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Original Article

Design and Simulation of a DC Stabilization System for Solar Energy System

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Abstract: During the last few years, the demand for solar photovoltaic (PV) energy has grown remarkably since it provides electricity from an exhaustible and clean energy source. The generated power of solar panels depends on environment conditions, which changes continuously due to many factors, for example, the radiation, the characteristics of the load, etc. In order for the solar energy system operates at its most efficiency, it needs to work at its maximum power point (MPP). Previous literature has dealt with either investigating Maximum Power Point Tracking (MPPT) algorithms or tracking a steady output voltage from solar panels. However, when the load is changed, the new MPP need to be defined. In this paper, a novel adaptive MPPT system was proposed to investigate the MPP and keep tracking MPP at the same time. The proposed system was implemented in Proteus simulation. As the results, when the load is changing, the system obtained a steady and reliable desired output voltage. It is not only able to obtain a reliable steady DC output voltage but also keep the solar energy system work at its maximum efficiency.

Keywords: Solar panels, MPPT, MPP, stability, DC-DC converter.

1. Introduction

Renewable energy has been rapidly growing utilized to replace the conventional fossil fuel plants, which is a primary source of global warming and greenhouse gas emissions. Other than the problem of environmental issues, fossil fuels has been depleting due to unlimited exploitation of humans. Moreover, the rapid increase in the demand for electricity has led to a need for an alternative source of energy. Renewable energy such as solar energy, wind power, hydropower has been used increasingly due to its affordability, sustainability and environment friendliness [1]. The most challenging problems of renewable energy are based on its efficiency and manufacturing cost.

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Among these sources, solar energy has been paid attention and offers promising results in providing clean energy. Solar energy system is made of photovoltaic cells which convert solar irradiation to electricity. Solar energy has been more and more popular due to its advantages such as low maintenance cost, pollution and noise free [1].

However, the efficiency of the solar panel is low, only between 10% and 12% in converting sunlight to electricity [2, 3]. The efficiency of the solar panels depends on the amount of sunlight falling on the panels and the electrical characteristics of the load. As the amount of sunlight varies, the load characteristic that gives the highest power efficiency changes. The efficiency of the system is optimized when the load characteristic changes to keep the power transfer at highest efficiency. Moreover, each solar system has its own peak point of energy and normally, it may not need to operate at its maximum point. Hence, a constant effort of researchers have been made to utilize the sunlight energy to its best. That is why the concept of Maximum Power Point Tracking (MPPT) has been developed, to find the maximum point of the output power from the solar system and keep the load characteristic there.

In recent literature, there are two trends that researchers have been concentrated on. The first one is conducting algorithms to find the best maximum power point; the second is to mainly concern on the stability of the output voltage extracted from solar panel. Our paper proposed a novel adaptive MPPT system, which could process both tasks at the same time. The results showed that our proposed system could provide any desired steady DC voltage, while keeping the solar panel operate at its most efficiency. In our simulation, we set the output voltage as 12V and 24 V for example, as it is the standard DC power supply in the market.

Conventional MPPT techniques work by sensing the current and voltage from the solar panels while duty cycle signal from the MPPT operates on the maximum power point (MPP) as presented in Figure 1. In order to maximize the output power from solar system, it has to be operated at a unique point with specified load resistance. This requires a separate power converter for the MPPT. In our design, a boost DC-DC converter is used to match the load to the PV array to extract the maximum power. Regarding the algorithm for MPPT, there are three most common traditional techniques, which are Perturb and Observe (P&O) [4-7], Incremental Conductance (InC) [5, 8, 9], and Hill Climbing (HC) [10, 11]. The details on each algorithm will be discussed later.

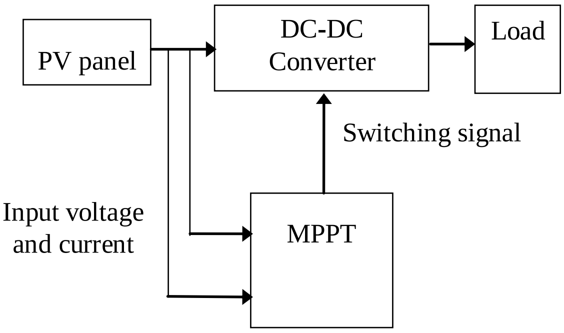

Figure 1. MPPT system block diagram.

In order to obtain a desired DC output voltage, in this research, we substitute a fixed load in Figure 1 by an adaptive load, which can output any desired voltage. In [12-15], a control law based on systematic state-space approach to keep the output voltage stable, which can be applied to solar energy system. In this paper, a simpler feedback is designed to obtain the desired output voltage as shown in Figure 2. Results confirmed our theory and will be illustrated in later section.

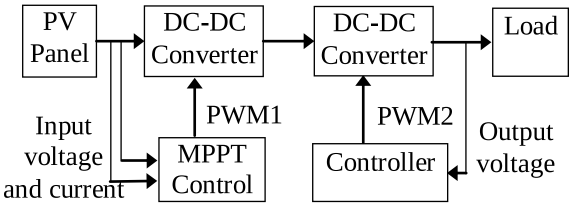

Figure 2. Design of the whole system.

The paper is organized as follow. Section 2 is the modelling and simulation of the PV panels. Section 3 is an overview on different traditional MPPT techniques. Section 4 presents the simulation's setup and results. Section 5 concludes the work.

2. Photovoltaic (PV) panels modelling and simulation

2.1. Modelling of the photovoltaic system

A practical model of a single solar cell can be modelled in Figure 3.

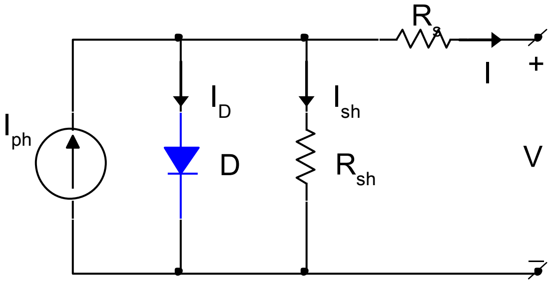

Figure 3. Modeling of the solar cell.

The solar cells can be connected in series or parallel due to its application's requirements. The interconnected solar cells are known as PV array. In this figure, R_s represents series resistance of pn junction cell and R_{sh} is the parallel resistance. I_D and I_{sh} are diode current and shunt leakage current, respectively. Applying the Kirchhoff's Current Law (KCL) in the equivalent circuit of solar cell, the total output current can be calculated as:

$$\boldsymbol{I = I_{ph} - (I_D + I_{sh})} \qquad (1)$$

If we let $I_o = I_D + I_{sh}$, is the solar cell reversed saturation current, which is calculated in [16]

$$I_o = I_{rs}\left(\frac{T}{T_{ref}}\right)^3 \exp\left[\left(\frac{qE_{go}}{AK}\right)\left(\frac{\Delta T}{T_{ref}T}\right)\right] \qquad (2)$$

where I_{rs} is the reserve saturation current of each cell for the nominal temperature and irradiance values and E_{go} is the band gap energy of semiconductor materials.

The photo current I_{ph} is generated on absorption of solar radiation by solar cell, hence it is directly related to variation in solar irradiance and temperature [17].

$$I_{ph} = (I_{scr} + k_i\Delta T)\frac{G}{G_r} \qquad (3)$$

Where in this equation, I_{scr} is the rated solar current at nominal weather conditions (temperature is at 25°C and solar irradiance is 1000W/m^2), k_i is the short circuit temperature coefficient. G is solar irradiance in W/m^2, and G_r is nominal irradiance in normal weather conditions. ΔT equals to $T - T_{ref}$, the difference between operating and nominal temperature.

The output current of the cell is given, according to [18]

$$I = I_{ph} - I_s\left[\exp\left(\frac{q(V+IR_S)}{kT_cA}\right) - 1\right] - \frac{V+IR_S}{R_{sh}} \qquad (4)$$

Where I and V are the current and voltage of the photovoltaic panel, respectively.

$I_{ph} = N_p I_{ph,cell}$ is the photo-generated current in the PV module consisting of N_p cells connected in parallel, $I_{ph,cell}$ is the current generated of each cell.

$I_s = N_p I_{s,cell}$ is the reverse saturation current of the PV module consisting of N_p cells connected in parallel, $I_{s,cell}$ is the reverse saturation current of each cell.

k is the Boltzmann's constant, $k = 1.38 \times 10^{-23} J/K$

q is the electronic charge, $q = 1.602 \times 10^{-19} C$

T_c is the temperature of the array in Kelvin

A is the ideality factor of the diode, $A = 1.0{\sim}1.5$

R_S is the equivalent series resistance of the PV array

R_{sh} is the equivalent parallel resistance of the PV array

2.2. Simulation of the photovoltaic system

a. Dependence of the output power on environment temperature

In this section, we will investigate how the output power from the photovoltaic array changes according to environment temperatures. According the above equations, when temperature increases, the output current from the solar panel will increase, then the power increases. In our simulation, when the series resistance R_S and the parallel resistance R_{sh} are set to 0.38Ω and 153.56 Ω, respectively, the photo-generated current I_{ph} is 3.81A.

The changes in the output power according to environment temperature are illustrated in Figure 4. When the temperature is set to 25°C, the maximum output power obtained is approximately 60W. When the outside temperature increases to 50°C, other factors are kept constant, the maximum output power extracted from the solar panel increases up to 65W.

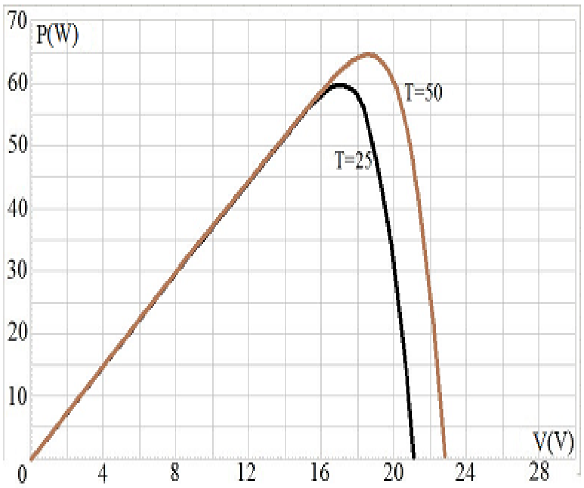

Figure 4. Output power changes according to environment temperatures.

b. Dependence of the output power on the photo-generated current

The dependence of the power on the photo-generated current I_{ph} is given in Figure 5. When the photo-generated current increases from 4.5A to 5A, the power increases from approximately 71W to 79W.

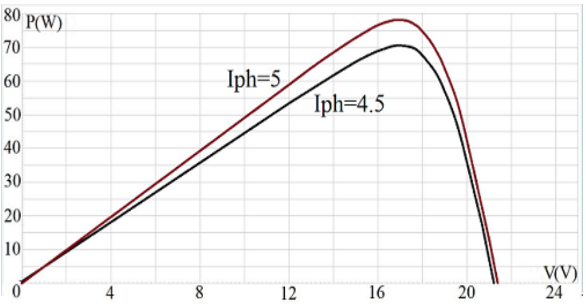

Figure 5. Output power changes according to Iph.

3. Maximum Power Point Tracking algorithms

The maximum power is generated by the solar panel at a point of the I-V characteristic where the product of voltage and current is maximum. This point is called the MPP. The role of the MPP is to ensure the operation of the PV module at its MPP, extracting the maximum available power. If there is a good irradiance condition, the photovoltaic system can generate maximum power efficiently while an effective MPPT algorithm is used. In recent literature, there are three traditional MPPT algorithms: Perturb and Observe, Incremental Conductance, Hill Climbing. The details on each algorithm are given as follow:

3.1. Perturb and Observe

The P&O algorithm locates the MPP by relating changes in the power generated from the array to changes in the control variable used to control the array. The MPPT technique works by sensing the current output power at time t and determining to increase or decrease the power according to the sensed power at $t+1$. If the sensed power at $t+1$ is greater than at t, then the new output power is updated as the value at the point $t+1$. Based on the characteristic of PV array power curve in Figure 6, on the left of the MPP, by incrementing the voltage, the power increases. On the right of the MPP, power decreases when voltage increases. Therefore, if there is an increase in power while the voltage is increasing, we keep increasing the voltage. The perturbation extends itself in the same orientation as long as the power increases. When the maximum power is reached, at the next instant of time, the power decreases progressively and the direction is reversed. If the voltage is increasing and the power is decreasing, we need to decrease the voltage. After each iteration, the value of the voltage is updated. The process is repeated periodically until the MPP is reached. Or in other words, if the current MPP is in the left-hand side, the system moves the next MPP to the right. Otherwise, if the MPP is on the right-hand side, the system makes the MPP move to the left until it reaches the maximum. The system then oscillates around the MPP. The relations are given as below:

$\frac{dP}{dV} = 0$ at MPP

$\frac{dP}{dV} > 0$ at the left of MPP

$\frac{dP}{dV} < 0$ at the right of MPP

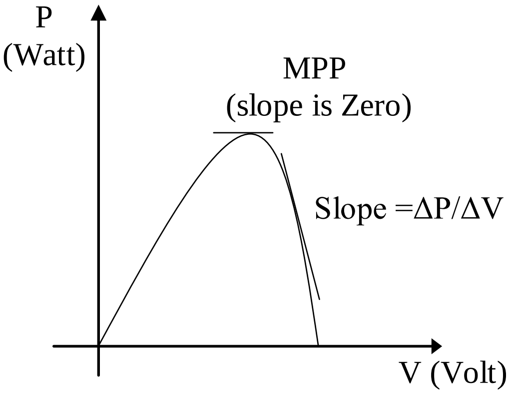

Figure 6. Characteristic of the PV Array Power Curve.

The advantage of this algorithm is simple and easy implementation; hence it is one of widest applied MPPT methods in practice [19] [20]. However, the algorithms only oscillate about the MPP but does not coincide to the point [21], and this problem is more realized under non-uniform condition. Moreover, the P&O algorithm works well only on the linear region of the voltage. Due to many other factors effect on the circuit, such as non-ideal capacitor, the voltage does not necessarily to be linear over time. When there is an instantaneous drop in the voltage, the P&O algorithm cannot track well.

3.2. Incremental conductance

This method exploits the fact that the slope of the PV curve is equal to zero at the MPP, greater than zero for operating points on its left and smaller than zero for points on its right [22] [23]. The derivative of the power with respect to the voltage can be written as following:

$$\frac{dP}{dV} = \frac{d(V.I)}{dV} = I + V.dI/dV \qquad (5)$$

Using the aforementioned facts, we have the following conditions:

$\frac{dI}{dV} > -\frac{I}{V}$ at MPP's left

$\frac{dI}{dV} = -I/V$ at MPP

$\frac{dI}{dV} < -\frac{I}{V}$ at MPP's right

At each iteration, the InC algorithm compares the incremental conductance (dI/dV) with the instantaneous conductance (I/V) and the voltage is updated. This algorithm overcomes the shortcomes of P&O algorithm. This has been proved in several papers [24, 25].

3.3. Hill climbing

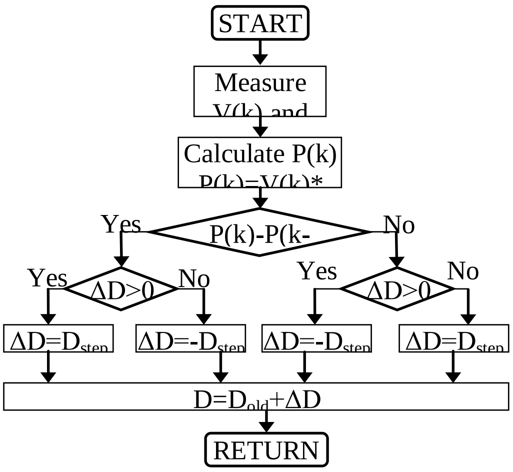

Figure 7. Flow chart of the HC algorithm for MPPT.

In this paper, we choose to implement Hill Climbing algorithm for tracking the maximum power point. The HC algorithm works in a similar way with the P&O, but instead of updating the value of the voltage every iteration, we update the duty cycle. Since in most applications, the maximum power point tracker is achieved by connecting a DC-DC converter between the PV array and load, the duty cycle can be directly controlled to reduce the system complexity.

The algorithm's flow chart is given in Figure 7. Since the HC keeps updating the duty cycle, it is able to track the power when the voltage is oscillating. Then, the extracted maximum power from the solar panels is robust and more stable.

4. Design and Simulation

The outputs (current and voltage) from solar panel are fed into a boost converter. In this stage, the HC algorithm is employed to extract the maximum power. Table 1 shows the selected specification for the output. The input voltage and voltage power are 17V and 60W, respectively (as shown in Figure 4). In this design, the desired output voltages are set to be 12V and 24V, as they are standard DC power supplies.

Table 1. Output specification

Input voltage (max voltage of PV)	17V
Maximum power from PV	60W
Output voltage	12V, 24V
Maximum power	30W
Output voltage ripples	5%

As shown in Figure 2, the load of this stage is adaptive, which includes another DC-DC converter, a fix load and a controller. This second stage can track the output according to a reference voltage, which guarantees a fix, steady and reliable output voltage.

4.1. Design of a proposed DC-DC converter

As mentioned before, the output of the MPPT stage is connected with an adaptive load instead of a fix load. This adaptive load includes a buck converter, a fix load and a controller. The final output will be a stable desired voltage at a specific value.

Assumed the buck converter is ideal, $V_o = DV_i$. The control law is designed as in Figure 8, where V_o is the output voltage, V_{ref} is the desired output voltage. D and D_{old} is the current and previous duty cycle, respectively, D_{step} is the step of the duty cycle. At each instant time, we measured the output V_o. If $V_o > V_{ref}$ then we update the current duty cycle D as the previous duty cycle D_{old} plus a step D_{step}, and vice versa. The process continues until a desired output voltage is reached.

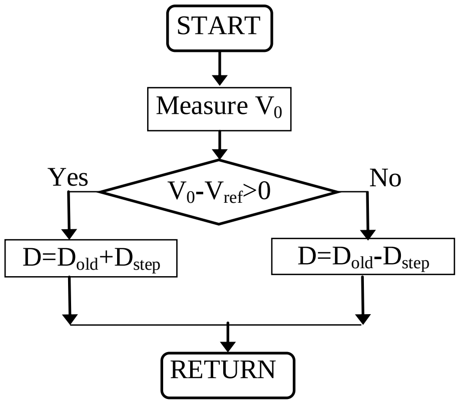

Figure 8. Flow chart of the control feedback law.

4.2. Design and simulation of whole system

We simulated the whole system in Proteus. The circuit diagram is given in Figure 9

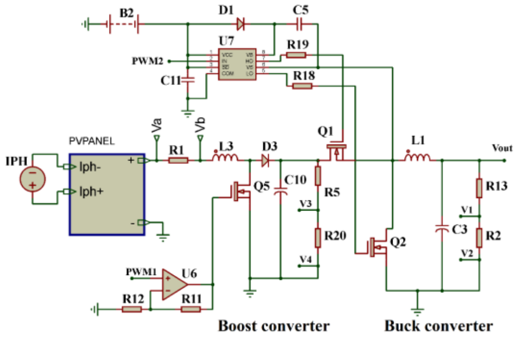

Figure 9. Schematic diagram of simulation circuit.

4.3. Simulation results

Considering a solar power system without any MPPT block, when the environment temperature is set at t = 25^{o}C, the photo-generated current in the PV module I_{ph}= 3.8128, the ideality factor A = 0.9784, the equivalent parallel resistance R_{sh}= 153.5644, the equivalent series resistance R_s= 0.38572, the output power is recorded as in Figure 4, with the maximum power is approximately 60W. When connecting the MPPT block, the circuit can be able to extract the peak power of 60W then oscillate slightly around that point, which is illustrated in Figure 10.

While the circuit works at its MPP, an adaptive load allows us to track the output voltage according to a reference. In this part, a simple control law is implemented. The instantaneous output voltage is sensed and compared with a predefined reference one. Then a feedback law is designed to allow the output voltage track along the reference. The reference is set to be 12V and 24V.

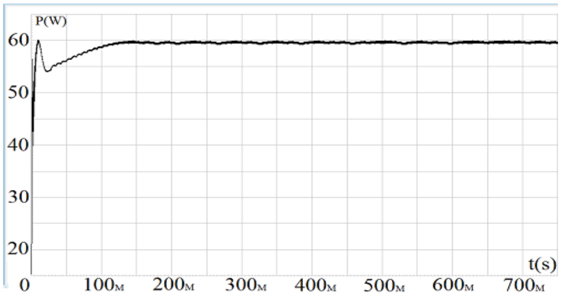

Figure 10. Maximum power extracted from simulation.

The results are presented in Figure 11. After about 500ms, it is able to track well the reference voltage. When the load is changed from 8**Ω** to 15 **Ω**, the system is still able to track the reference well. The ripple is approximately 210mV when the output voltage is 12V. When output voltage is 24V, the ripple is approximately 410mV. The ripples in both cases are smaller than 5%, which is within the limit of the design.

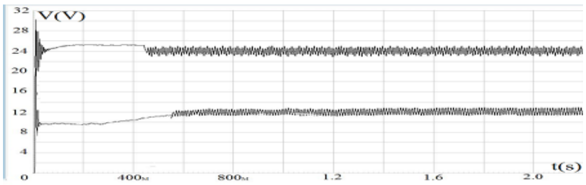

Figure 11. 12V-24V DC output voltage.

5. Conclusion

The paper has successfully investigated, modeled and simulated the whole PV panel system in Proteus, which can both work at its most efficiency and provide a desired steady output. The output power from the solar panel is extracted through a converter and is kept at its maximum power point via the control algorithm. This most efficient output power from the solar panel is fed into another converter to get a desired output voltage. The ripple size of the output voltage is smaller than 5%. For future research, the MPPT algorithm can be improved using more modern techniques, which includes optimization algorithms in order to get more robust and stable results. The output voltage may take less time to the steady state by using more efficient control law.

Acknowledgments

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