturbation. From the flowchart shown in **Fig. 6,** the next direction of perturbation can be determined by an increase or decrease the reference voltage, **Xuejun, 2010**.

5. IMPLEMENTATION OF HARDWARE

To test the performance of the proposed system a prototype hardware is implemented as shown in **Fig. 7**.The system was created and tested with a polycrystalline PV module of 50 W maximum output power to corroborate the proposed design. The system consists of the PV module; the charge controller contains a DC-DC converter and an Arduino microcontroller in which the MPPT algorithm was implemented. The tests were carried out to measure characteristics of the synchronous buck converter. The microcontroller provides the pulse-width-modulation (PWM) signal to control the synchronous buck DC-DC converter. The schematic hardware of the proposed MPPT with the converter is shown in **Fig.8**.

5.1 Photovoltaic PV Module

Single poly-crystalline solar module specifications given by the manufacturer are presented in **Table 1**.The electrical characteristics of a PV module, given by manufacture’s data sheet at the nominal temperature of 25 °C and irradiation of 1000W/m^2.The panel equipped with TPM-10 Temperature Sensor to monitor its temperature during experiments. The solar module is calibrated according to standard procedure available in the energy laboratory.

5.2 Synchronous Buck Converter

In this work The DC-DC converter is a 50W Synchronous Buck converter working at a switching frequency of 50 kHz, it is used to interface the PV panel output to the load and to track the maximum power point of the PV panel. The parameters of the converter are given in **Table 2**. The system output parameters and it is loaded determined the designing first step in the buck converter circuit. The operation frequency, the size of inductor and output capacitor size are very important since they determine the ripple size of current and voltage. It is desired to have an as smaller ripple of current and voltage as possible.

A general rule is when the frequency higher the inductor and the output capacitor size are smaller, and a smaller inductor size and capacitor size generally reduces the system cost. However, the PWM of higher frequencies reduces the efficiency of the system because of losses in MOSFETs switching, so a tradeoff has to be reached. Calculating the value of the inductor is most critical in a step-down switching converter designing which meets the design constraints of the end system.

For this research, the inductor was toroidal core and it is hand-wounded from old computer power supply as shown in **Fig.9**. To reduce the voltage overshoot and the step-down converter output ripple the output capacitance is required. The look for the suitable MOSFET for a particular design includes reducing the switching losses and Find out how to rely on switching frequency, current, duty cycle, and shift times up and downs of these losses. The Half-Bridge driver is an IC designed specifically for driving MOSFETs. The driver takes the PWM signal coming from the microcontroller then drives High and Low-Side outputs MOSFET. The driver used is IRS2104 half bridge driver manufactured by International Rectifier, this driver allows 2-PWM signals to be connected to High and Low-Side outputs MOSFET, this gives the chance to the MOSFETs dead band switching fine tune. The converter was tested on a breadboard in the lab and the PWM output signal from the buck converter shown in **Fig.9**.

5.3 Microcontroller

The ATmega328P microcontroller with Arduino bootloader offers all hardware functionality required in charge controller design. This microcontroller provides all the digital and analog pins needed by the sensors and other peripherals. This microcontroller features an 8-bit, 6-PWM channel, 8 analog inputs, and 14 digital input/output pins. Arduino microcontroller mainly used to control the DC-DC converter, the program controlled duty cycle via PWM outputs that provide from microcontroller channel. Arduino microcontroller has many features such as great memory size, analog to digital converter on-chip, PWM outputs, consumption low power and low cost all that was needed for the suggested system. The Arduino bootloader allows programming directly from PC through the USB cable, eliminating the need for a programmer in separate hardware to implement new code. The Arduino programming language was selected because it is easy, learning curve relatively shorter, and facilitates faster learning due to the large and active community. The language and IDE are completely free and open source, and Arduino website enables many resources about all kind of sensors, motors, LEDs, communication tutorials, etc. The language is both easy to use and robust, providing all the functionality needed for interfacing with analog sensors, I^2C components, and TTL serial peripherals among others. Moreover, numerous libraries have been written for popular sensors and other peripherals which helped in the learning and implementation of components in MPPTs. **Gibb, 201, and Durfee, 2011.**

6. EXPERIMENTAL RESULTS

6.1 The Synchronous Buck Converter

The system was constructed and tested with a 50 W maximum output power PV panel as shown in **Fig. 7** to validate the proposed design. The system consists of the PV panel; the charge controller contains a DC/DC converter and an Arduino microcontroller in which the MPPT algorithm was implemented. The tests were carried out to measure characteristics of the buck converter and the MPPT charge controller.

The first aspect of the converter to be verified was the voltage regulation. The voltage regulation was found by measuring the input and output voltages at different duty cycle levels. The output voltage was divided by the input voltage to obtain the voltage regulation. **Fig.10** shows the measured voltage regulation of the converter compared to the expected voltage regulation results value that had been calculated from **Equation 9**. The experimental results were measured with the converter connected to the PV panel as an input source, at fixed input voltage.

As can be seen in **Fig.10**, the voltage regulation results from the actual converter are nearly identical to the calculated values until an 80% duty cycle. This result shows two things. First, from the correlation of the regulation ratios 0.05 up to 0.75, it is observed that the converter is acting as expected. The results are the same as the calculated expectation for the circuit.

Second, something can also be learned from the results of a duty cycle of 75%. The calculations do not take into account real-world parameters and physical limits on components. The results from the equation were taken with the assumption that the converter connected to an ideal voltage supply at 17 volts. This voltage supply was said to be able to supply unlimited current while staying at the 17-volt level. The PV panel, however, is not an ideal source. This fact is what contributes to the limiting factor on the voltage regulation of the circuit at the higher duty cycles. As previously presented a PV panel has a finite limit on the amount of voltage, current, and power it can output.

When the converter is running at higher duty cycle values the PV panel is outputting very high currents, close to the short-circuit value. Since the panel does have a finite amount of power it can produce this high current causes the panel’s output voltage to become much lower. This high current, low voltage output characteristic effectively limits the voltage regulation of the converter by not allowing the circuit the power it needs to properly step down the output voltage to the expected level.

The second attribute of the converter that needed to be tested was the circuit’s efficiency. Testing of the efficiency was performed with the converter being connected to the output of the PV panel. The input current and voltage was measured using solar module analyzer PROVA 200.the output current and voltage was measured using a multimeter. The test was performed on the converter alone without any of the current and voltage sensing technologies in place. The results of the efficiency test can be seen in **Fig.11**and **Table 3**.

There are a few things to note about **Fig.11**. First of all is that the effective result for a duty cycle of 95% is not included in the graph. This is simply because the result is so much lower than the others that it makes the graph harder to see, the result can still be seen in **Table 3.** The second thing to notice about the graph is that the efficiencies are highest when the duty cycle is lowest. This was expected due to the large inductance values. The final and most compelling aspect of the graph is the almost uniform efficiency over the band of duty cycles that the MPPT system will use on most normal days. This band covers the duty cycles from 5% to 75%. Over this area, there is a minimum efficiency of 92.4% and a maximum of 95.4%.

Fig.12 indicates the comparison of the Present Synchronous Buck Converter Efficiency with Previous Buck Converter Efficiency Designed by **Putri, et al, 2015**. The present converter efficiency is clearly higher than the previous design, this is related to the losses caused by the diode in buck converter design while in present synchronous buck converter design using Mosfet instead of diode reduced losses and thus improved efficiency.

6.2 The MPPT Control

The MPPT system was tested over a variety of situations. The algorithm is implemented by connecting the 50w solar panel to buck converter. The duty cycle of this converter is controlled by the Arduino microcontroller. The same panel was then connected to a solar analyzer PROVA 200A, which has a fixed internal resistance. The value of this resistance was set so that the panel will be able to output the maximum power as described in the PV panel manual. The resistance was calculated by taking the rated voltage at maximum power (V_{MP}) of the panel (17.5V) and dividing it by the rated current at maximum power (I_{mp}) of the panel (2.9A). The voltage and current sensor send the information to the microcontroller to run the MPPT system. These values for panel were then multiplied together to obtain the power output of panel, and then compare it with the values that PROVA200 calculated

The first test was performed on a cold sunny day. The results of this test can be seen in **Fig13**. In this Figure, the system ran for almost a full day when there were almost no clouds in the sky and the temperature was 16˚C. A system reset as described before can again be seen at the very beginning of this graph. The Figure also shows a great improvement when using the system compared to using a fixed resistance. A notable aspect of this Figure was how much of an improvement there was when the system was at maximum power output when the sun is at its highest point in the sky. This large improvement was due to the test being performed during a winter month (2016/11/21).

In the winter month, the sun is at a lower angle in the sky so it is not hitting the PV panel dead on. This causes less light to be absorbed by the panel that would be during a summer month. The lower light absorption due to the angle can also be seen in that the maximum power output barely exceeds 30 watts when the panel is rated at 50watts

The second test was performed on a hot sunny day. The results of this test can be seen in **Fig.14**. In this Figure, the system was run for almost a full day when the sky was clear and the temperature was41˚C. This Figure shows the same results seen in **Fig.13** when there was a great improvement when using the MPPT system compared to using a fixed resistance. A notable aspect of this figure was the two curves almost are identical at the peak of these curves. This was related to the test being performed during a summer month (2016/9/15) when the sun is hitting the panel directly and the PV panel was output putting the maximum rated power.

The MPPT system curve was identical with fixed resistance curve at peak points because the fixed resistance was implemented according to the values of voltage and current at maximum power. While the MPPT circuit performed better during all other times of the day. It had been the same performance as the fixed resistance over the time when the panel was operating at its rated power output. This can be noticed during the interval when the sun was at the highest point in the sky and the amount of radiation was at its biggest values. The values of voltage and current at maximum power are finite and cannot be exceeded by the tracking circuit.

A second notable thing about **Fig.14** was that the peak point or the highest power that the solar panel was produced at 1160W/m^2. This was because the incident angle of the sun in the summer months or this day of the year is higher than the winter month.

7. CONCLUSION

The PV solar module output power carried to a load can be maximized using MPPT control systems, which consist of a power converter to interface the photovoltaic output to the load, and a control unit, which drives the power converter such that it extracts the maximum power from a PV solar module. In this research, a low cost, low power consumption MPPT system for battery charging has been developed and tested. The system consists of a high efficiency, Buck converter and a microcontroller-based unit which controls the DC/DC. The experimental results show that the use of the proposed MPPT control increases the PV output power; hence increases the overall solar system efficiency. The synchronous Buck converter test results used in this design showed high converter efficiency up to 95% of the power produced from the solar module, which intern reduced the power loss because of the power transfer process from PV module to the loads.

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NOMENCLATURE

$\overline{H}_T$: The average radiation on the tilted surface, W/m^2
A: The idealist factor for the p-n junction.
DC = direct current, dimensionless
E_{go}: The band-gap energy of the semiconductor used in solar cells module.
I_D: The diode saturation current, A
I_{MPP} = Current at maximum power point, A
I_o: The reverse saturation current, A.
I_{or}: The saturation current at Tr, A.
I_{ph}: The generated current of solar cells module, A
I_{PV}: The output photovoltaic cell current, A
I_{PV} = terminal current, A
I_{sh} = short circuit current, A
KB: The Boltzmann's constant in Joules per Kelvin, 1.38*10-23 J/k.
KI: The short circuit current temperature coefficient.
MPP = maximum power point, dimensionless
MPPT = maximum power point tracking, dimensionless
P = output power of the solar module, W
PCB = printed circuit board, dimensionless
PWM = pulse width modulation, dimensionless
q: The charge of the electron in Coulombs, 1.6*10-19C.
R_P: Parallel resistance, Ω
R_S: Series resistance, Ω
T: The temperature, T_r: The reference temperature, K^o.
V = output voltage of the solar module, V
V_D: The diode voltage, V
V_{MPP} = voltage at maximum power point, V
V_{oc} = open circuit voltage, V
V_{PV}: The output photovoltaic cell voltage, V
V_{PV} = terminal voltage, V

Table 1. Module Specifications at STC as Presented by the Manufacturer.

Rated Power	**50 W**
Voltage at Maximum Power (V_{max})	17.5 V
Current at Maximum Power (I_{max})	2.9 A
Open Circuit Voltage (V_{oc})	22 V
Short Circuit Current (I_{sh})	3.1 A
Total Number of Cells in Series	36
Weight	5.6 Kg

Table 2. DC-DC Converter Parameters.

Component	**Description**
MOSFET	IRF3205
MOSFET driver	IRS2104
Inductor L	47 mH
Capacitor C_O	220 µF
Switching frequency	50 KHz

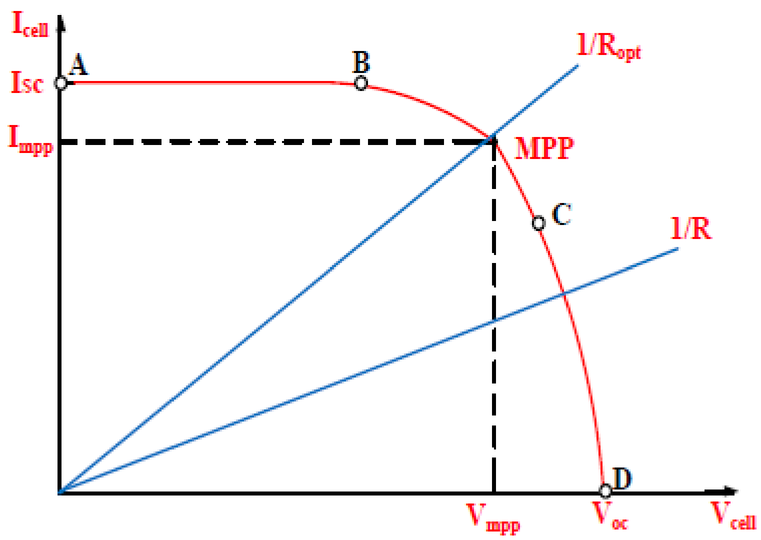

Figure 1. I-V Characteristics of the PV and a resistive load, **Elbaset, et al., 2014.**

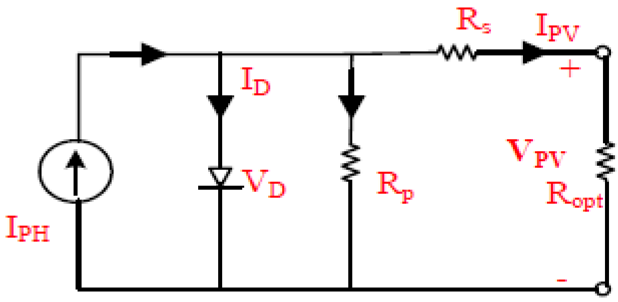

Figure 2. Single-diode circuit model of PV cell, **Elbaset, et al., 2014.**

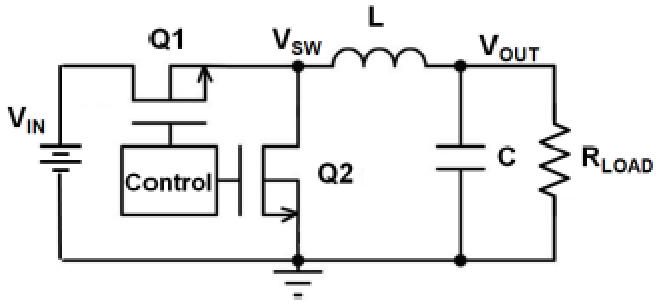

Figure 3. Synchronous Buck Converter**, Coder-tonic, 2016.**

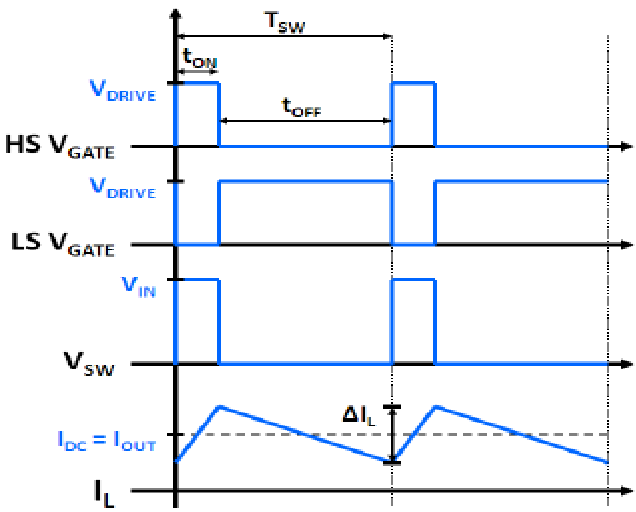

Figure 4. Synchronous Buck Converter Waveforms**, Coder-tonic, 2016.**

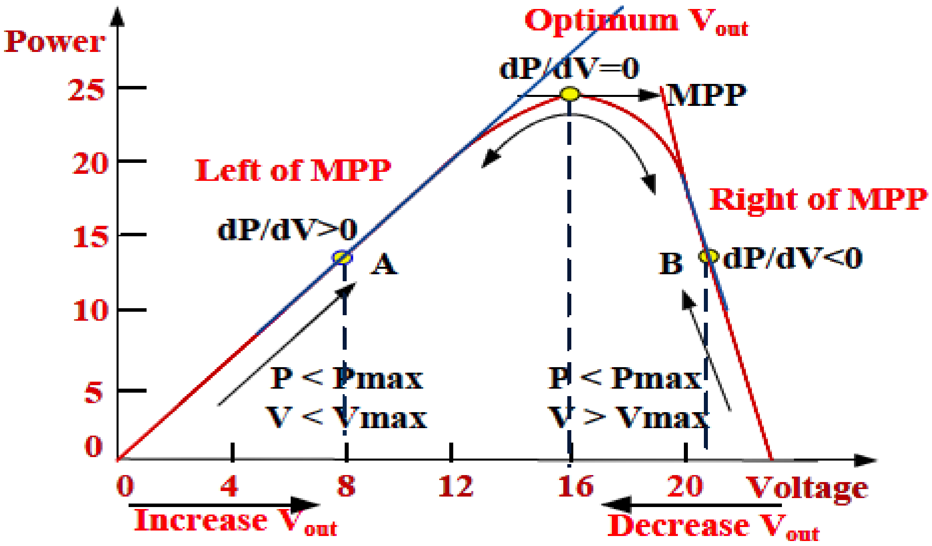

Figure 5. Sign of dP/dV at different positions of the power characteristic curve, **Elbaset, et al., 2014.**

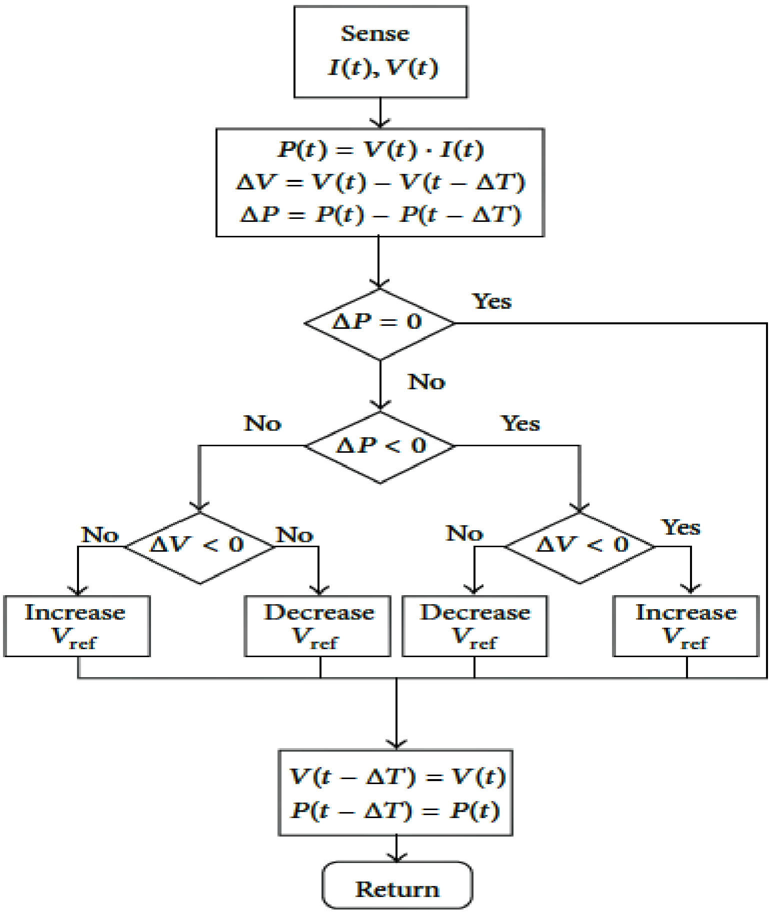

Figure 6. Perturb and Observe Flow Chart, **Tofoli, et al., 2015.**

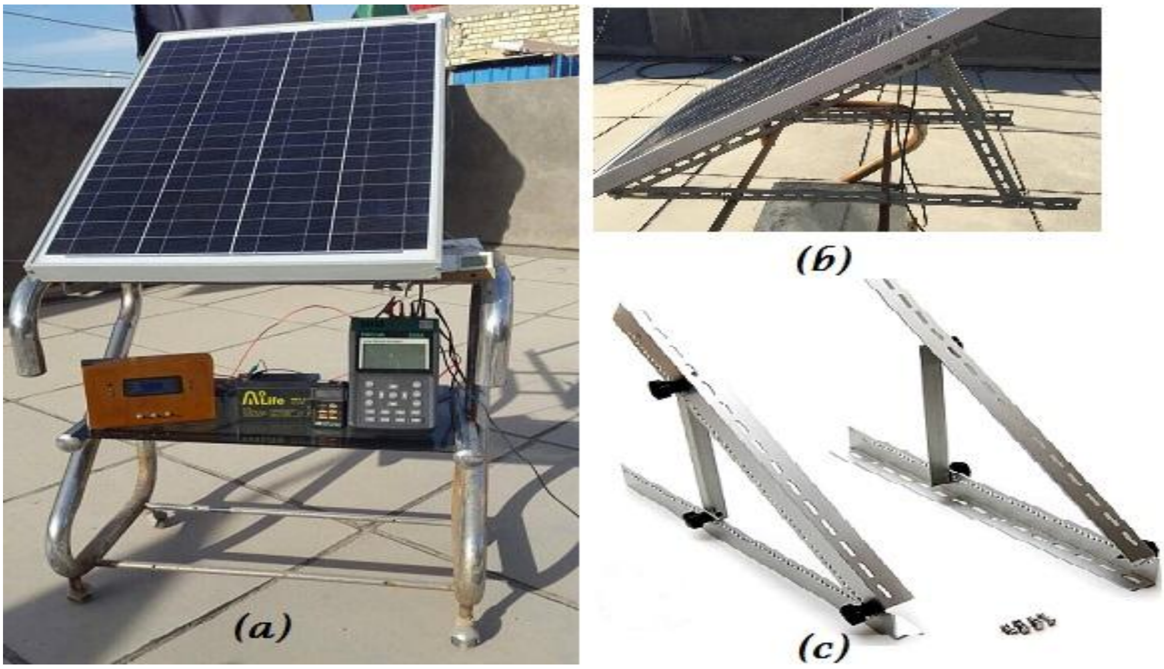

Figure 7. Photograph of the outdoor testing setup (a) front view, (b) side view (c) Pivot Mounts for Solar Panel.

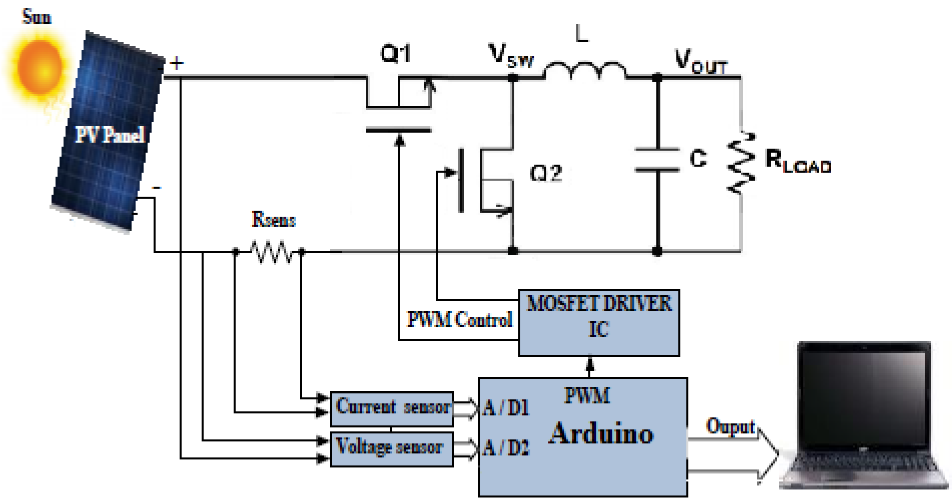

Figure 8. Schematic hardware of the proposed MPPT.

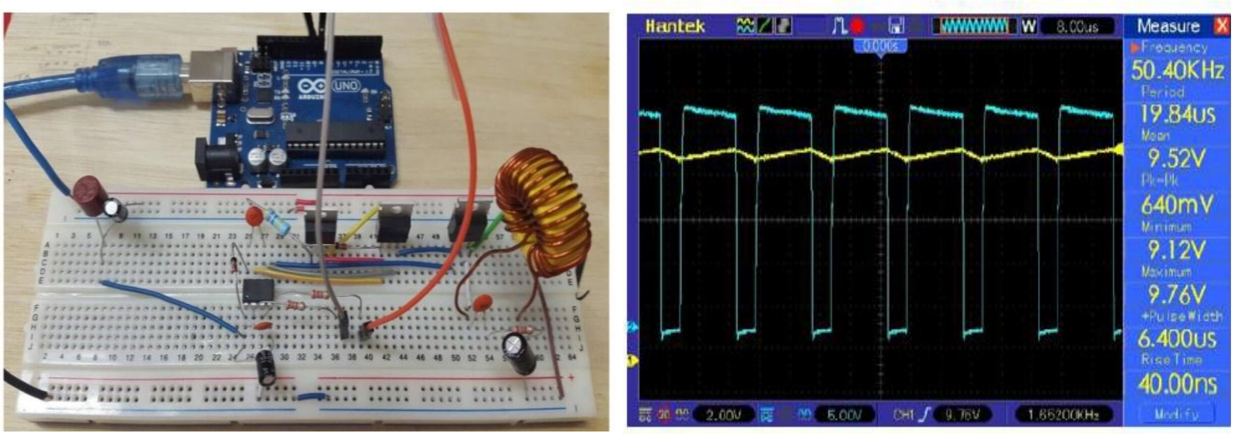

Figure 9. Buck Converter Lab test on the left and PWM output signal from the converter.

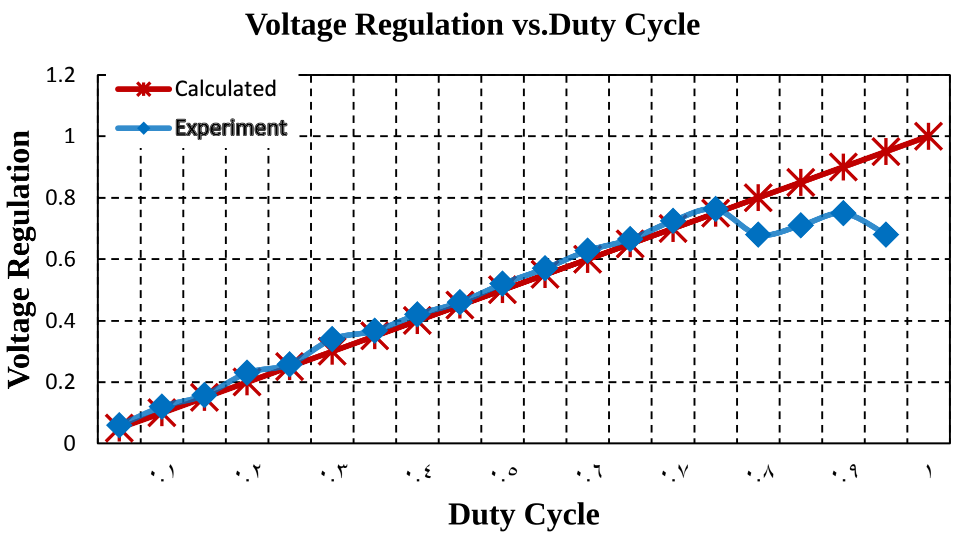

Figure 10. Calculated and Experimental Results of Voltage Regulation.

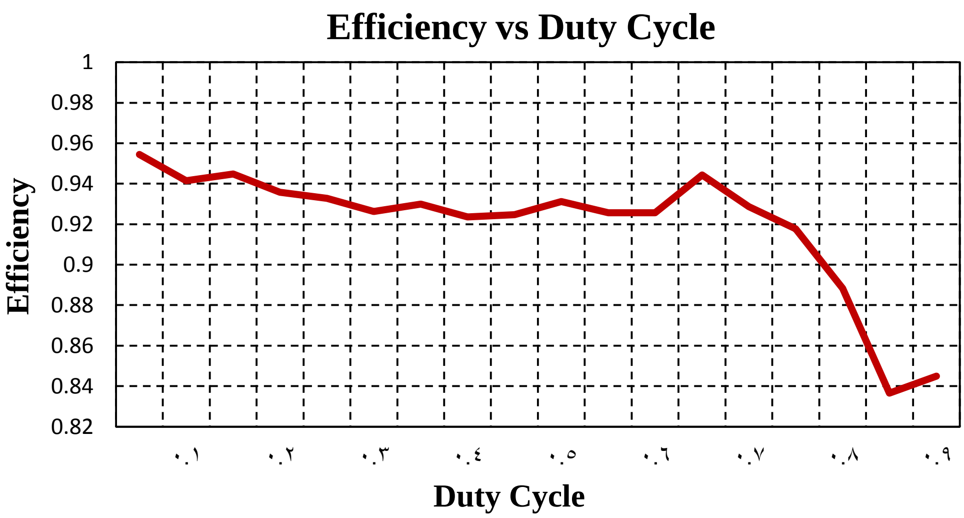

Figure 11. Efficiency of the Buck DC-DC Converter.

Table 3. Results of the converter efficiency test**.**

Duty Cycle	Input Voltage (V)	Output Voltage (V)	Input Current (A)	Output Current (A)	Input Power (W)	Output Power (W)	efficiency
0.05	21.5	1.075	0.328	6.26	7.05	6.73	95.44%
0.10	21.4	2.14	0.341	3.202	7.27	6.85	94.15%
0.15	21.25	3.187	0.522	3.272	11.05	10.43	94.477%
0.20	21.25	4.25	0.683	3.16	1.445	13.43	93.57%
0.25	21.15	5.037	0.734	2.858	15.439	14.4	93.28%
0.30	20.8	6.24	0.891	2.87	19.42	17.97	92.624%
0.35	20.55	7.192	0.962	2.55	19.728	18.34	92.985%
0.40	20.35	8.14	1.321	3.046	26.862	24.8	92.36%
0.45	20.3	9.135	1.682	3.45	34.104	31.53	92.47%
0.50	19.8	9.9	1.741	3.24	34.452	32.09	93.126%
0.55	19.3	10.615	1.812	3.04	34.933	32.337	92.57%
0.60	18.7	11.22	1.983	3.054	37.029	34.277	92.56%
0.65	18.77	12.2	2.392	3.47	44.86	42.39	94.437%
0.70	16.5	11.55	2.441	3.23	40.26	37.36	92.86%
0.75	12.7	9.525	2.842	3.474	36.068	33.099	91.77%
0.80	8.29	6.63	0.223	0.244	1.82	1.616	88.826%
0.85	5.05	4.292	0.323	0.314	1.616	1.3519	83.66%

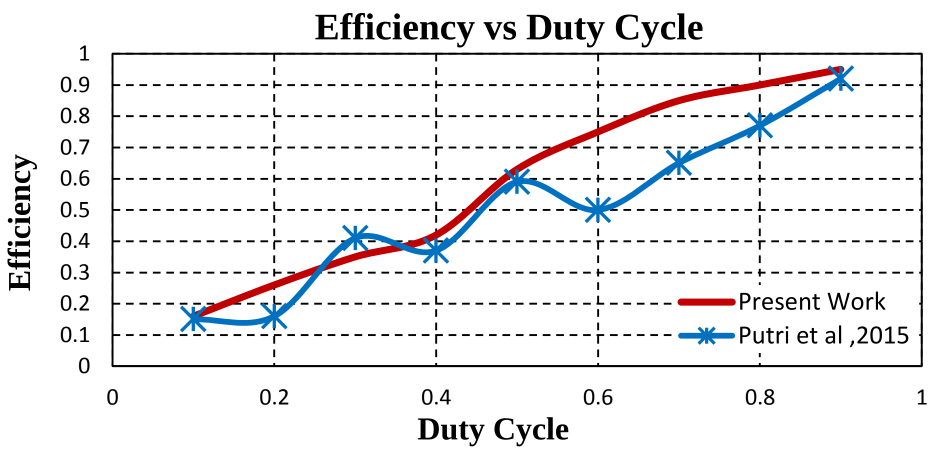

Figure 12. Comparison of the Present Synchronous Buck Converter Efficiency with Previous Buck Converter Efficiency Designed by **Putri, et al, 2015**.

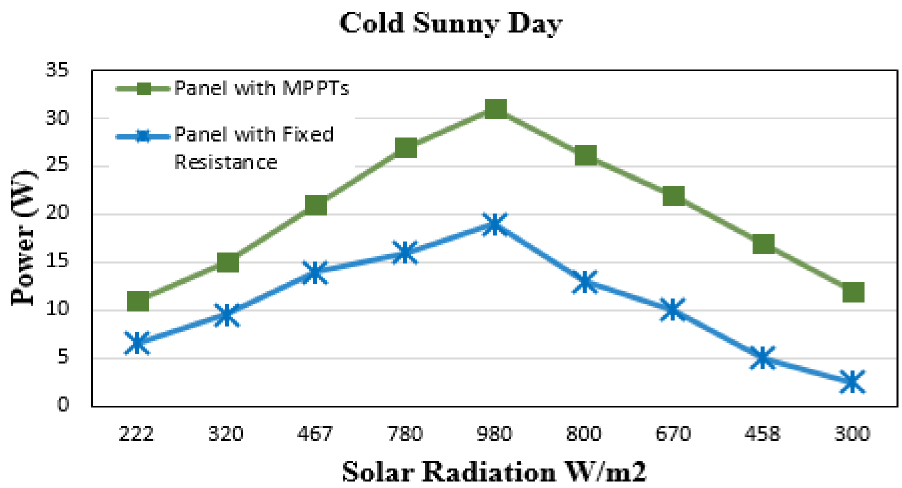

Figure 12. MPPT Comparison of the power output of the PV panel with the proposed converter and MPPT control system with the PV panel connected directly to a fixed resistance at cold sunny day.

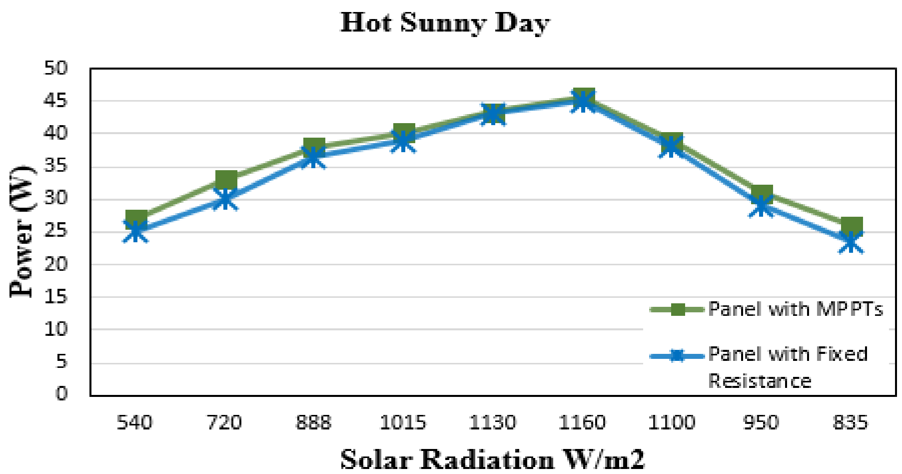

Figure 13. MPPT Comparison of the power output of the PV panel with the proposed converter and MPPT control system with the PV panel connected directly to a fixed resistance at hot sunny day.