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Implementation of a Solar Powered Universal Motor Pump Set without Battery Backup for Residential and Industrial Applications

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ABSTRACT: Photovoltaic power control is one of the burning research fields these days. When compared to fossil fuels, solar energy is relatively untapped source of energy. Solar energy represents a promising alternative that will likely supplement fossil fuel based energy supply, and eventually replace the fossil fuel source as the availability of latter declines. A solar powered pump is a normal pump with an electric DC motor. Solar powered pumps will naturally work best during sunny days. Electricity for the motor is generated on-site through a solar panel which converts solar energy to DC. A solar photovoltaic water pumping system (SPWPS) consists of PV array, motor-pump set, associated electronics and an On/OFF switch.

KEYWORDS: Incremental Conductance, MPPT, Photovoltaic, SPWPS, Universal Motor.

I. INTRODUCTION

Energy is required for a wide range of applications. Electrical energy is the most convenient form of energy which can be converted to all other forms of energy. It is one of the most versatile forms of energy, form the point of view of transmission, distribution and control.

The current trends in energy consumption are neither secure nor sustainable. For an indication, the share of primary energy sources in total world energy requirement is shown in figure. There is a significant growth in the consumption of renewable energy sources[1]. Solar energy represents a promising alternative that will likely initially supplement fossil fuel based energy supply, and eventually replace the fossil fuel source as the availability of the latter declines. Photovoltaic power control is one of the burning research fields these days[2].

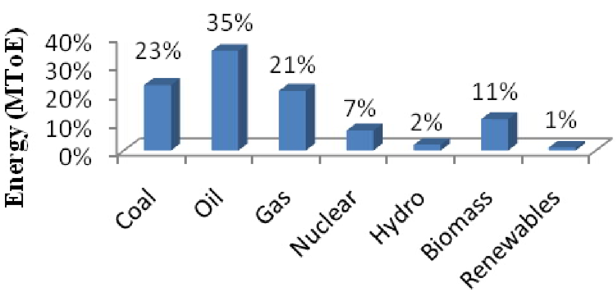

Figure 1. Share of primary sources in world's total energy supply

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II. PHOTO VOLTAIC SYSTEMS

One of the methods to generate electricity from solar energy is by making use of PV cells that converts the solar energy falling on them directly into electricity. Large scale applications of PV for power generation either on roof tops or in large fields connected to the utility grid are promising as well to provide clean, safe and sound alternatives to current methods of electricity generation.

A. Solar cell Characteristics[3]

Solar cells are characterized and compared with each other with four parameters:

- Short circuit current (I_{SC})
- Open circuit voltage (V_{OC})
- Fill factor (FF)
- Efficiency (η)

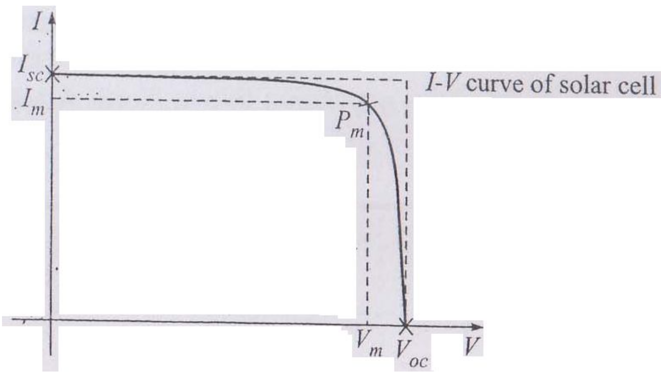

Figure 2. Typical I-V curve of a solar cell and its parameters

B. Losses in Solar Cells

1. Fundamental losses:

- *Losses due to low energy photons*
- *Losses due to excess energy in photons*
- *Voltage loss.*
- *Fill factor loss*

2. Technical losses:

- *Loss by reflection*
- *Loss due to incomplete absorption*
- *Loss due to metal coverage*
- *Recombination losses* [4].

C. Model of a Solar Cell

Solar cells or PV cells are the basic components of PV module and it is the element in charge of transforming the sun rays or photons directly into electric power. An ideal PV is modelled by a current source in parallel with a diode[5]. R_s is the intrinsic series resistance whose value is very small. R_p is the equivalent shunt resistance which has a very high value.

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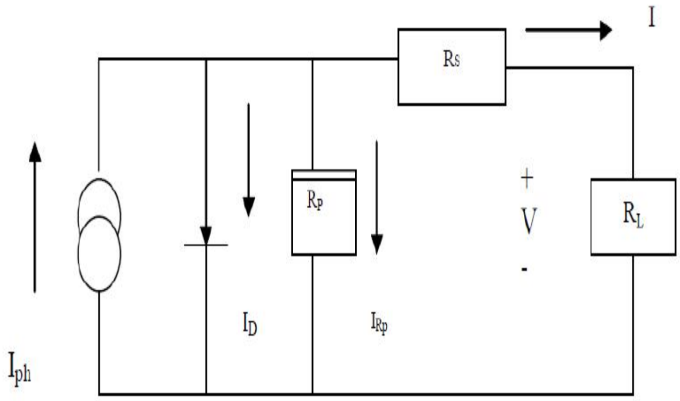

Figure 3. Equivalent circuit of a P-N junction solar cell

Applying Kirchhoff's current law to the node where I_{ph}, diode, R_p and R_s meet, we get

$$I_{ph} = I_D + I_{R_p} + I$$

We get the following equation for the photovoltaic current:

$$I = I_{ph} - I_D - I_{R_p}$$

where, I_{ph} is the insolation current, I is the cell current, I_D is the diode current and I_{Rp} is the current through the parallel resistor

PV cells are grouped in larger units called PV modules which are further interconnected in series-parallel configuration to form PV arrays or PV generators. The PV mathematical model used to simplify our PV array is represented by the equation:

$$I = n_p I_{ph} - n_p I_{rs}\left[\exp\left(\frac{q}{KTA} * \frac{V}{n_s}\right) - 1\right]$$

where I is the PV array output current; V is the PV array output voltage; n_s is the number of cells in series and n_p is the number of cells in parallel; q is the charge of an electron; K is the Boltzmann's constant; A is the p-n junction ideality factor; T is the cell temperature (K); I_{rs} is the cell reverse saturation current. The factor A determines the cell deviation from the ideal p-n junction characteristics; it ranges from 1 to 5.

The cell reverse saturation current I_{rs} varies with temperature according to the following equation:

$$I_{rs} = I_{rr}\left(\frac{T}{T_r}\right)^3 \exp\left(\frac{qE_G}{KA}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right)$$

Where T_r is the cell reference temperature, I_{rr} is the cell reverse saturation temperature at T_r and E_G is the band gap of the semiconductor used in the cell.

The photo current I_{ph} depends on the solar radiation and cell temperature as follows:

$$I_{ph} = \left[I_{scr} + K_i\left(T - T_r\right)\right]\frac{S}{100}$$

where I_{scr} is the cell short-circuit current at reference temperature and radiation, K_i is the short circuit current temperature coefficient, and S is the solar radiation in mW/cm^2

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D. PV Ratings

The solar PV modules are rated in terms of their peak power (Wp) output. The Wp is specified by the manufacturer under the so called Nominal Operating Cell Temperature (NOCT). The NOCT is defined as the temperature reached by the cell in an open circuited module under the following conditions:

- Irradiation: 800W/m^2
- Ambient temperature: 20^0C
- Wind speed: 1m/s
- Mounting: open back side

III. MAXIMUM POWER POINT TRACKING

Maximum Power Point Tracking, frequently referred to as MPPT, is an electronic system that operates the PV modules in a manner that allows the modules to produce all power they are capable of. MPPT is not a mechanical tracking system that physically moves the modules to make them point more directly at the sun

A. Need for MPPT

When a solar PV module is used in a system, its operating point is decided by the load to which it is connected. Also, since solar radiation falling on a PV module varies throughout the day, the operating point of module also changes throughout the day. Maximum power point tracking is a technique that is used to get the maximum possible power from solar panels. Solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear efficiency as shown in figure[8]. For any given set of operational conditions, cells have a single operating point where the values of the current (*I*) and Voltage (*V*) of the cell result in a maximum power output. A photovoltaic cell, for the majority of its useful curve, acts as a constant current source. However, at a photovoltaic cell's MPP region, its curve has an approximately inverse exponential relationship between current and voltage. From basic circuit theory, the power delivered from or to a device is optimized where the derivative (graphically, the slope) *dI/dV*of the I-V curve is equal and opposite the *I/V* ratio (where d*P/dV*=0). This is known as the maximum power point (MPP) and corresponds to the "knee" of the curve.

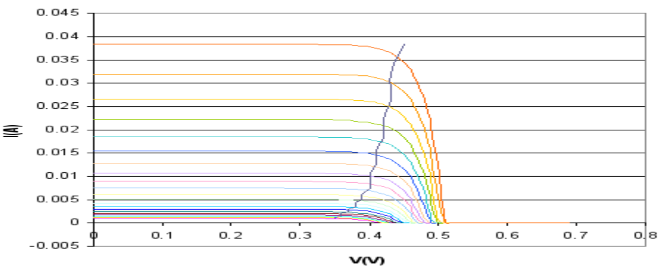

Fig 3. Solar cell I-V curve in varying sunlight

Maximum power point trackers utilize different types of control circuit or logic to search for this point and thus to allow the converter circuit to extract the maximum power available from a cell.

B. Block Diagram of Standalone PV System with MPPT

The maximum power tracking mechanism makes use of an algorithm and electronic circuitry[9,10]. The mechanism is based on the principle of impedance matching between load and PV module which is done by using a DC-DC converter. Using a DC-DC converter, the impedance is matched by changing the duty cycle d of the switch. Figure shows a simple system using MPPT.

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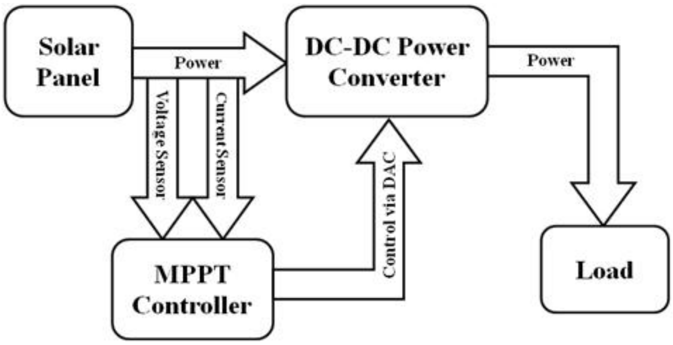

Fig 4. Block diagram of PV system with MPPT

C. Algorithm for MPPT

The incremental conductance method is used in this paper. In the incremental conductance method, the controller measures incremental changes in array current and voltage to predict the effect of a voltage change[11]. The incremental conductance method computes the maximum power point by comparison of the incremental conductance (I_{Δ} / V_{Δ}) to the array conductance (I / V). When these two are the same (I/V = I_{Δ} / V_{Δ}), the output voltage is the MPP voltage. The controller maintains this voltage until the irradiation changes and the process is repeated.

Figure shows that the slope of the P-V array power curve is zero at The MPP, increasing on the left of the MPP and decreasing on the Right hand side of the MPP[17]. The basic equations of this method are as follows. In the voltage source region,

$$\frac{\delta I_{PV}}{\delta V_{PV}} > -\frac{I_{PV}}{V_{PV}} \rightarrow d = d + \Delta d (\text{i.e., increment duty cycle})$$

In the current source region,

$$\frac{\delta I_{PV}}{\delta V_{PV}} < -\frac{I_{PV}}{V_{PV}} \rightarrow d = d - \Delta d (\text{i.e., decrement duty cycle})$$

At MPP,

$$\frac{\delta I_{PV}}{\delta V_{PV}} = -\frac{I_{PV}}{V_{PV}} \rightarrow d or \Delta d = 0 (\text{i.e., retain duty cycle})$$

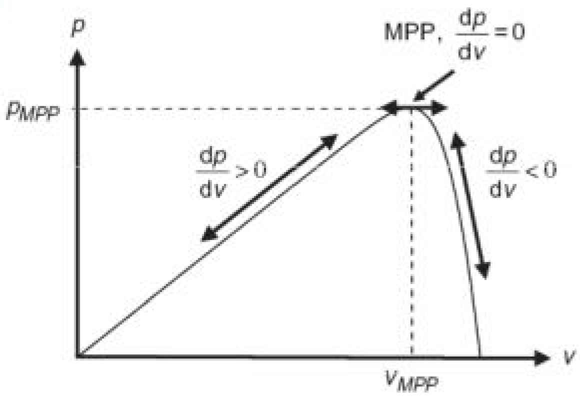

Figure 6. Incremental conductance MPPT method

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IV. Photovoltaic Pump System

A solar-powered pump is a normal pump with an electric DC motor[18]. Electricity for the motor is generated on-site through a solar panel which converts solar energy to direct-current (DC) electricity[12].

A. Components of Solar PV Water Pumping System

A solar photovoltaic (SPV) water pumping system consists of[13]:

1. *PV array:* The SPV water pumping system should be operated with a PV array capacity in the range of 200 Watts peak to 5000 Watts peak, measured under Standard Test Conditions (STC).
2. *Motor Pump Set:* The SPWPS may use any of the motor pump sets like surface mounted motor pump set, submersible motor pump set or floating motor pump set. The 'Motor Pump Set' should have a capacity in the range of 0.2HP to 5HP.
3. *Electronics:* Maximum Power Point Tracker (MPPT) should be included to optimally use the Solar panel and maximize the water discharge
4. *Mounting structures:* The solar panels should be tilted at an angle to horizontal to maximize power output[14].
5.

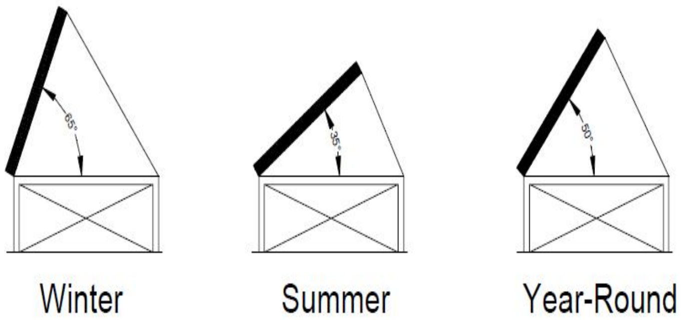

Figure 7. Tilt angles of solar panel

6. *Interconnect Cables and "On-Off" switch:* A good reliable switch suitable for DC / AC use is to be provided with the motor pump set.

B. Design of PV Powered DC Pump

If the amount of water to be pumped is not a parameter, then design of the PV powered DC pump system is very trivial[15]. One has to simply match the power and voltage rating of the pump and that of PV module. A simple block diagram of a PV pumping system is as shown in the figure.

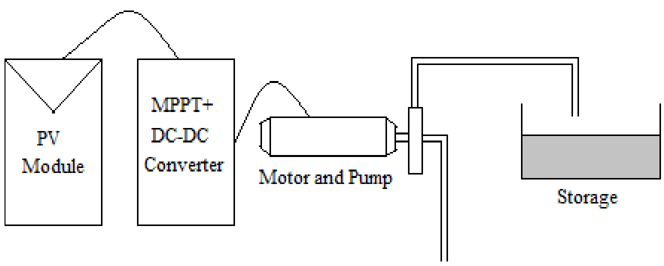

Figure 8. Possible configuration of DC water pump powered by PV modules

Basic terms associated with a pumping system:

Daily water requirement (litre per day or m^3 per day): The size and cost of the system depends on the amount of water required per day.

Total dynamic head [TDH] (m): It signifies the effective pressure at which the pump must operate. It primarily consists of two parameters, total vertical lift and total frictional losses. The total vertical lift is the sum of elevation, standing water level and draw down parameters.

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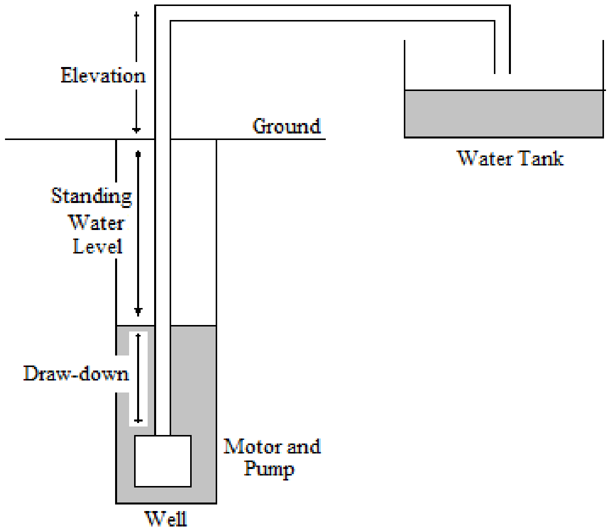

Figure 9. Typical PV water pumping system and its terminology

Frictional loss (equivalent m): Frictional loss is the pressure required to overcome friction in the pipes from the water pump outlet to the point of water discharge.

The overall design can be divided into 5 steps as given below

Step 1: Determine the amount of water required per day (as per the given specifications)
Step 2: Determine the total dynamic head (TDH) for water pumping
Step 3: Determine the hydraulic energy required per day (Wh/day).
Step 4: Determine the solar radiation available at the given location.
Step 5: Determine the size and number of solar PV modules required and motor rating.

V. SIMULATIONS AND RESULTS

The proposed PV system is simulated using the scheme as shown in the following figures

1. Simulations

1.1. PV Array Modelling

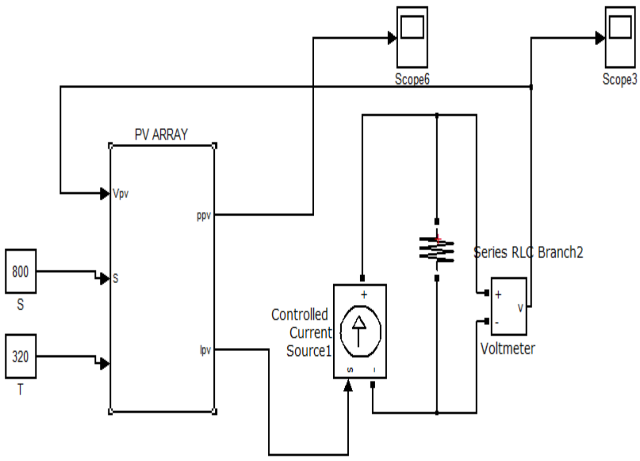

Figure 10. PV array modelling

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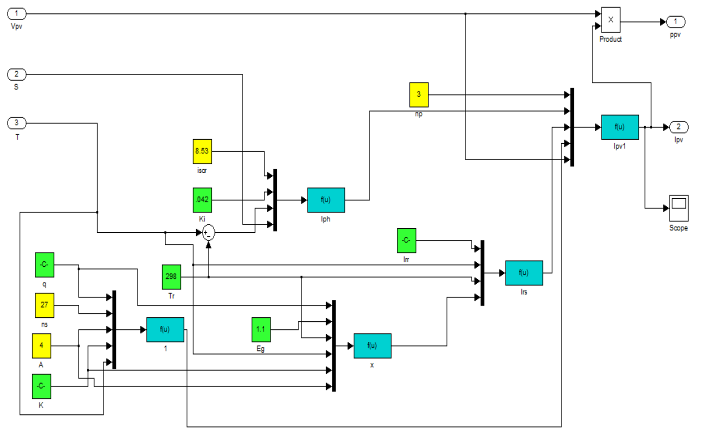

Figure 11. PV cell modelling

1.2.PV System with MPPT

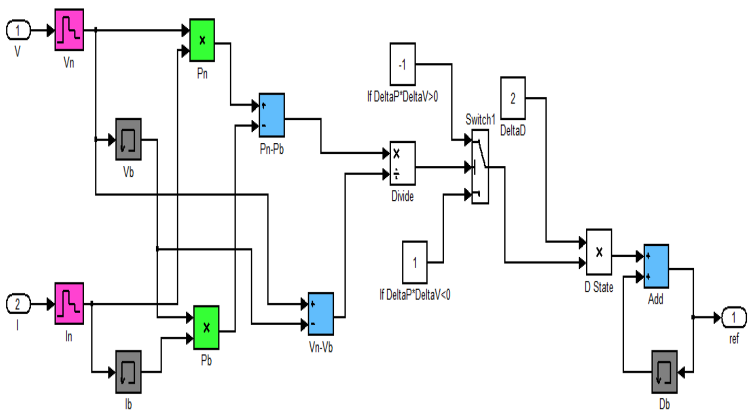

Figure 12. Implementation of incremantal conductance

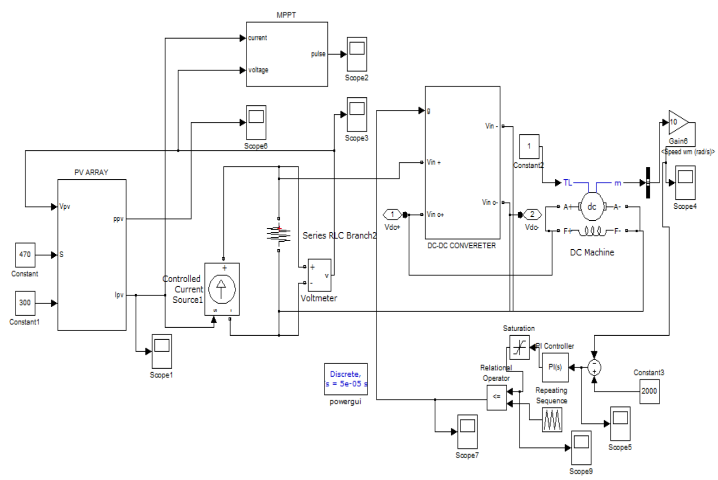

Figure 13. PV system with MPPT

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II. Results

1.3.Characteristics of PV panel

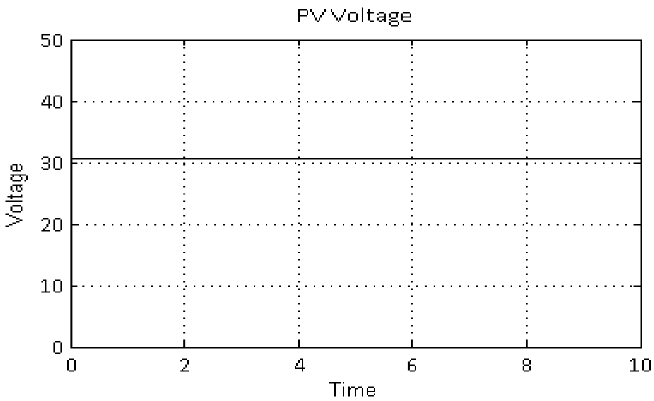

Figure 14. Output of PV panel

1.4.VI and PV characteristics

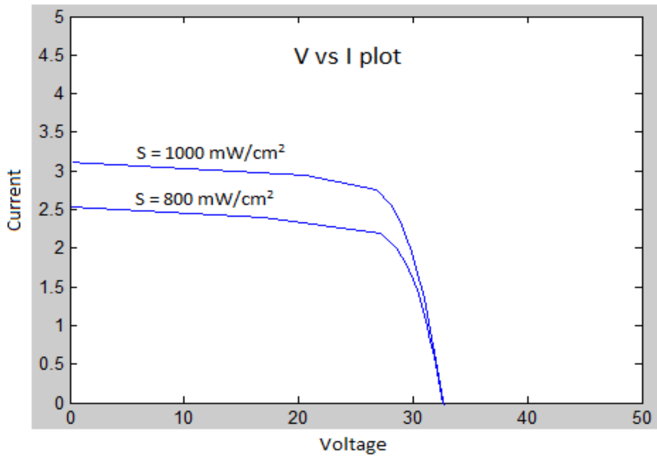

Figure 15. V-I characteristics of PV panel

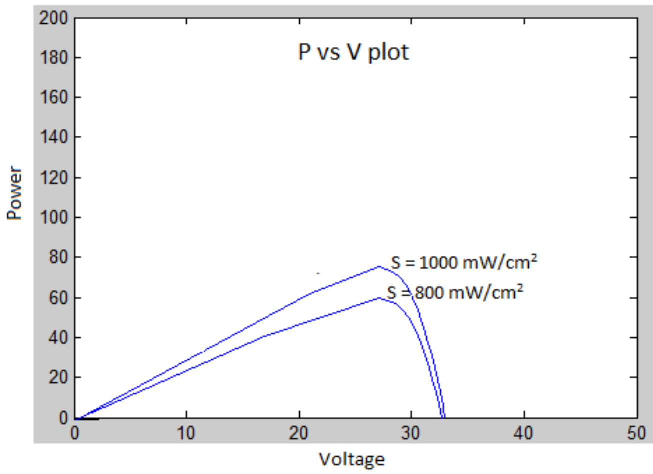

Figure 16. P-V characteristics of PV panel

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1.5.MPPT Output

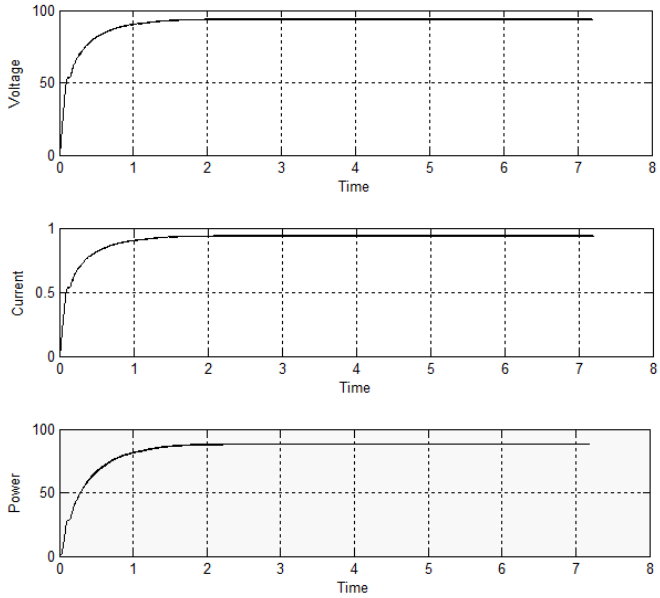

Figure 17. Output of MPPT algorithm

III. CONCLUSION

The advantages of using SPWPSs are identified:

i. SPWPSs have become commercially popular due to proper financing schemes by the government.
ii. The use of DC motor pump-set will improve the efficiency as it reduces the conversion losses.
iii. Effective heat sinks have been developed for extracting heat from SPWPSs.
iv. MPPT techniques are being used to improve the performance of SPWPSs during fluctuations in solar intensity.

The following major limitations of SPWPSs are identified[18]:

i. Dust accumulation over the solar photovoltaic panels can lose up to 30% of the energy output within a few weeks of installation.
ii. The ambient relative humidity and wind velocity will affect the performance of the SPWPS.

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