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Simulation, Design and Analysis of Different Types of Solar Based Charge Controllers on MATLAB/Simulink

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Abstract
Solar charge controllers are designed to efficiently charge batteries such as Lead-Acid batteries with photovoltaic (PV) cells/array as the input power source. The most popular and widely used solar charge controllers are the Pulse Width Modulation (PWM) based and the Maximum Power Point Tracking (MPPT) based. The PWM and MPPT based charge controllers are designed on MATLAB/Simulink. The performances of these charge controllers are determined for various criterions such as constant irradiance and temperature, variable irradiance, variable temperature etc. so as to choose the right charge controller for the efficient charging of the battery. The PWM based charge controller works best at high irradiance and when the voltage rating of the solar panel is similar to that of the battery's voltage rating, whereas the MPPT based charge controller works best at high irradiance, low temperature and high solar panel ratings.

Keywords: Buck Converter, Charge Controllers, Irradiance, Lead-Acid Battery, Maximum Power Point Tracking (MPPT), Perturb and Observe Algorithm, Photovoltaic (PV), Pulse Width Modulation (PWM), Temperature.

I. INTRODUCTION

The advancement in field of industrialization and population explosion has resulted in the exponential rise of fossil fuel consumption. The ever-increasing demand for conventional sources of energy such as fossil fuels has resulted in an energy crisis. Thus, the world is turning towards the incorporation of renewable sources of energy such as solar energy, wind energy, hydro energy etc. to meet the rising needs. The most popular and widely used renewable source of energy is solar energy.

Solar energy can be defined as the energy from the sun in the form of heat and light. This energy is harvested with the help of photovoltaic (PV) cells/array. Photovoltaics (PV) is defined as the conversion of light energy into electrical energy at the atomic level [1]. The electrical energy thus obtained can be used for various purposes such as heating of water, charging of a battery etc. To reduce the burden on conventional sources of energy, the need of the hour is to make use of the available renewable sources. Thus, to charge batteries such as Lead-Acid batteries, solar based charge controllers are designed.

A solar charge controller circuit is used for interfacing a PV panel with a load such as a battery. It is not ideal to directly connect the load to the PV panel as this will result in inefficient charging of the battery thereby reducing the life of the battery. If there is no controller circuit then the battery may also discharge into the panel during night time, which is dangerous and will result in damage of the solar panel. Thus, charge controllers are necessary to ensure that the battery is efficiently charged and also protect the panel from the discharge current of the battery. Solar charge controllers can be broadly classified into two types: Pulse Width Modulation (PWM) based charge controller and Maximum Power Point Tracking (MPPT) based charge controller. In order to charge the battery efficiently, it is crucial to select the right charge controller. The selection of a charge controller depends on the electrical characteristics of the input source i.e. the PV panel and the battery specification.

The Pulse Width Modulation (PWM) based charge controller is designed and analysed using MATLAB/Simulink. The basic working principle of the PWM based charge controller is that with the change in the duty cycle (percent ON time), the average value of the power varies [2]. The heart of the PWM based charge controller is a MOSFET (Metal Oxide Semiconductor Field Effect Transistor) which is used as the switching element. The MOSFET is turned ON/OFF with the help of a PWM signal applied at the gate terminal of the MOSFET, whose duty cycle is varied in accordance with the input voltage as well as the battery voltage so as to charge the battery efficiently [3].

The Maximum Power Point Tracking (MPPT) based charge controller works on the principle of tracking the point of maximum power of the PV panel at any given irradiance and temperature so as to ensure that the battery is charged efficiently even with change in the weather conditions [4]. The Maximum Power Point (MPP) is tracked with the help of an algorithm called the Perturb and Observe (P&O) Algorithm [5]. The heart of the MPPT based charge controller is the Buck Converter (DC-DC converter). The buck converter ensures that maximum power is always available to charge the battery efficiently and minimum power is lost across the charge controller circuit itself [6] [7].

Most of the research in this field has not delved into understanding the performance of these charge controllers for conditions such as variable temperature, variable insolation (irradiance) in simulation. Thus, the motivation behind this paper is to bring to light the behaviour of these charge controllers as well as to determine the best suited charge controller. The main objective of this paper is to study the behaviour of the PWM based as well as MPPT based charge controllers under various parameters such as constant irradiance, constant temperature, variable irradiance and variable temperature. Based on the performance characteristics of both the charge controllers for the different parameters, the characteristics of the PV panel used at the input and the state of charge (SOC) of the Lead-Acid battery available at the output, the best and most suitable charge controller can be chosen for the optimal charging of a Lead-Acid Battery.

II. BACKGROUND

A Solar based charger is composed of a photovoltaic (PV) array, a charge controller circuit and a load such as a battery bank. The PV array exhibits non-linear characteristics. These non-linear characteristics of the PV (Photovoltaic) array can be understood by designing a mathematical model of the PV array on MATLAB/Simulink. A photovoltaic cell maybe considered as a constant current source. By using the equations governing the nature of the photovoltaic cell, the mathematical model is developed [1]. The variation of voltage and power for different values of irradiance and temperature are obtained from the mathematical model.

A charge controller circuit is used for interfacing a PV panel with a load such as a battery. There are two main types of solar charge controllers: The Pulse Width Modulation (PWM) and the Maximum Power Point Tracking (MPPT) based charge controller.

The Pulse Width Modulation (PWM) based charge controller is simple in design, it requires only a switching element such as a MOSFET. The MOSFET switch is used for ensuring power delivered to the battery is controlled. By applying a pulsating signal at the gate of the MOSFET with its duty cycle varied accordingly, the output voltage and thus the output power of the MOSFET can be controlled. The duty cycle is varied by taking into consideration the voltage of the battery at the load side and the voltage available at the input side i.e. the panel voltage. This allows controlling the amount of current flowing into the battery and thus helps in preventing overcharging of the battery. The authors [2] implemented a hardware version of the PWM circuit. They used an ATMega328P microcontroller to adjust the duty cycle of the switching element and they transmitted all their data obtained via an ethernet shield module. The PWM based charge controller is preferred when the rated voltage of the panel is similar to the rated voltage of the battery.

The Maximum Power Point Tracking (MPPT) based charge controller is a more advanced charge controller in comparison to the PWM based. Since PV panels exhibit non-linear characteristics, they exhibit a unique feature called as the Maximum Power Point [1]. There are several algorithms which can be used for tracking the point of maximum power [8]. These include the Perturb and Observe method, Incremental Conductance method, Fractional Open-Circuit Voltage method, Fuzzy Logic control, Neural Network approach etc. According to researchers [9], the Perturb and Observe algorithm is a simple algorithm which can used to quickly and efficiently track the MPP for both analog as well as digital circuitry. The authors [5] claim that although the P&O algorithm tracks and maintains the MPP, there are however some power losses due to constant oscillation at the MPP. Authors [3] designed a pulse width modulation based solar charge controller. The duty cycle of the PWM signal was controlled with the help of a PIC microcontroller and these signals were applied to power MOSFETs of a DC-DC converter. The SCC designed by the authors was tested under no load and load conditions, the efficiency of the PWM based SCC was high (approx. 98%) during both charging and discharging of the battery.

The MPPT algorithm is usually used with DC-DC converters. Since at the load end a battery is used, DC-DC converters are chosen. If the load were a grid then an inverter (DC-AC converter) would be used along with the MPPT algorithm. The authors [10] implemented the P&O algorithm with a boost converter having a resistive load on MATLAB/Simulink. A mathematical model of the P&O model is implemented to control the switching of the power switch of the boost converter. The output power of boost converter designed by the authors was nearly equal to the output power of the PV array at constant temperature and irradiance, implying that MPPT was achieved. Authors [11] implemented a MPPT controller using a buck- boost converter with a battery at the load end on MATLAB/Simulink. Since the voltage of battery was lower than the input voltage the converter stepped down the voltage and increased the current, thus power available for charging the battery was always constant. The researchers [7] implemented an MPPT based charge controller using a buck converter to which the P&O algorithm was applied. The authors used as Arduino Uno to implement the P&O algorithm which controlled the duty cycle of the pulses applied to the MOSFET of the buck converter. The MPPT controller designed by the authors worked with high efficiency when there were slow changes in irradiance, however the authors suggest using incremental conductance algorithm when there are sudden changes in irradiance.

Since most of these papers were based on determining the response of a single type of charge controller at a particular constant parameter such as constant irradiance and temperature, thus, this paper aims to provide a comprehensive analysis of the performance of two types of charge controllers namely the PWM based and the MPPT based under various criterions such as constant irradiance, constant temperature, variable irradiance and variable temperature. This paper also aims to help in choosing the best suited charge controller based on the input power supply characteristics as well as the load available at the output.

III. METHODOLOGY

This section deals with the design, simulation and analysis of the two solar based charge controllers, namely the Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT) based charge using MATLAB/Simulink.

III.I Pulse Width Modulation (PWM) Based Charge Controller

Pulse Width Modulation (PWM) refers to the variation in the percent ON time (duty cycle) of a signal so as to control the average voltage/power value of the input signal. Higher the value of duty cycle of the signal, higher is the average value of voltage/power. A PWM based charge controller is designed using a power switch such as a MOSFET. The MOSFET is rapidly switched ON/OFF with the help of a PWM signal applied at the gate of the MOSFET. The rapid switching of the MOSFET results in a pulsating voltage. The output voltage of the MOSFET is pulsating and its average

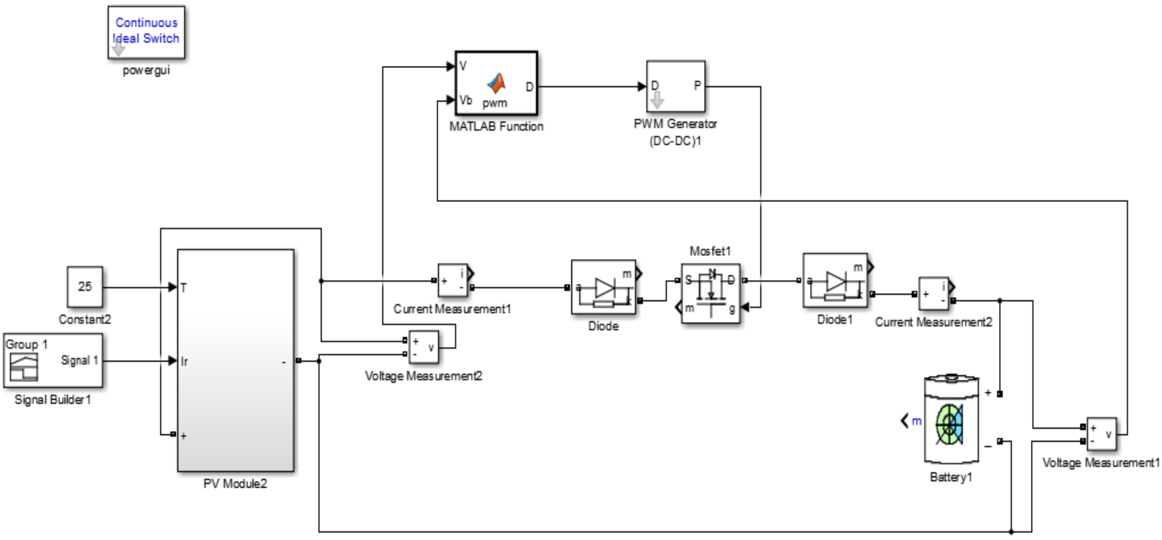


Fig. 1. Simulink Model of PWM based charge controller.

Editor - Block: pwm/MATLAB Function*

MATLAB Function*

```
function D = pwm(V,Vb)

    if((V>Vb)&&(Vb <= 9))
        D = 0.9;
    elseif((V>Vb)&&(Vb>9)&&(Vb<=12))
        D = 0.2;
        pause(10);
    elseif((V>Vb)&&(Vb>12)&&(Vb<=14))
        D = 0.1;
  else
    D=0.1;
    end
```

Fig. 2. Code written in MATLAB Function Block.

value depends on the duty cycle of the pulse. By adjusting the duty cycle, the output of the switching element is controlled thereby, the power available to charge the battery can be controlled. The duty cycle of the signal applied at the gate terminal is varied by taking into consideration the voltage of the PV panel and the battery voltage [3]. As the battery charges, the duty cycle is reduced so as to gradually decrease the power delivered to the battery and thereby, preventing the battery from being overcharged. This is required according to the state of charge (SOC) of the battery. The PWM based charge controller is used in those cases where the battery voltage is similar to that of the panel voltage [2].

Fig. 1 represents an illustration of PWM based charge controller designed on MATLAB/Simulink. A simple circuit is designed using a MOSFET and diodes from the SimElectronics Library. A mathematical model of the PV array is designed on MATLAB/Simulink [1]. The designed PV array (120W/21.6V) is interfaced with a 12V Lead-Acid battery, through the MOSFET power switch. The gate of the MOSFET is controlled by the MATLAB Function block, where the algorithm for controlling the duty cycle of the pulses is written as seen in Fig. 2. A PWM generator is used to generate pulses in accordance with the value of duty cycle obtained from the function block. Diodes are connected to prevent the reverse flow of current from the battery to the PV Module.

Fig. 2 represents the code used for ensuring efficient charging of a Lead-Acid battery (12V, 1.5Ah) by a PWM based charge controller on MATLAB/Simulink. The values of the duty cycle of the PWM signal applied at the gate are varied in accordance with both panel voltage and battery voltage.

III.I.I Performance Analysis of Pulse Width Modulation (PWM) based Charge Controller

The performance characteristics of the PWM based charge controller is determined for the following parameters:

1) At constant Irradiance (1000W/m^2) and Temperature (25 ^{0}C)

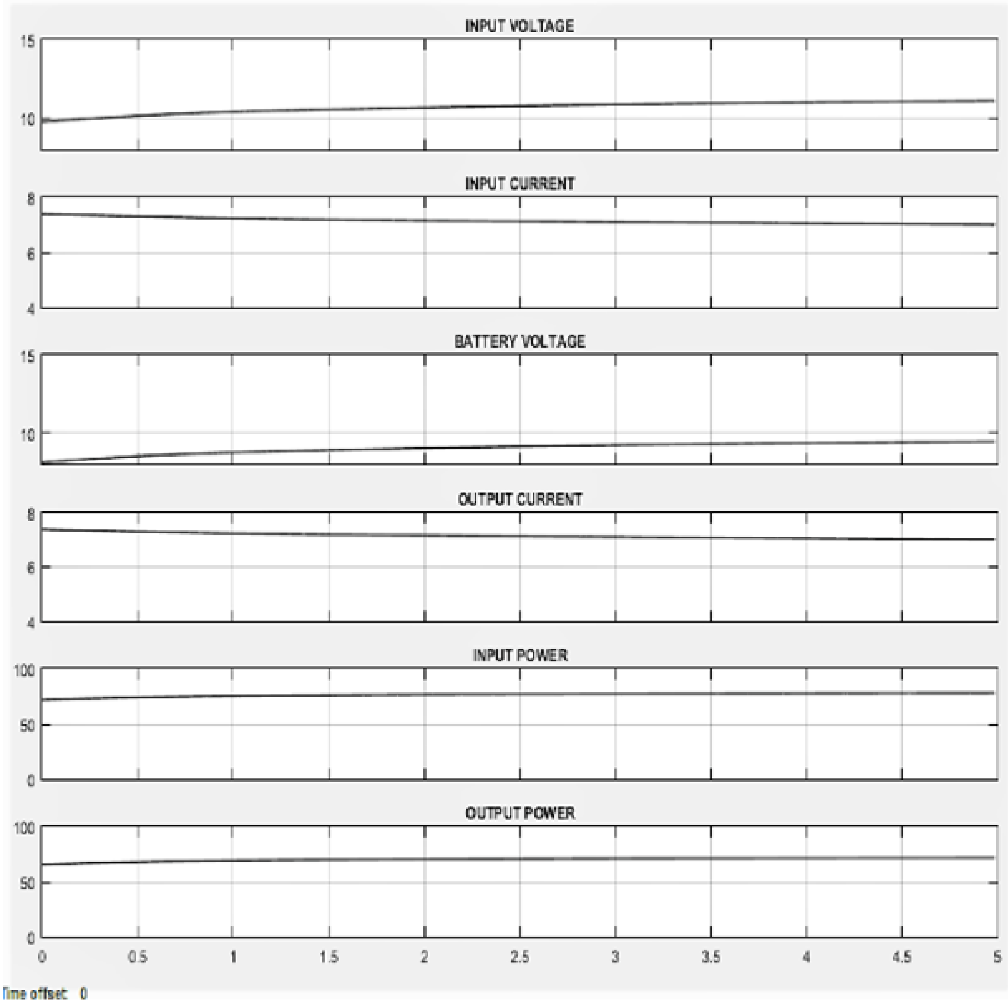
The simulated solar panel is subjected to constant irradiance and temperature to understand its performance.

From Fig. 3, it is observed that as the battery is charged i.e. as the battery voltage increases, the input panel voltage also increases. When MOSFET is switched ON, the PV panel is directly connected to the battery, the panel voltage drops down to a voltage similar to that of the battery (≈ 10V), since its voltage rating (21.6V) is higher than that of the battery (12V). This results in the reduction of efficiency of the panel itself i.e. if panel is rated at 120W/21.6V then the current delivered is approximately 5.5A maximum and as a result of drop in voltage the panel now operates at 55W, resulting in a loss of 65W of power. With rise in battery voltage, the current drawn by the battery decreases, thus, it is observed that the input current decreases and since output current is nearly equal to the input current, the output current also decreases. The output power is nearly 80-90% of the input power. For example, when input power was observed to be 75.18W at time t = 5 seconds the output power obtained was 68.79W, thus percent efficiency is approximately 91.5%.

2) At different temperatures, constant irradiance (1000W/m^2)

The simulated solar panel is subjected to constant irradiance and variable temperature (5 ^{0}C – 40 ^{0}C) to understand its performance. From Fig. 4, it is observed that as temperature increases the output power available to charge the battery decreases. From the non-linear characteristics of the PV (Photovoltaic) array, it was observed that maximum voltage decreases with increase in temperature. In PWM based charge controllers it is observed that the voltage of the PV panel drops to a value similar to that of the battery due to the direct connection of the panel with the battery every time the switch is turned ON, resulting in the decrease in the efficiency of the panel itself. At the higher temperatures the panel itself operates at a lower voltage, thus, the power lost across the panel is also minimized. Although the power available to charge the battery may be lower, the voltage available for charging the battery is always maintained by the MOSFET switch Hence, PWM based charge controllers are preferred for use at higher temperatures. It is also observed that the output power delivered to the battery is about 80- 90% of the input power, indicating that there are minimal losses offered by the charge controller circuit itself.

(a) Voltage(V)
(b) Current (A)
(c) Voltage (V)
(d) Current (A)
(e) Power (W)
(f) Power (W)



Time (s)

Fig. 3. Circuit Parameters with respect to time (seconds) at Constant Irradiance and Temperature, (a) Input Voltage (Panel Voltage), (b) Input Current (Panel Current), (c) Battery Voltage, (d) Battery Current (Charging output Current), (e) Input/Panel Power, and (f) Output power available to charge the battery.

3) At different values of irradiance, constant temperature (25 ^{0}C)

The performance of the PWM based charge controller is evaluated at different values of irradiance and at constant temperature. In Fig. 5, it is clearly observed that higher the irradiance, higher the power available to charge the battery. Although PWM based charge controllers are simple in terms of circuit design, however, they cannot be used when panel voltage is much higher than the battery voltage as this will result in the decrease in efficiency of the panel itself. Hence, PWM based charge controllers work best at high values of irradiance, higher temperature and when panel voltage rating is similar to battery voltage rating.

III.II Maximum Power Point Tracking (MPPT) Based Charge Controller

The Maximum Power Point Tracking (MPPT) based charge controller works on the principle of tracking the point of maximum power at any value of irradiance and temperature, thus, ensuring that maximum power is available for the charging of the battery at all times irrespective of the change in weather conditions [4].

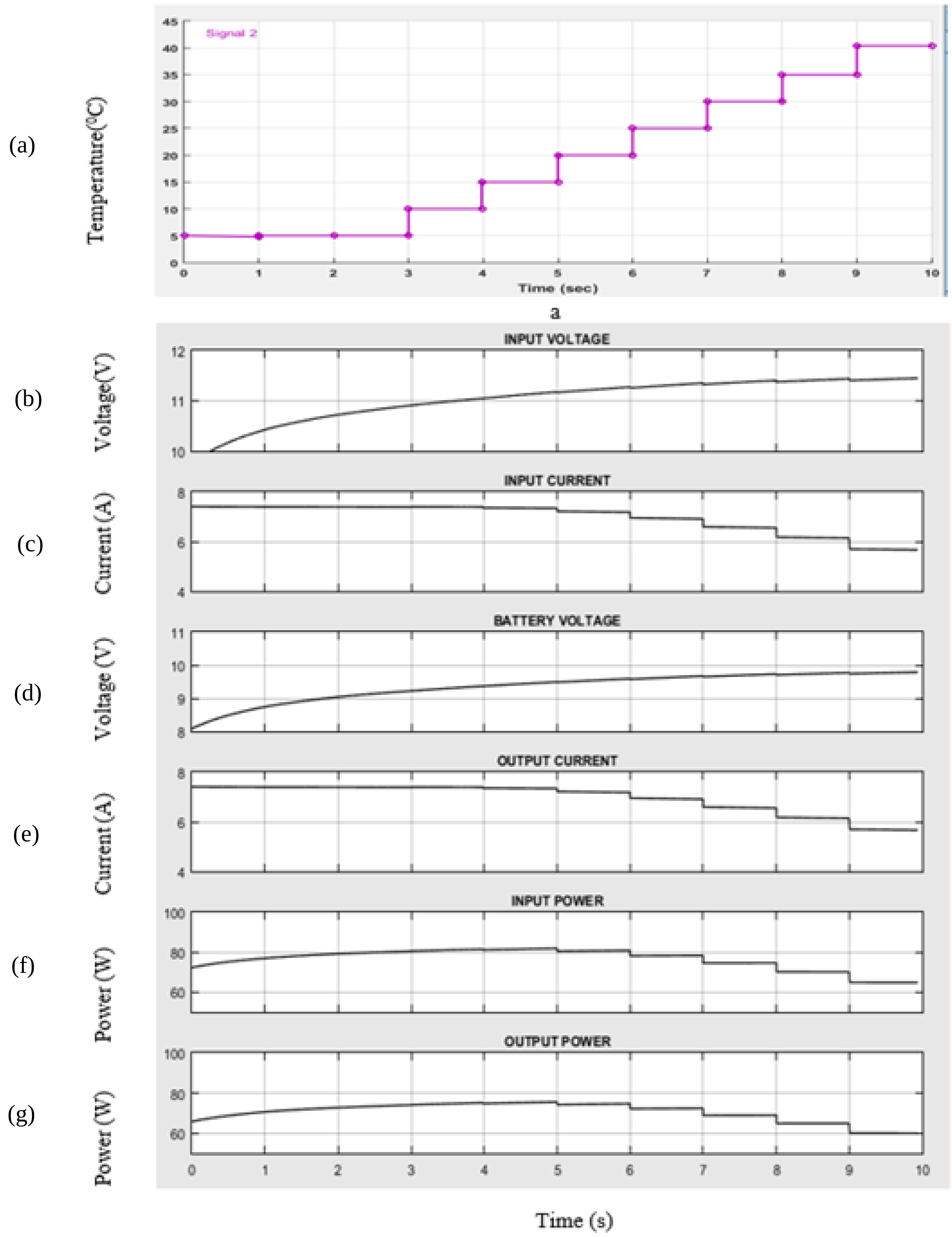


Fig. 4. Circuit Parameters at Constant Irradiance (1000W/m^2) and Variable Temperature, (a) Step Variation of Temperature (5^0C– 45^0C) with respect to time (10s), (b) Input Voltage (Panel Voltage), (c) Input Current (Panel Current), (d) Battery Voltage, (e) Battery Current (Charging Current), (f) Input Panel Power, and (g) Output power available to charge the battery.

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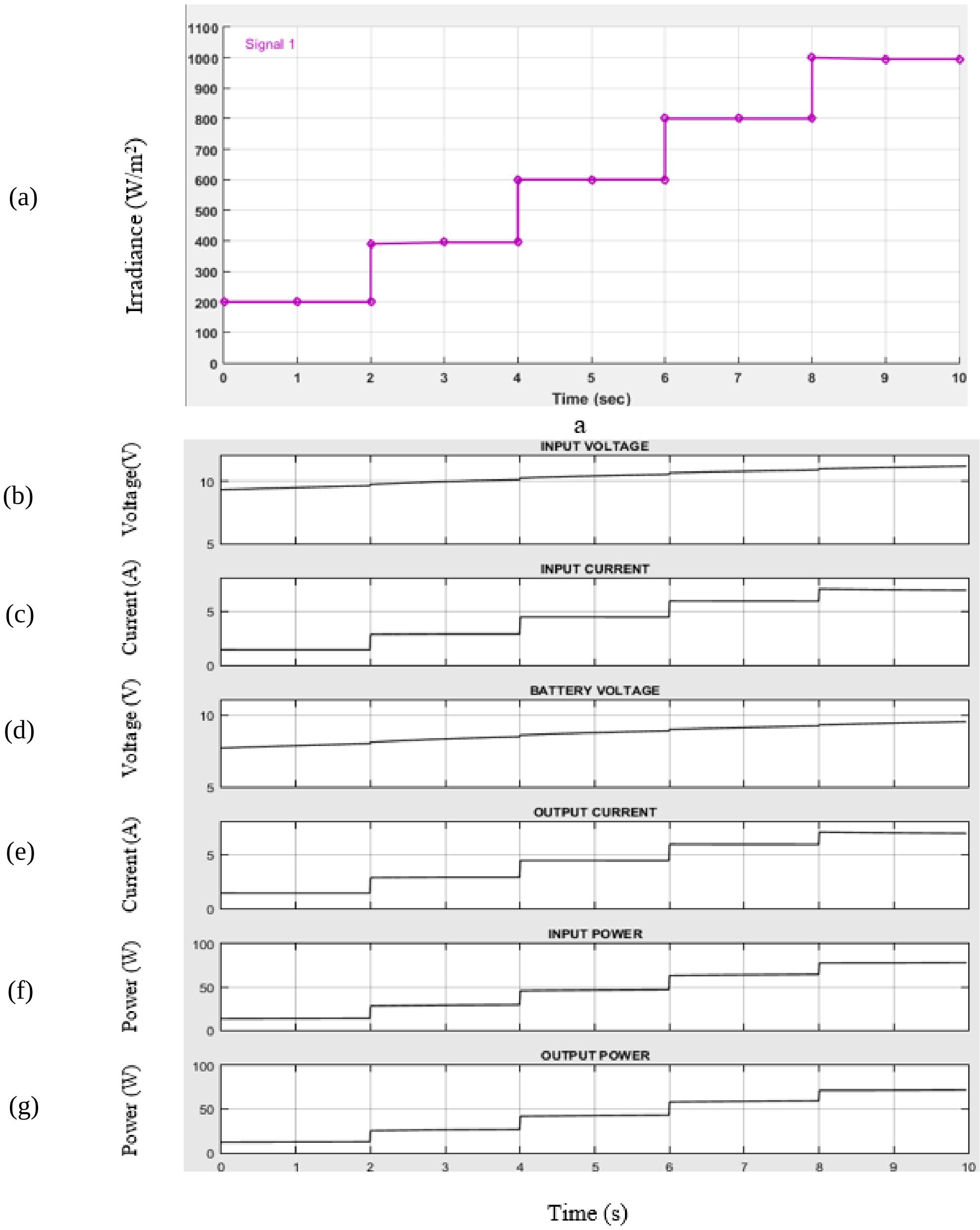

Fig. 5. Circuit Parameters at Constant Temperature (25 ^{0}C) and Variable Irradiance, (a) Step Variation of Irradiance (200-1000W/m^2) with respect to time. (b) Input Voltage (Panel Voltage), (c) Input Current (Panel Current), (d) Battery Voltage, (e) Battery Current (Charging output Current), (f) Input Panel Power, and (g) Output power available to charge the battery.

The MPPT based charge controller is designed using a DC-DC converter [6]. DC-DC converters are also referred to as switch mode regulators. The working of a DC-DC converter is similar to that of a transformer. The output voltage may be greater or lesser than the input voltage. If the output voltage is greater than the input voltage it is called as boost converter and if the output voltage is lesser than the input voltage, it is referred to as buck converter. If the output voltage is to be either stepped up or down then a buck-boost converter is preferred [12]. A buck converter is preferred for charging the battery since the panel voltage is to be stepped down [6]. Using a buck converter allows the use of panels of higher voltage ratings. The buck converter is designed with an n-MOSFET power switch [7]. Passive components such as inductors and capacitors are also used. The values of the inductors and capacitors depend on the frequency of the PWM signal applied at the gate terminal of the MOSFET device [13]. It is crucial to select the proper ratings for the inductors and capacitors so as to reduce the ripple observed in the output current of the MOSFET as observed in Fig. 6.

The Maximum Power Point (MPP) is tracked with the help of an algorithm called the Perturb and Observe (P&O) algorithm. The Perturb and Observe algorithm is a simple and efficient algorithm [9]. It is also referred to as the hill climbing methodology. This MPPT algorithm is used to vary the duty cycle of the pulses which are used to control the gate

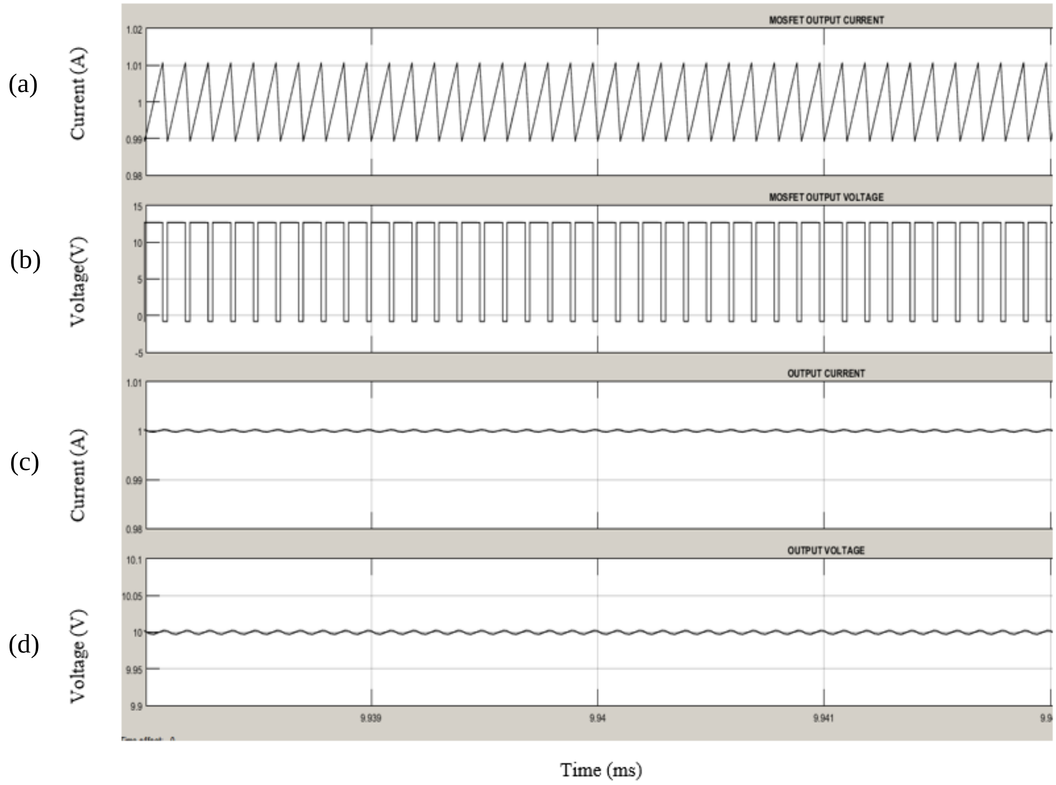

Fig. 6. Circuit Parameters of Buck Converter observed at time interval of 1ms, (a) Current seen at the output of MOSFET, (b) Output Voltage as seen at the MOSFET, (c) Output current through the load resistance, and (d) Output voltage across the load resistance.

of the MOSFET switch. The MPP is tracked by continuously monitoring the variation in the voltage and power of the PV panel. Based on the variation, the duty cycle of the gate pulses is varied, but the variation in the duty cycle is maintained at a very small value so as to ensure that maximum power is delivered to the load at all times and to decrease the steady state error as a result of oscillation about the MPP [5].

III.II.I Evaluation of MPPT algorithm with boost converter across a resistive load

The Perturb and Observe algorithm is used to monitor any changes in the input power and voltage and alters the duty cycle such that maximum power is available for the charging of the Lead-Acid battery even with variation in irradiance. In order to understand the working of the MPPT algorithm with the DC-DC converters, this algorithm is tested with both buck as well as boost converters having a resistive load at the output [14].

Fig. 7 illustrates the circuit diagram of a boost converter controlled by the Perturb and Observe (P&O) MPPT algorithm. A MATLAB Function is used for controlling the duty cycle of the pulses given to the gate of the MOSFET. The MATLAB function block contains the MPPT algorithm. Thus, a pulsating input is given to the gate of the MOSFET i.e. a PWM signal is given at the gate to rapidly switch the MOSFET and thereby control the amount of current flowing into the load. The output obtained at different stages of the circuit are viewed in the scope block and the numerical values of both the input and output parameters are displayed on the Display block. The different circuit parameters of the boost converter for different input parameters are observed as shown in Fig. 8 and Fig. 9. The values of the different circuit parameters are tabulated as seen in Table 1 and Table 2.

1) At Constant Irradiance (1000W/m2) and Temperature (25 ^{0}C)

The voltage, current and power of the boost converter at the input and output sections at constant irradiance and constant temperature are observed as shown in Table 1 and Fig. 8.

2) At Step Irradiance and constant Temperature (25 ^{0}C)

The voltage, current and power of the boost converter at the input and output sections at step irradiance and constant temperature are observed as shown in Table 2 and Fig. 9. From the figure it can be clearly observed that as irradiance increases the input current, input voltage and input power increases and this in turn affects the output parameters too.

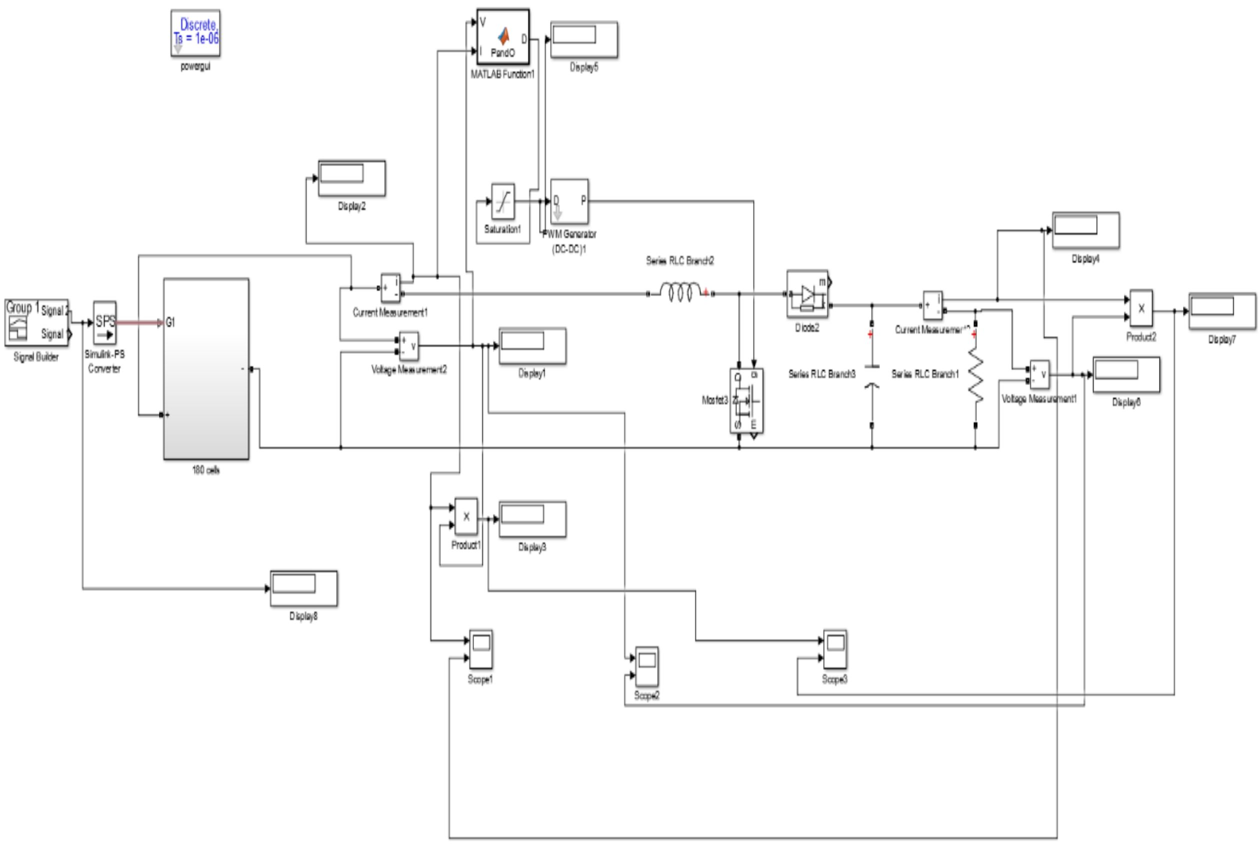

Fig. 7. Circuit diagram for boost converter with MPPT algorithm.

III.II.II Evaluation of MPPT algorithm with buck converter across a resistive load

The Perturb and Observe algorithm is implemented using a buck converter having a resistive load at its output. Fig. 10 illustrates the circuit diagram of a buck converter controlled by the Perturb and Observe (P&O) MPPT algorithm. A Matlab Function is used for controlling the duty cycle of the pulses given to the gate of the MOSFET. The Matlab function block contains the MPPT algorithm. Thus, a pulsating input is given to the gate of the MOSFET i.e. a PWM signal is given at the gate to rapidly switch the MOSFET and thereby control the amount of current flowing into the load. The output obtained at different stages of the circuit are viewed in the scope block and the numerical values of both the input and output parameters are displayed on the display block [13]. It is crucial to design an accurate input and output filter circuit in order to obtain the expected output. In a buck converter, impedance matching at the input and output should be taken care so that the buck converter works as desired [6].

Table 1: Circuit Parameters of Boost Converter at Constant Irradiance (1000W/m^2) and Temperature (25 ^{0}C)

Boost Converter	Voltage(V)	Current (A)	Power(W)
Input	21.6	4.239	91.56
Output	42.03	2.109	88.3

Table 2: Circuit Parameters of Boost Converter at Step Irradiance

Irradiance (W/m^2)	Input current(A)	Output current(A)	Input Voltage(V)	Output voltage(V)	Input Power(W)	Output Power(W)
200	3.796	1.876	19.37	37.51	73.51	70.51
400	3.986	1.973	20.33	39.45	81.04	77.62
600	4.092	2.024	20.88	40.48	85.45	81.94

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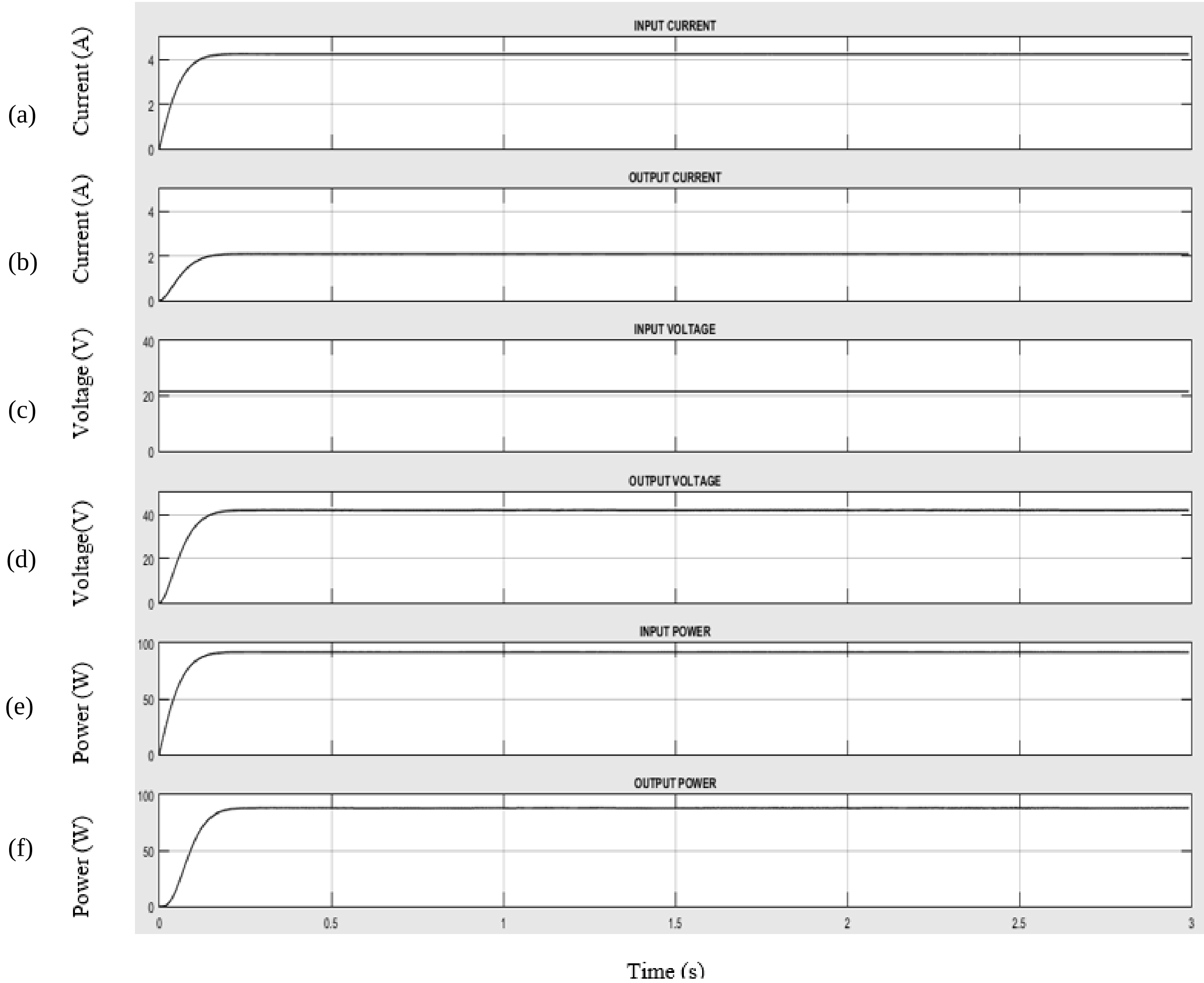


Fig. 8. Circuit Parameters at Constant Irradiance and Temperature at intervals of 0.5s, (a) Input Current (Panel Current), (b) Output Current through the load, (c) Input Voltage (Panel Voltage), (d) Output Voltage across load, (e) Input Power delivered by Panel, and (f) Output Power available at the resistive load.

1) At Constant Irradiance (1000W/m^2) and Temperature (25 ^{0}C)

The voltage, current and power of the buck converter at the input and output sections at constant irradiance and constant temperature are observed as shown in Table 3 and Fig. 11. From the table it is clearly observed that the output power obtained is nearly equal to the input power implying that there are minimal losses across the converter itself.

Table 3: Circuit Parameters of Buck Converter at Constant Irradiance (1000W/m^2) and Temperature (25 ^{0}C)

Boost Converter	Voltage(V)	Current (A)	Power(W)
Input	21.6	0.4849	10.47
Output	9.308	0.9308	8.66

Table 4: Circuit Parameters of Buck Converter at Step Irradiance

Irradiance (W/m^2)	Input current(A)	Output current(A)	Input Voltage(V)	Output voltage(V)	Input Power(W)	Output Power(W)
200	0.5225	0.922	19.33	9.288	10.1	8.516
600	0.5692	1.006	20.89	10.05	11.87	10.1
1000	0.5901	1.043	21.59	10.43	12.7	10.88

2) At Step Irradiance and constant Temperature (25 ^{0}C)

The voltage, current and power of the buck converter at the input and output sections at step irradiance and constant temperature are observed as shown in Table 4 and Fig. 12. From the figure. it can be clearly observed that as irradiance increases the input current, input voltage and input power increases and this in turn affects the output parameters too.

III.II.III Maximum Power Point Tracking (MPPT) based charge controller circuit with Lead-Acid battery as load

The Maximum power point tracking (MPPT) based charge controller is designed on Simulink using a buck converter as the main power converter circuit for a battery load at the output. Fig. 13 Illustrates the circuit diagram of an MPPT based charge controller. This charge controller is basically a buck converter which is controlled by the Perturb and Observe (P&O) algorithm.

The PV module described in this circuit diagram is developed with Solar cell from the SimElectronics library. The P&O algorithm is written in the MATLAB function block. The value of the duty cycle is defined by this block. The PWM generator block generates a PWM signal having a duty cycle defined by the function block as seen in Fig. 14. Thus, the current flowing to the battery is controlled thereby, ensuring that maximum power is available to charge the battery even with varying weather conditions [5].

The performance of the Maximum Power Point Tracking (MPPT) based charge controller with a Lead- Acid battery at the load end is determined for constant temperature and constant irradiance, variable temperature and constant irradiance and variable irradiance and constant temperature.

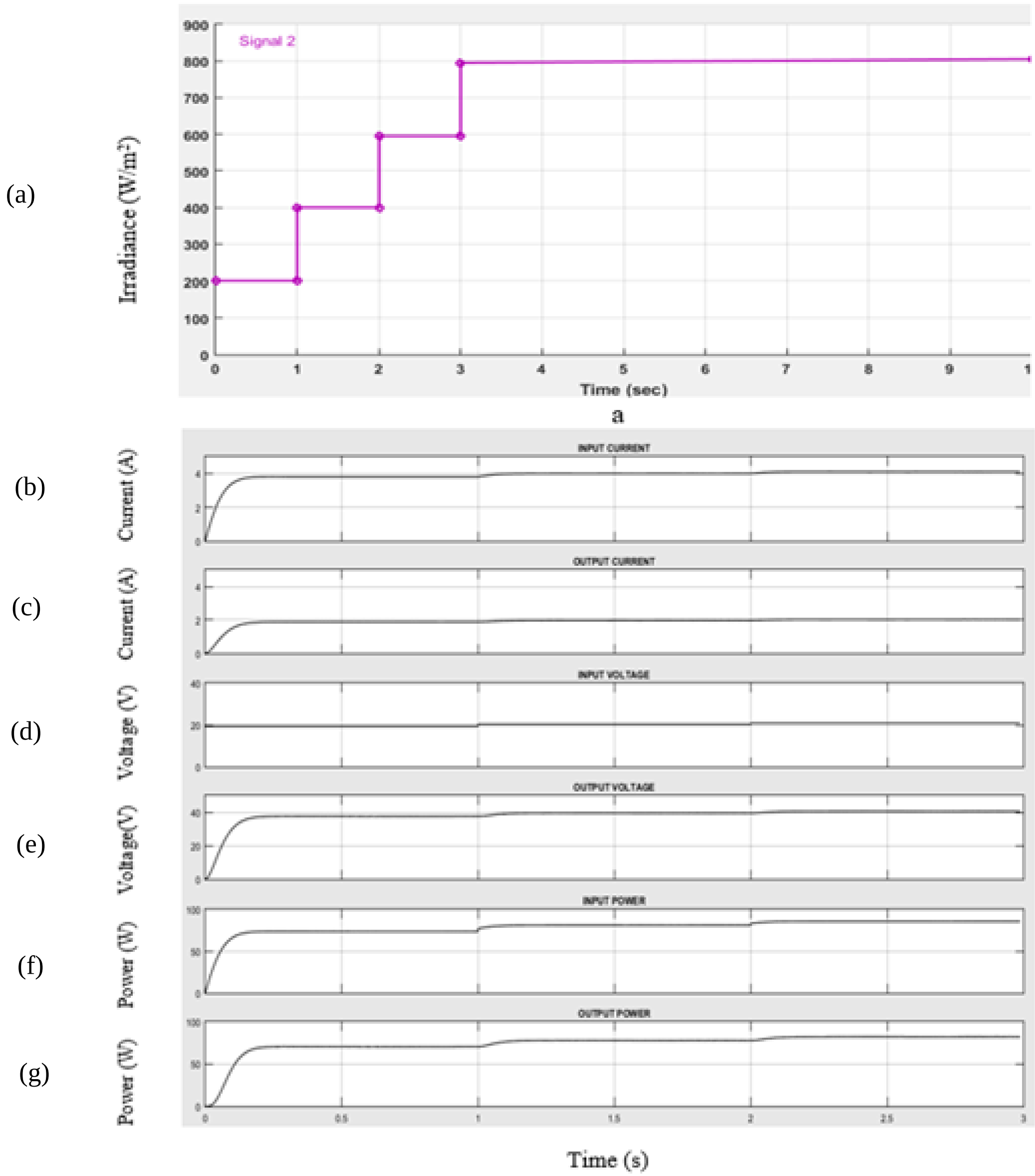


Fig. 9. Circuit Parameters at Step Irradiance and Constant Temperature (25 ^{0}C), (a) Variation of Irradiance (200W/m^2 - 800W/m^2) in steps of 200W/m^2 for 3s, (b) Input Current (Panel Current), (c) Output Current through the resistive load, (d) Input Voltage (Panel Voltage), (e) Output Voltage across load, (f) Input Power delivered by Panel, and (g) Output Power available at the resistive load.

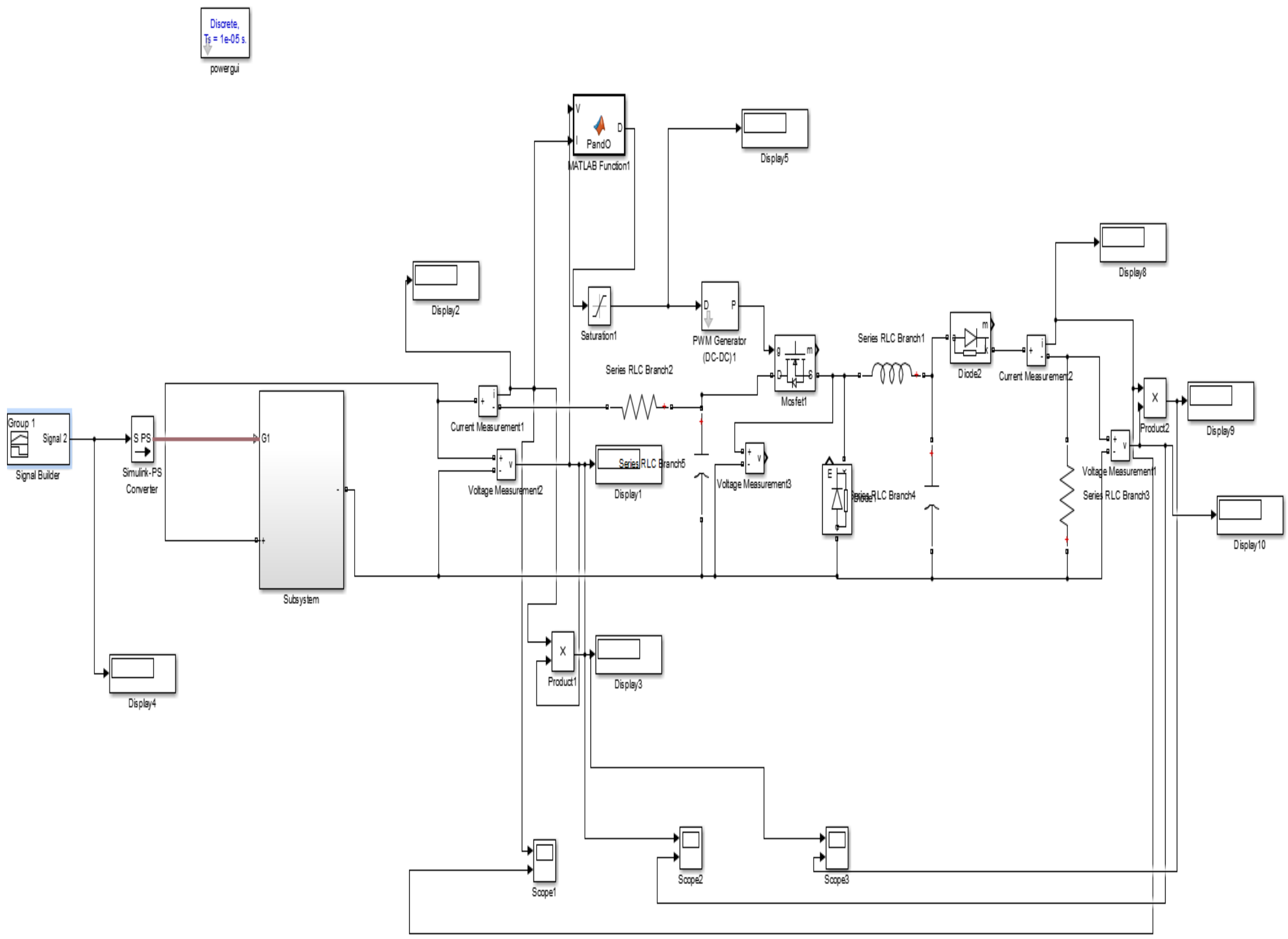


Fig. 10. Circuit Diagram of Buck Converter with MPPT Algorithm.

1) At Constant Irradiance (1000W/m^2) and Temperature (25 ^{0}C)

From Fig. 15, it is observed that the input voltage remains constant for a particular value of irradiance. The MOSFET output voltage pulsates between 21.6V (input voltage) and 0V. The average voltage obtained depends on the duty cycle of the pulses. The battery charges steadily. The input current drawn decreases as the battery charges. The output current is boosted in accordance with duty cycle. The output power available to charge the battery is nearly equal to the input power.

2) At Step Irradiance and Constant Temperature (25 ^{0}C)

From Fig. 16, it is observed that as irradiance increases, the value of input current increases and panel voltage increases slightly. Thus, at higher values of irradiance, the power delivered by the panel is higher and the MPP (Maximum Power Point) increases with increase in irradiance. Hence, MPPT charge controllers work best at higher values of irradiance. Since, the input current increases with irradiance even the output current increases. This is because the output current is a function of the input current. Thus, the output power available to charge the battery also increases with irradiance.

3) Variation of Temperature at Constant Irradiance (1000W/m^2)

From Fig. 17, it is observed that as the temperature varies between 5 ^{0}C and 40 ^{0}C in steps of 5 ^{0}C, the input voltage of the battery decreases with increase in temperature. The input current and the output current vary slightly with temperature. It is the panel voltage which is most affected by change in temperature. The maximum output power is delivered to the battery at 5 ^{0}C. Hence, MPPT based charge controllers are most efficient at lower temperatures.

The advantages of using MPPT based charge controller are: Maximum power is delivered to the battery at all times, irrespective of the change in irradiance and temperature. Minimal losses offered by the charge controller circuit itself. Panels of higher ratings can be used. Works with best efficiency at low temperatures and high values of irradiance. Although, the MPPT based charge controllers have several pros there are few cons such as, the DC-DC converters used are expensive and the circuit involves complex designs such as the design of the DC-DC converters, design of the inductor used in the converter etc.

IV. RESULT AND DISCUSSION

Solar charge controllers play a vital role in ensuring that a battery is charged efficiently when a photovoltaic panel is used as the input power supply. There are two main types of solar charge controllers: The PWM (Pulse Width Modulation) based and the MPPT (Maximum Power Point Tracking) based. The authors [2] implemented a hardware version of the PWM (Pulse Width Modulation) circuit. They were able to successfully transmit the voltage and current data from the controller circuit via an ethernet shield, which helped in determining whether the controller is working. The authors [3] designed a pulse width modulation based solar charge controller with a DC-DC converter. The SCC designed by the authors was tested under no load and load conditions, the efficiency of the PWM based SCC was high (approx. 98%) during both charging and discharging of the battery.

Researchers [7] implemented an MPPT based charge controller using a buck converter to which the P&O algorithm was applied. The authors used as Arduino Uno to implement the P&O algorithm which controlled the duty cycle of the pulses applied to the MOSFET of the buck converter. The MPPT controller designed by the authors worked with high efficiency when there were slow changes in irradiance, however the authors suggest using incremental conductance algorithm when there are sudden changes in irradiance. However, the performance of these charge controllers at different parameters like varying irradiance and temperature were not determined. Thus, this article helps to not only understand the design and but also the behaviour of the system under varying conditions. The conditions such as variable temperature and irradiance was chosen in order to imitate the varying weather conditions in real time, thereby helping one to design the actual hardware circuit.

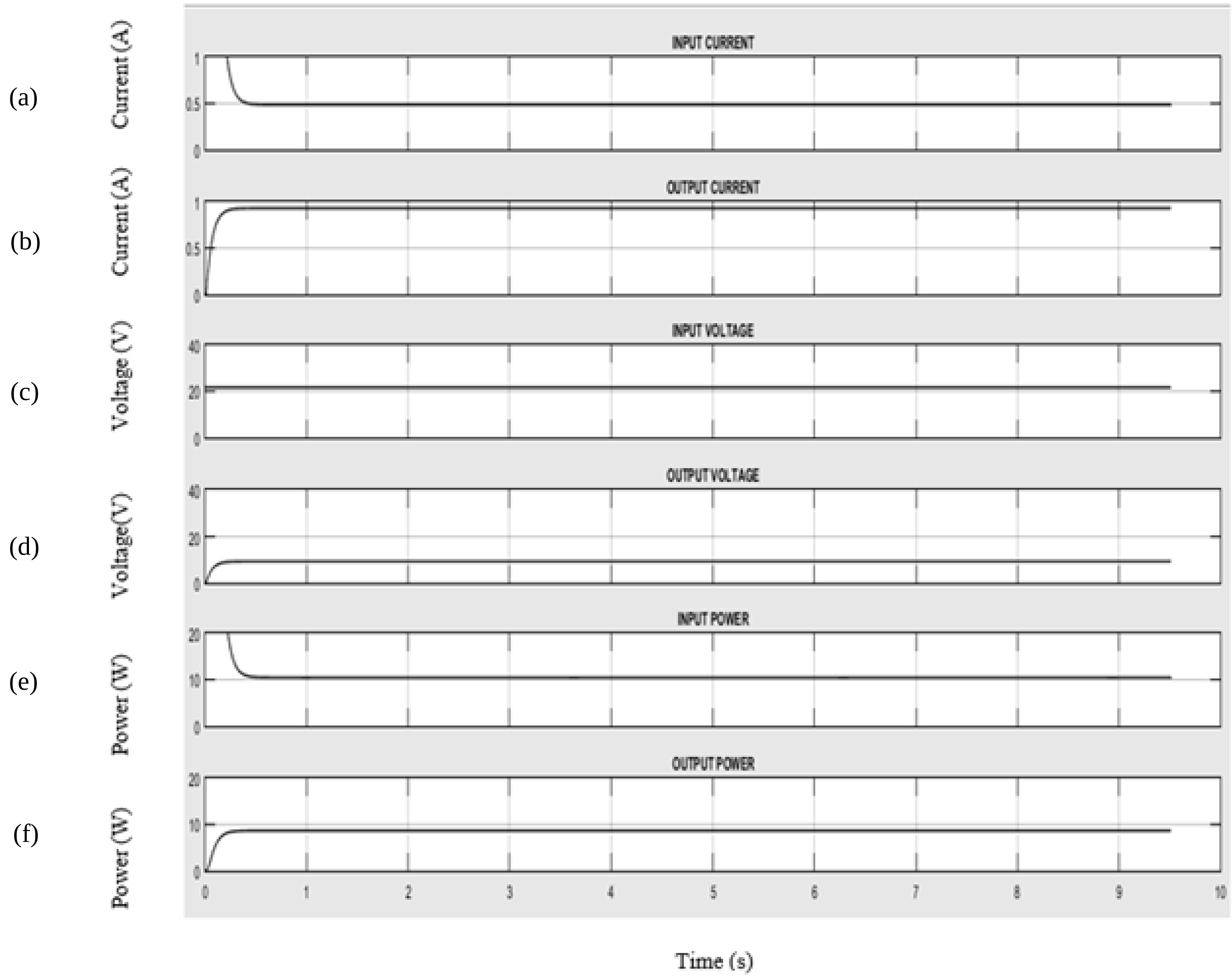


Fig. 11. Circuit Parameters at Constant Irradiance and Temperature at intervals of 1s, (a) Input Current (Panel Current), (b) Output Current through the load, (c) Input Voltage (Panel Voltage), (d) Output Voltage across load, (e) Input Power delivered by Panel, and (f) Output Power available at the resistive load.

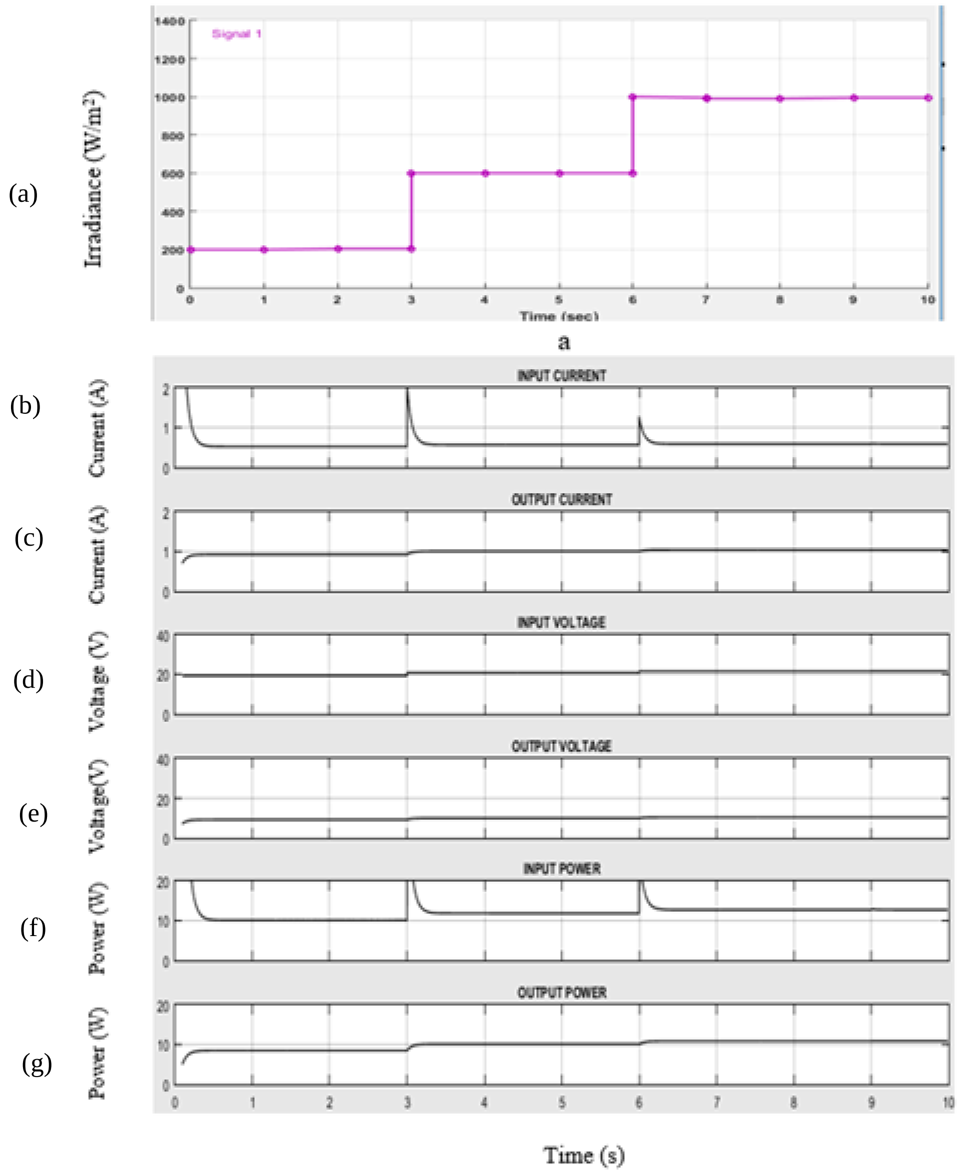


Fig. 12. Circuit Parameters at Step Irradiance and Constant Temperature (25 ^{0}C), (a) Variation of Irradiance (200W/m^2 - 1000W/m^2) in steps of 400W/m^2 for 10s, (b) Input Current (Panel Current), (c) Output Current through the resistive load, (d) Input Voltage (Panel Voltage), (e) Output Voltage across load, (f) Input Power delivered by Panel, and (g) Output Power available at the resistive load.

The following results were obtained in this article: (a) The PWM based charge controller is preferred when the voltage rating of the PV panel is similar to that of the battery, at high values of irradiance and high temperature. (b) The charge controller is highly efficient since the output power of the controller is nearly equal to the input power indicating that the power loss across the controller is minimal.

The MPPT based charge controller is preferably used for higher panel ratings and it works best at high values of irradiance and low temperature, since maximum power is delivered by the panel at these conditions [1]. The controller is highly efficient since the power loss across the controller is minimal. This article provides a comprehensive understanding of the solar based charge controllers under various criterions, however, when implemented with actual hardware the behaviour of the system may deviate from the behaviour obtained by simulations due to sudden and unpredictable changes in weather patterns.

V. CONCLUSION

The solar charge controller is a necessity whenever a solar panel is to be interfaced with a load. It is very crucial to select the right type of charge controller required, since each charge controller works best for different set of parameters. The two most widely used solar based charge controllers are: The PWM (Pulse Width Modulation) based and the MPPT (Maximum Power Point Tracking) based. In order to choose the best suited solar charge controller, the performance of both these controllers were determined for different conditions such as constant irradiance, constant temperature, variable irradiance and variable temperature. From the results obtained we can conclude:

1. If the battery voltage is similar to the panel voltage, temperature as well as irradiance is high then the PWM based charge controllers are preferred.
2. For higher panel ratings, high irradiance and low

temperatures, MPPT based charge controllers are preferred. Although, both charge controllers are highly efficient since the losses across the controllers themselves are minimal, yet the MPPT based charge controller is considered the best charge controller as it ensures maximum power is delivered to the battery at all times. The future scope of this project would be to create a machine learning model from the data obtained from the actual hardware circuits of the PWM as well as the MPPT based charge controllers so to design the most optimal charge controller for the efficient charging of a battery. By using the most appropriate algorithm required for the data collected, we can further analyse the circuit and establish certain design criterions required for a charge controller by training the machine learning model with the experimental data obtained.

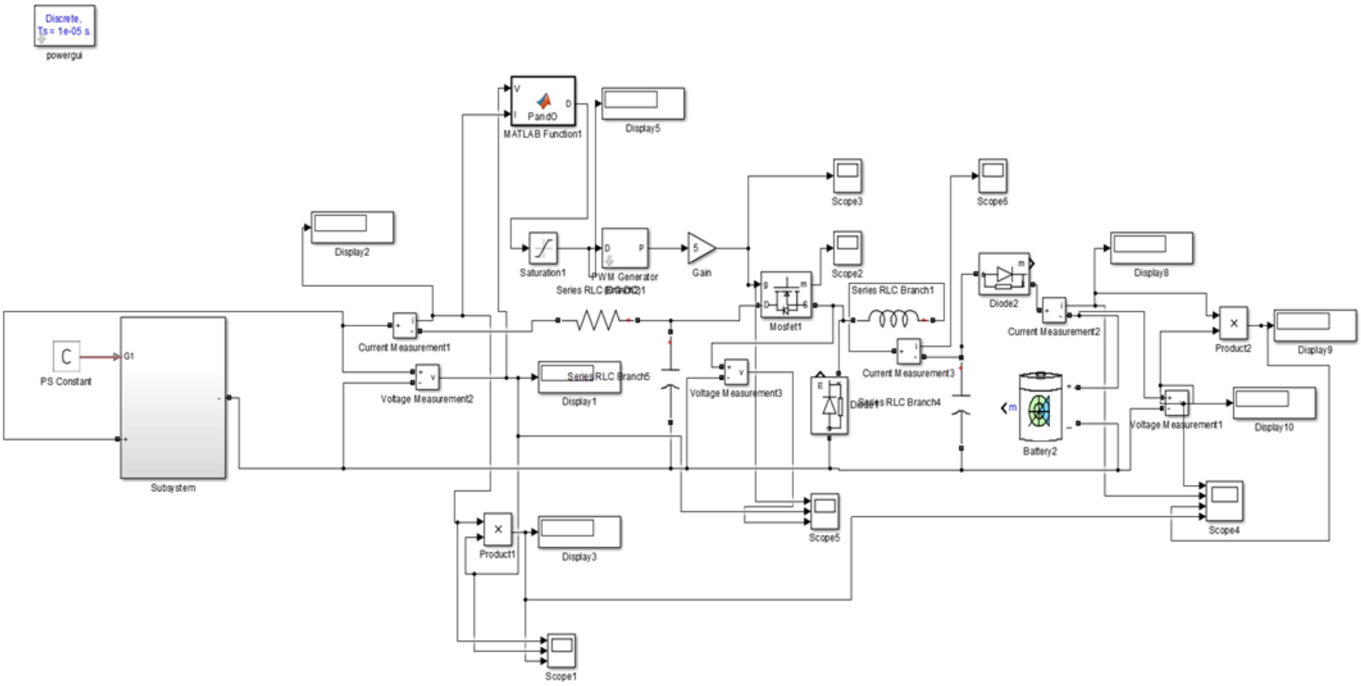
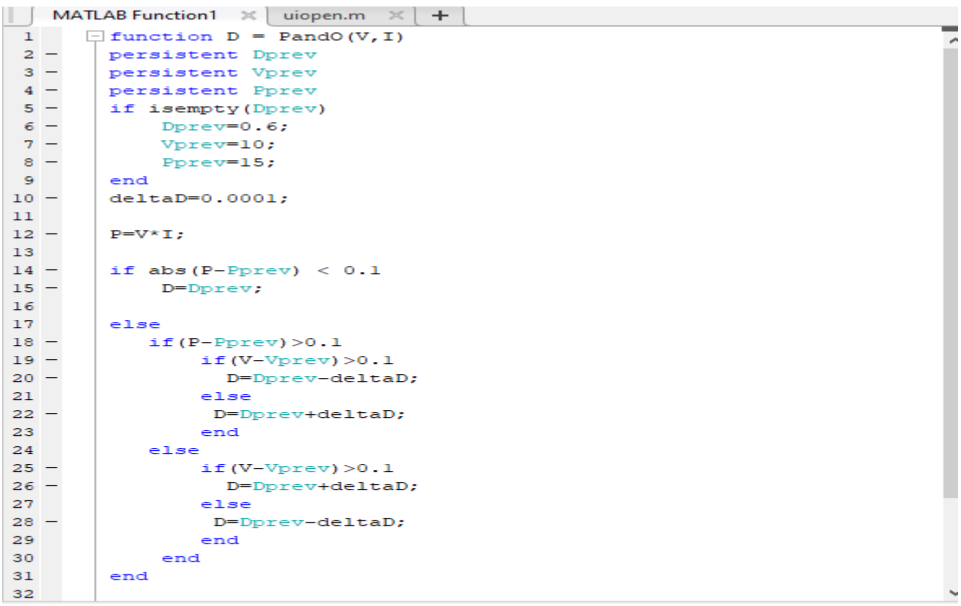


Fig. 13. Circuit Diagram of MPPT Based Charge Controller.



```
function D = PandO(V,I)
persistent Dprev
persistent Vprev
persistent Pprev
if isempty(Dprev)
    Dprev=0.6;
    Vprev=10;
    Pprev=15;
end
deltaD=0.0001;

P=V*I;

if abs(P-Pprev) < 0.1
    D=Dprev;

else
   if(P-Pprev)>0.1
       if(V-Vprev)>0.1
         D=Dprev-deltaD;
       else
        D=Dprev+deltaD;
       end
   else
       if(V-Vprev)>0.1
         D=Dprev+deltaD;
       else
        D=Dprev-deltaD;
       end
    end
end
```

Fig. 14. Code written in MATLAB Function for MPPT based charge controller.

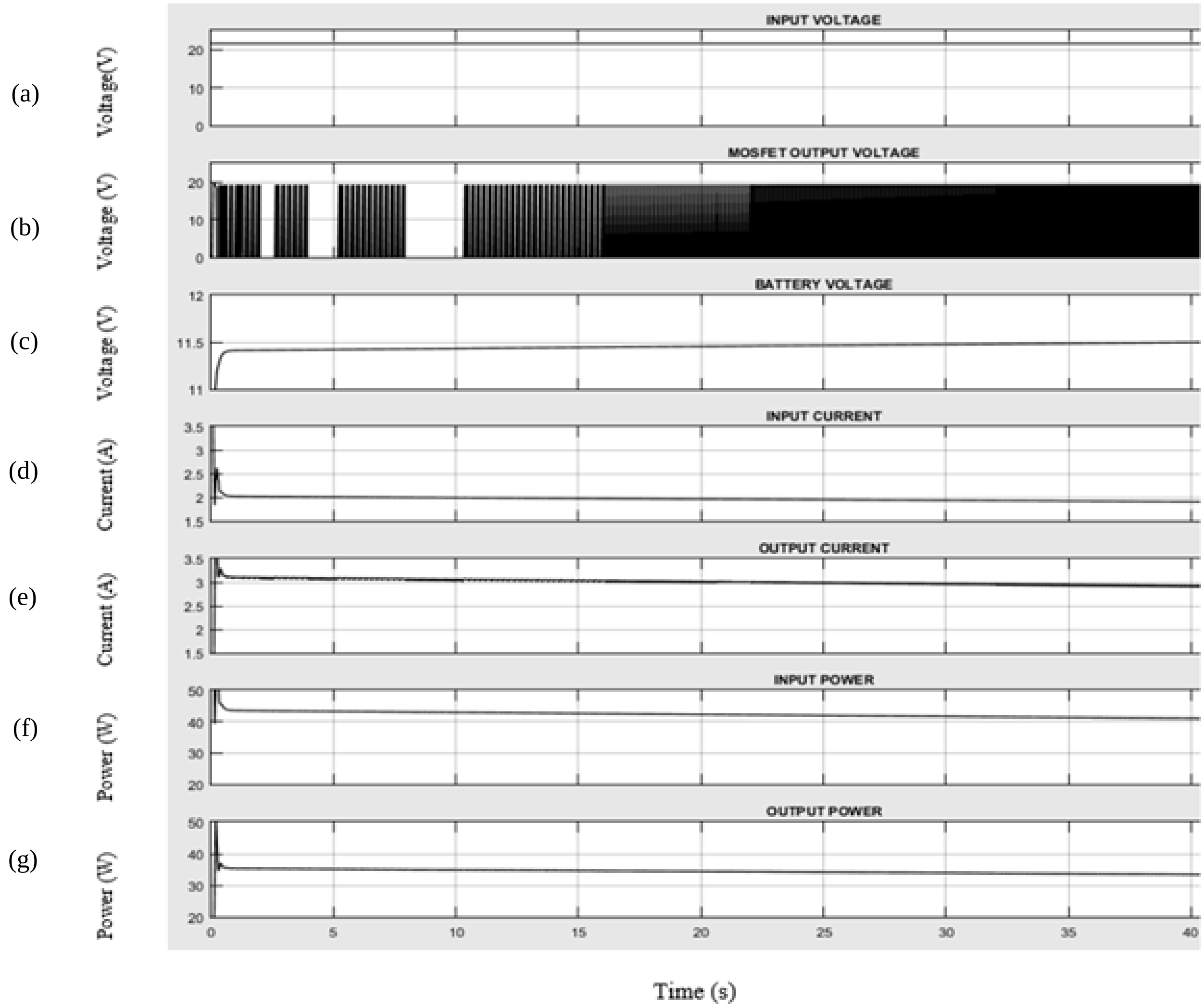


Fig. 15. Circuit Parameters at Constant Irradiance and Temperature at an interval of 5s, (a) Input Voltage (Panel Voltage), (b) Output Voltage of MOSFET, (c) Battery Voltage, (d) Input Current (Panel current), (e) Output Current, (f) Input Power (Power delivered by panel), and (g) Output Power (Power available to charge the battery.

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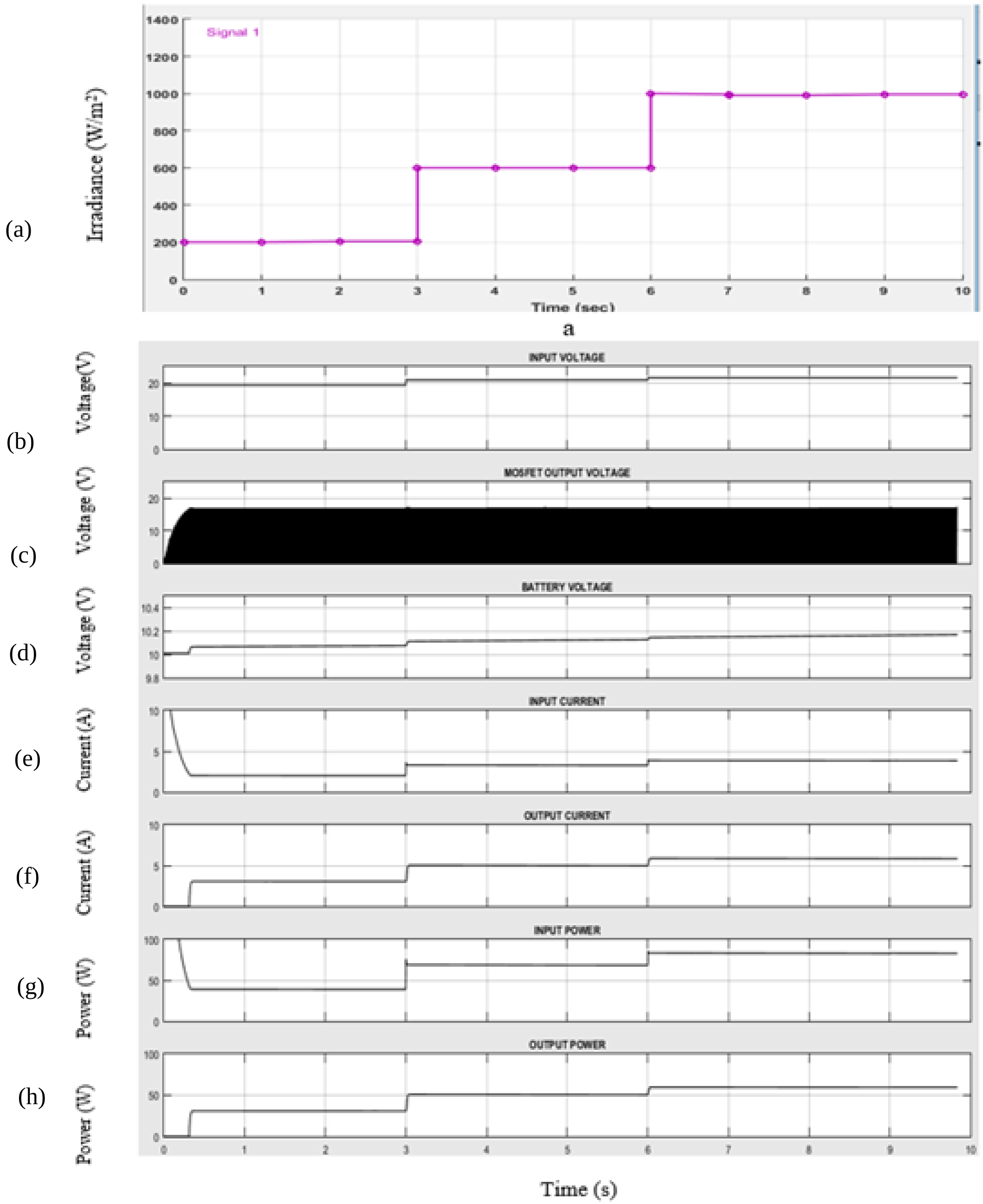

Fig. 16. Circuit Parameters at Step Irradiance and Constant Temperature ($25\,^{0}C$), (a) Variation of Irradiance (200W/m^2 – 1000W/m^2) in steps of 400W/m^2 for 10s, (b) Input Voltage (Panel Voltage), (c) Output Voltage of MOSFET, (d) Battery Voltage, (e) Input Current (Panel current), (f) Output Current, (g) Input Power (Power delivered by panel), and (h) Output Power (Power available to charge the battery).

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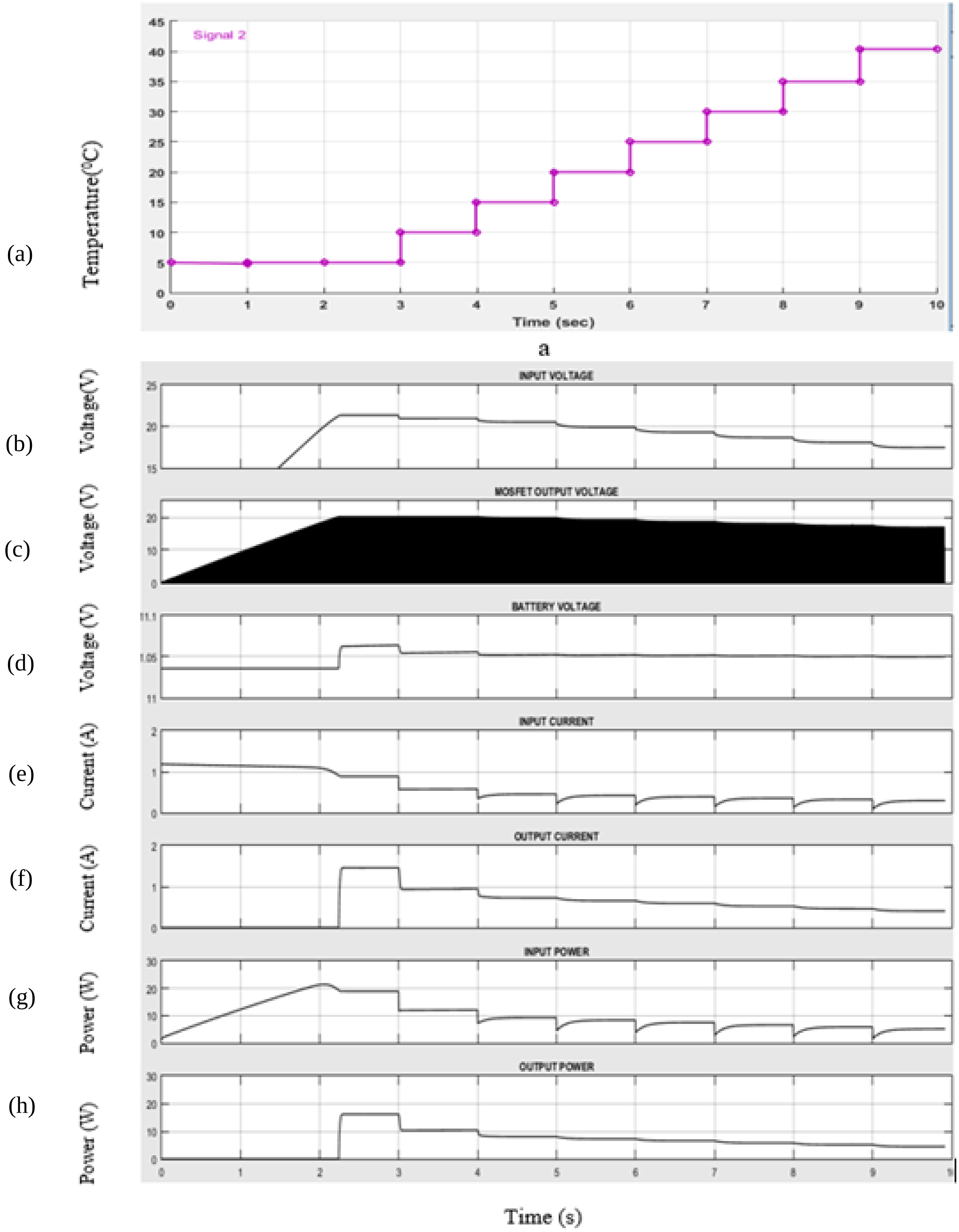

Fig. 17. Circuit Parameters at Constant Irradiance (1000W/m^2) and Variable Temperature of a panel rated at 25W, (a) Step Variation of Temperature (5 ^{0}C– 40 ^{0}C) with respect to time, (b) Input Voltage (Panel Voltage), (c) Output Voltage of MOSFET, (d) Battery Voltage, (e) Input Current (Panel current), (f) Output Current, (g) Input Power (Power delivered by panel), and (h) Output Power (Power available to charge the battery.

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