Photovoltaic powered DC-DC boost converter based on PID controller for battery charging system

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Abstract: The input voltage of battery charging system is always above the battery nominal voltage and it should be remained constant. But it depends on the type of input voltage sources. A battery charged directly by photovoltaic (PV) module as the input voltage source can cause the output voltage of PV module or the input voltage of battery charging system can fluctuate, because the output voltage of PV module depends on the solar irradiance. This problem can be solved by installing DC-DC boost converter between the PV module and battery. This paper presents a DC-DC boost converter based on PID controller for battery charging system. It is designed for the input voltage of 12V and output voltage of 14.7V system because it is applied to charge a 12 V, 7 Ah lead acid battery. Based on the simulation result of battery charging system shows that the output voltage of DC-DC boost converter can be remain around 14.7 V. It is due to the PID controller can damp the voltage oscillation and remain its steady state voltage. The time needed by the DC-DC boost converter to charge the battery in the fully charging condition is 1 hour: 3 minutes: 37seconds.

1. Introduction

The heat radiation produced by the sun is classified into two layers. They are inner and outer layer heat radiation. The heat radiation of inner layer is hotter than the heat radiation of outer layer. The heat radiation contents the power density that it can be called solar irradiance in W/m² and energy density that it can be called solar irradiation in Wh/m². The solar irradiation goes to atmosphere and arrives the surface of the earth and it can be converted to be the other energy [1].

The solar irradiance is converted to be the electrical energy by a photovoltaic (PV) module. It generates direct current (DC) electrical energy. The level of voltage, current and power of PV module depend on the solar irradiance which arrives on its surface and also depends on the temperature. The voltage, current and power of PV module increase by the increasing of solar irradiance. Inversely, they decrease by the increasing of temperature [2]. In this case, it is not suitable to be applied directly to charge a battery. A DC-DC boost converter is suitable to be installed between PV module and the battery.

Some types of DC-DC converter (buck, boost, Cuk, SEPIC and Zeta converter) are implemented by [3] using SIMULINK MATLAB. Each component of inductor and capacitor is connected to a resistor. I causes loses or dissipated power, thus the efficiency of DC-DC converter reduce. The DC-DC converter is open loop system, it means there is no a feedback controller which control the output voltage of the DC-DC converter.
A DC-DC boost converter is developed by [4] for a school experimental system. A mathematical modelling is introduced to calculate the value of inductance of inductor and capacitance of capacitor. The circuit uses MSOFET, but it only use function generator to generate pulse wave and drive the gate of MOSFET. It is classified in the open loop system.

This paper presents a DC-DC boost converter with PV module as its DC main voltage source and it is applied for charging a battery. The output voltage of DC-DC boost converter is remained in constant value, thus a PID controller is applied as a feedback control system.

2. Methodology

A modelling of photovoltaic powered DC-DC boost converter for charging system is presented in this section. It consists of PV module, DC-DC boost converter controlled by PID controller and battery as shown in block diagram of Figure 1. The DC-DC boost converter is modelled to charge a 12 V, 7 Ah leadacidbatterywithmainDCvoltagesourcefroma12V,3WDIYpolycrystallinesiliconPVmodule.

![Figure 1. Block diagram of PV powered DC-DC boost converter](image)

**Modelling of PV module**

A 3 W, 12 V PV module with the data sheet at Standard Test Condition (STC) as shown in Table 1 is applied in the DC-DC boost converter system. The application of PV module is due to its output voltage at maximum power is boosted above 12 V and it is suitable to charge the 12 V battery.

SIMULINK MATLAB software is applied for simulating the curve of power versus voltage (P-V curve) and the curve of current versus voltage (I-V curve) of 3W, 12V PV module. The simulation results on the STC are compared to data sheet of 3 W, 12 V PV module using percentage error, $e$. The simulation results are acceptable and applicable if the error percentage range of $\pm 10\%$[5].

| Parameters                  | Value  |
|-----------------------------|--------|
| Maximum power, $P_{\text{max}}$ (watt) | 3      |
| Voltage at $P_{\text{max}}$ (volt)    | 12     |
| Current at $P_{\text{max}}$ (ampere)  | 0.25   |
| Open circuit voltage, $V_o$ (volt)   | 13.2   |
| Short circuit current, $I_{\text{sc}}$(ampere) | 0.3    |

**DC-DC boost converter**

Figure 2 shows a DC-DC boost converter, it is designed for the source voltage, $V_s$ of 12 V, the output voltage, $V_o$ of 14.7 V, output power, $P_o$ of 100 W with the efficiency, $\eta$ and system frequency, $f_s$ are $100\%$ and 25 kHz, respectively. The inductance of inductor, $L$ and capacitance of capacitor, $C$ should be calculated to fulfill the required condition following the equation (1) to (5) [6]–[8].
The duty ratio, \( D \) of the DC-DC boost converter is given by equation (1)

\[
D = 1 - \left( \frac{V_s}{V_o} \right) \eta
\]  

The inductance of inductor, \( L \) is given by equation (2).

\[
L \geq \frac{V_s \text{ (min)} \times D}{f_s \times I_L}
\]  

\( \Delta I_L \) is current ripple, it is 20\% to 40\% of inductor current. In this case, it is supposed by 30\% of the inductor current.

The DC-DC converter is designed for the efficiency, \( \eta \) of 100\%. It means that the input power, \( P_s \) is equal to the output power, \( P_o \). The inductor current, \( I_L \) is also equal to the source current, \( I_s \) when the MOSFET is in the condition ON. Their relationship is given by equation 3.

\[
P_o = I_s \times V_s - I_o \times V_o
\]  

The capacitance value of capacitor, \( C \) is given by equation (4).

\[
C = \frac{I_o \text{ (min)} \times D}{f_s \times V_C}
\]  

\( \Delta V_C \) is voltage ripple, it is 0.1\% to 5\% of capacitor voltage. In this case, it is supposed by 0.1\% of the capacitor voltage. It is due to the capacitor and resistor load are connected together in parallel, thus the capacitor voltage, \( V_C \) is equal to the output voltage, \( V_o \).

The output power, \( P_o \) is a maximum power and it can be achieved for the suitable resistance value, \( R \) following the equation (5).

\[
R = \frac{V_o^2}{P_o}
\]  

**PID controller**

The application of PID controller on the DC-DC converter is to control or maintain the output voltage, \( V_o \). Figure 3 shows a block diagram of transfer function of PID controller supposed in the DC-DC converter. The signal of output voltage, \( V_o \) multiplied by gain of 1/14.7 is a sinput signal is compared or added to the reference voltage, \( V_{reff} \). Its result is as input signal of PID controller block and output signal of PID controller block goes to pulse wave generator to drive the gate of MOSFET. The S-
domain function of PID controller is given by equation (6)[9].

\[
\begin{align*}
V_{in} &= 1 \\
\frac{V_o}{V_i} &= \frac{1}{S-1} + \frac{1}{S} + \frac{N}{1 + NT}
\end{align*}
\]

\[\text{PID controller} = K_p + K_i \frac{1}{S-1} + K_d \frac{N}{1 + NT} \frac{1}{S-1} \quad (6)\]

Where \(K_p, K_i\) and \(K_d\) are constant of proportional, integral and derivative, respectively. \(T_s\) is S-domain time and \(N\) is filter coefficient.

\section*{Modelling of photovoltaic powered DC-DC converter based on PID controller}

The photovoltaic powered DC-DC converter based on PID controller is modelled using SIMULINK MATLAB for battery charging system as shown in Figure 4. The modeling consists of four blocks, they are block of PV module, DC-DC converter, PID controller and battery.

The block of PV module is constructed by SIMULINK block of PV module by filling its electrical parameters following Table 1. The performance of PV module depends on the solar irradiance and temperature as shown on the left side of PV module. They can be varied following the real weather condition. The PV module modelling is tested at STC to validate it by clicking the plot button of block parameters of PV module. The PV module has a voltage at maximum power of 12 V. A resistor of 48 Ω has to be connected to the output terminal of PV module to achieve the voltage at maximum power of 12 V. A controlled voltage source has to be also connected to the output voltage measurement to be the PV module as DC voltage source of 12 V.

The block of DC-DC converter is constructed based on the circuit of DC-DC converter as shown in Figure 2. It is designed for the PV module input voltage, \(V_s\) of 12 V, the output voltage, \(V_o\) of 14.7 V and the output power, \(P_o\) of 100 W. The choice of output voltage, \(V_o\) of 14.7 V is due to that the voltage is suitable for the cycle of charging voltage (4.5 V to 5.0 V). The values of inductance of inductor, \(L\) and capacitance of capacitor, \(C\) are calculated following the equation (1) to (4) to achieve the output voltage, \(V_o\) of 14.7 V and the output power, \(P_o\) of 100 W.

The block of PID controller is constructed following Figure 3. The S-domain function as shown in the equation (6) is the main function of PID controller. The values of \(K_p, K_i\) and \(K_d\) are filled in the block parameters of discrete PID controller. The signal input of PID controller is the subtraction result of reference voltage and output voltage and signal output of PID controller goes to the signal input of PWM generator.

The block of battery is constructed by SIMULINK block of battery. The type of battery is 12 V, 7 Ah lead acid battery. The battery is as load of DC-DC boost converter and connected to capacitor in parallel connection. The values of state of charge (SOC), battery current and battery voltage are observed using display and scope block.
3. Results and Discussion

Results and discussion related to the photovoltaic powered DC-DC boost converter based on PID controller for battery charging system are presented in this section. Firstly, the results of PV module performances for the curve of current against voltage and curve of power against voltage are discussed to validate the simulation result and data sheet of 3 W, 12 V PV module. The design of DC-DC boost converter for input voltage, $V_s$ of 12 V, output voltage, $V_o$ of 14.7 V and output power, $P_o$ of 100W is implemented using SIMULINK MATLAB for with and without battery connection. They are observed and analysed based on the waveform of PV module voltage, inductance current, output current, output voltage, output power and battery performance (state of charge, battery current and battery voltage).

Validation of PV module

3W, 12V PV module is modelled, simulated and validated following its datasheet. An error percentage is applied in the validation and it is as indicator that the PV module modelling can be implemented as DC voltage source of the DC-DC boost converter. Figure 5 and Figure 6 show the curve of current against voltage and power against voltage, respectively at the standard test condition (STC) of 1000 W/m² and 25°C. The simulation results and data sheet of PV module are validated for the open circuit, $V_{oc}$, short circuit current, $I_{sc}$ and maximum power, $P_{max}$ as shown in Table 2.
Table 2. Validation of 3 W, 12 V PV module

| Parameters          | Data sheet | Simulation | Error percentage |
|---------------------|------------|------------|------------------|
| Maximum power, $P_{max}$ | 3 W        | 3.116 W    | 3.87 %           |
| Open circuit voltage, $V_o$  | 13.2 V     | 12.88 V    | 2.42 %           |
| Short circuit current, $I_{sc}$ | 0.3 A      | 0.3 A      | 0.00 %           |

Table 2 shows that the datasheet and simulation result of maximum power are 3W and 3.116 W, respectively. It means that the error percentage of maximum power is 3.87 %. The error percentage of open circuit voltage is 2.42 % for open circuit voltage data sheet of 13.2 V and open circuit voltage simulation result of 12.88 V. A very perfect error percentage of 0.00 % is achieved for the short circuit current. It means that they has same value of short circuit current of 0.3 A. It can be analyzed that the all error percentage in the range ± 10 %. It indicates that the PV module modelling is acceptable and applicable in the DC-DC boost converter.

Performance of DC-DC boost converter on the maximum load power

The 12V to 14.7V DC-DC boost converter is designed for the efficiency of 100% and the output power of 100 W. It means that the output power equals the input power. The output current is 6.8 A following the equation (3). The inductance of inductor of 34.6 µH and capacitance of capacitor of 3330 µF are achieved for the current ripple is 30% of the inductor current, the capacitance voltage ripple is 0.1% of the capacitor voltage and the duty ratio is 0.18 following the equation (1) to (4). The output power of 100 W is also achieved for the resistance load of 2.16 Ω following the equation (5). The all parameters of DC-DC converter are filled into the simulation circuit in Figure 4. It is simulated, observed and analyzed for the performance of DC-DC converter in the condition that its output terminal is connected to the resistor of 2.16 Ω or it is not connected to a battery as shown in Figure 7 to Figure11.
module. It indicates that the model occurs a transient voltage condition in a momentary time, but it can reach fast in a steady state voltage condition of 12.22 V for long time. The voltage drops from 12.88 V on the open circuit voltage condition of PV module (refer to Figure 5) to be 12.22V. The voltage of PV module drops around 0.66V. The PV module voltage of 12.22 is still in required voltage value in the design of DC-DC boost converter.

![Figure 8](image1.png)  
**Figure 8.** Induction current on the maximum load power

![Figure 9](image2.png)  
**Figure 9.** Output current on the maximum load power

The transient condition is reflected also by the inductance current and output current as shown in Figure 8 and Figure 9, respectively. They oscillate in negative and positive current values for the momentary time. The transient condition is caused by the components of capacitor for charge and discharge condition and inductor as energy storage and also affected by the MOSFET switching which is driven by the pulse generator. This condition can be controlled by PID controller to reach the all steady state parameter values.

The simulation result of steady state induction current and output current are 8.547 A and 6.807 A as shown in Figure 8 and Figure 9, respectively. They are almost same if the induction current of 8.33A and load current of 6.8A are calculated by the equation (3). If the steady state inductance current is compared to the calculation induction current and the steady state output current is compared to the calculation output current, thus they have induction current error percentage, $e$ of 2.61% and output current error percentage, $e$ of 0.10%. They indicate that the simulation results are acceptable and applicable.
The DC-DC boost converter is designed for the output voltage of 14.7 V at the maximum load power of 100 W. The output voltage of 14.69 V and output power of 100.1 W are achieved in the simulation results as shown in Figure 10 and Figure 11, respectively. They do voltage and power oscillation before they reach their steady state values. If they are compared to the designed values, thus the output voltage has an error percentage, $e$ of 0.068% and output power has an error percentage, $e$ of 0.1%. They also indicate that the simulation results are acceptable and applicable for battery charging system.

**DC-DC boost converter for battery charging system**

A 12 V, 7 Ah lead acid battery is connected to the output terminal of DC-DC boost converter by removing the resistance load of 2.16 Ω. In this condition, the battery is charged for the initial state of charge (SOC) of 25% (11.85 V) and fully charged condition is 13.06 V [10]. The modelling of PV powered DC-DC boost converter based on PID controller is run for 1 second in condition of battery charging to observe and analyze the voltage of PV module as shown in Figure 12, output voltage as shown in Figure 13, output current as shown in Figure 14 and battery voltage, current, SOC as shown in Figure 15.

The voltage of PV module has a voltage oscillation or transient condition at the initial time. Its maximum and minimum peak voltage are in the range of nominal voltage of PV module. It is due to the effect of capacitor charging and discharging that it is done by the MOSFET is been driving by pulse generator. But this condition can be stabilized by the PID controller, thus a new steady state PV module voltage of 11.99V can be achieved at 0.0000005s as shown in Figure 12(b). If it is compared to the open circuit voltage of PV module of 12.88 V as shown in Figure 5 and the voltage of PV module loaded maximum load power of 12.22 as shown in Figure 7 shows that the voltage of PV module with DC-DC boost converter connected to the battery has voltage drops around 0.23 V and 0.89 V compared to the PV module with DC-DC boost converter connected to the maximum load power and open circuit condition, respectively. But the voltage value is still tolerated limitation to serve the DC-DC boost converter connected to the battery charging system.
The output of DC-DC boost converter is observed in term of output voltage as shown in Figure 13 and output current as shown in Figure 14 in the condition of battery charging connection. The output voltage and current occur transient condition at the initial time, but they can be stabled back in their steady state values because the PID controller works well. The output voltage can maintain in the output voltage level of 14.71V. It is fulfill the required output voltage in the design of DC-DC boost converter. It also indicates that the DC-DC boost converter has good performance when it is connected to the battery charging system.

The battery connected to the output terminal of DC-DC converter is as its DC load. When the output voltage of 14.7V is controlled in the constant value, thus the output current depends on the loads connected to the output terminal of DC-DC converter. The battery has internal resistance of 0.47Ω and it represents load when the battery connected to the output terminal of DC-DC converter. The output current of 31.56 A as shown in Figure 14 is equal to the current flows through the battery.

The battery voltage, current and SOC are shown in Figure15. Normally, the output voltage of DC-DC converter is equal to the battery voltage of 14.7 V. It is a very good constant maintained value although the battery is loaded. It is also the output current is equal to the battery current of -31.49 A, only the negative value of battery current reading as shown in Figure 15 indicates that the battery is in
charging condition. The battery starts to be charged in the SOC of 25% (11.85 V) and in the charging time of 1 second shows that the SOC reaches 25.13%. It means that the battery charging process needs 1 second to increase the SOC by 0.13%. It is due to the range of 75% for the SOC of 25% to 100%, thus the charging time needed by battery to be fully charging condition is 577 seconds or 1 hour: 3 minutes.

![Battery Voltage, Current and State of Charge (SOC)](image)

Figure 15. Battery voltage, current and state of charge (SOC)

4. Conclusion

A DC-DC boost converter has been designed for the input voltage of 12V and the output voltage of 14.7V for serving the maximum load power of 100W. Some statements are concluded following below. The inductance and output current are 8.33A and 6.8A, respectively for the condition of maximum load power and assuming the efficiency of DC-DC boost converter of 100%. It gives the suitable values of inductor and capacitor are 34.6 µH and 3330 µF, respectively. The DC-DC boost converter is a closed loop system with PID controller as a feedback controller and it is operated by PV module. The function of PID controller is to damp the oscillation of PV module voltage waveform, the waveform of inductance current, and output voltage and output current. Lastly, it is to achieve steady state condition of all required electrical parameters. The main objective of DC-DC boost converter based on PID controller is to charge 12 V, 7 Ah battery. The battery charging voltage can be remained in 14.7 V. When the starting charging time the SOC of 25%, it can increase the SOC of 0.13%, thus the time needed to be in fully charging condition is 1 hour: 3 minutes: 37 seconds.

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