

Fixed Output Voltage for Solar Cells Based on Buck Converter

Ahmed Mohamed Bakir

Misurata University, Faculty of Engineering, Electrical and
Electronic Engineering Department
Misurata, Libya.
ahmed.bakir@ucdenver.edu

Ahmed Abdulhamid Baaiu

Misurata University, Faculty of Engineering, Electrical and
Electronic Engineering Department
Misurata, Libya.
ahmed.baaiu@eng.misuratau.edu.ly

Abstract— In order to overcome the shortcomings such as extended time and high cost of using solar cells to experiment, this paper successfully used a DC power supply and a variable resistor to simulate the solar cells output characteristic curves. Operating principles, equivalent circuits, and illustrative example in terms of computer simulation are presented in order to validate the approach. This paper deals the design of DC/DC converter which can make voltage maintained at a specified value. MATLAB simulation for Open-loop and Closed-loop controlled Buck converter for the solar cells is discussed and the results are presented.

Index Terms: Solar cells, Voltage control, Buck converter, DC/DC converter, Open & closed loop control.

I. INTRODUCTION

Recently, Dc–Dc converters are widely used to interface the dc output of renewable energy resources with power distribution systems in order to facilitate the use of energy at the customer side [1]. The progressively growing interest in the applications of Renewable Energy Sources (RES), with all the related problems of their optimal exploitation, has increased the need of experimental equipment to carry out measurements and tests, without the direct use of the renewable source. As a matter of fact, to investigate the behavior of a photovoltaic generator (PV), a wide outer surface is needed. Since the produced energy depends on solar irradiance and temperature; moreover the weather conditions are not always reproducible. Solar energy becomes more and more people's attention as a kind of green energy with no pollution, no noise and inexhaustibility [2, 3, 4, 5, 6]. Feeding a load of fixed voltage is one of the important applications of solar cells power generation system. Solar cells output power will change when the work environment changes, especially the light intensity or ambient temperature changes. In General, changes of solar cells output characteristic curve are proportional to the changes of light intensity [3, 4, 5, 6]. The Buck converter is the most frequently used DC/DC converter topology in power management and microprocessor voltage-regulator applications [7].

Those applications can convert a voltage source into a lower regulated voltage [8, 9]. So Buck converter is used to modify the output of solar cells in this paper. As the light intensity, ambient temperature and other conditions are not controllable. The study of the characteristic curve is inconvenient in solar cells. Furthermore, using direct experimental solar cells will make some defects such as extended time and high cost. Therefore, a simple simulator is implemented in order to simulate solar cells output characteristics in this paper, so that it can be controlled to conduct experimental research in a lab environment to conveniently [2, 3, 4, 5, 6].

II. SOLAR CELLS CHARACTERISTICS AND IT'S SIMULATOR

Recently, The technology of photovoltaic (PV) is essentially concerned with the conversion of this energy in to usable electric form. The basic element of the PV system is the solar cell. Solar cell can convert the energy of sunlight directly into electricity. A simplified equivalent circuit of a solar cell consists of a current source in parallel with a diode variable resistor is connected to the solar cell generator as a load. The well known general mathematical model for a PV cell is obtained by describing the relation between its terminal current and voltage through the single-diode equivalent circuit of the cell, reported in Figure. 1, see also [2, 3, 6, 10].

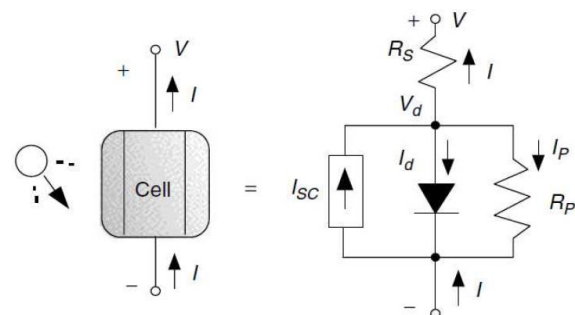


Figure 1. Model of PV Cell.

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A. Solar Cells Characteristics

Solar panel is composed of a number of solar cells, and each one solar cell is a semiconductor of P-N section which converts solar energy directly into electrical energy; therefore, it can be assumed that a solar panel generates an independent current sources and its own by the light irradiation to supply load [11]. The output characteristic of solar cells is nonlinear and It is subject to light intensity, ambient temperature and other factors [3, 6, 10]. Typical solar panel output characteristic curves are shown in Figure. 2, and Figure. 3. Its characteristic equation can be described as the following :

$$I = I_{LG} - I_{os} \left(\exp \left[\frac{q}{AkT} (V + IR_s) - 1 \right] \right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

Where

$$I_{os} = I_{or} \left(\frac{T}{T_r} \right)^3 \exp \left[\frac{qE_{GO}}{Bk} \left(\frac{1}{T_r} - \frac{1}{T} \right) \right] \quad (2)$$

$$I_{LG} = [I_{SCR} + K_1(T - 25)]\lambda / 100 \quad (3)$$

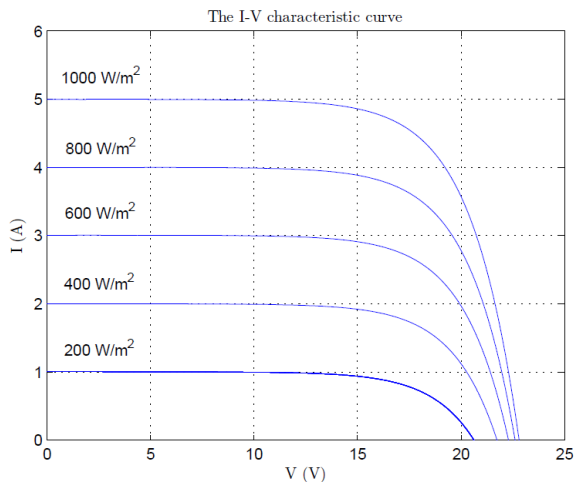


Figure 2. Output Voltage-Current Characteristic Curves.

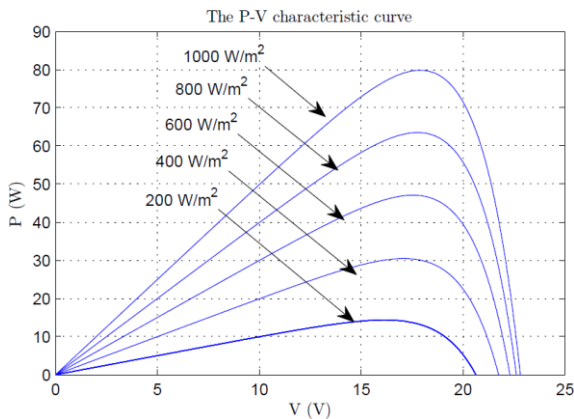


Figure 3. Output Voltage-Power Characteristic Curves.

Where I and V are respectively solar cells output current and voltage, I_{os} is solar cells reverse saturation current, T is solar cells temperature ($^{\circ}C$), k is the Boltzmann constant, q is electronic charge, λ is sunlight intensity (W/m^2), I_{SCR} is short-circuit current at $25^{\circ}C$ and $1000W/m^2$, I_{LG} is the current produced by light, $k_1 = 0.0017 A/^{\circ}C$, which is the temperature coefficient under short-circuit current I_{SRC} , E_{GO} is silicon bandwidth, $B = A = 1.92$, which are ideal coefficients, $T_r = 301.18^{\circ}C$, which is the reference temperature, I_{or} is the solar cells saturation current at T_r , R_{sh} is the equivalent parallel resistance, R_s is the equivalent series resistance (ESR) [10].

B. Solar Cells Simulator and Buck Converter

In order to make the experiment conveniently and reliable, DC power supply with variable resistor can be used to simulate the solar cells output characteristic curve [4]. Its experimental circuit is shown in Figure. 4. The section inside the dashed border is the simulator of solar cells, which consists of a DC power supply V_s and a variable resistor R_1 . V_i is the output voltage of the simulator for solar cells. Outside the dashed border is the power conversion circuit, Buck converter is used in DC/DC section, its topology is shown in Figure. 5. V_s in Figure. 4, is the output voltage of photovoltaic array, R_1 is the equivalent resistance of photovoltaic array, V_i and V_o are the input voltage and output voltage of the Buck converter respectively, I_1 is the average input current and R_2 is the load. Supposing d is the duty ratio, on the assumption that all the circuit components are ideal components and there is no power loss during the transmission from input to output, the Buck converter will be described by the following equation :

$$V_o = d \cdot V_i = d \cdot (V_s - R_1 I_1) \quad (4)$$

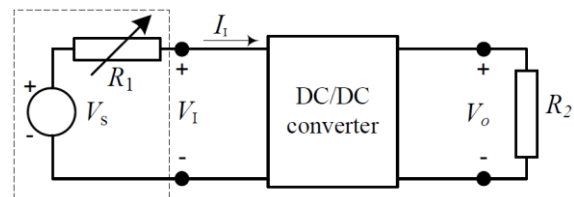


Figure 4. The Diagram of Solar Cells Simulator.

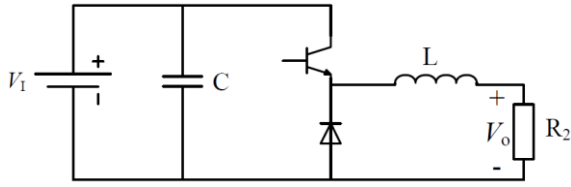


Figure 5. Topology of Buck Converter.

From eq. (4), by varying the duty-cycle of the switch, the output voltage can be controlled when R_1 is changed. The practical photovoltaic energy conversion system block diagram is shown in Figure. 6.

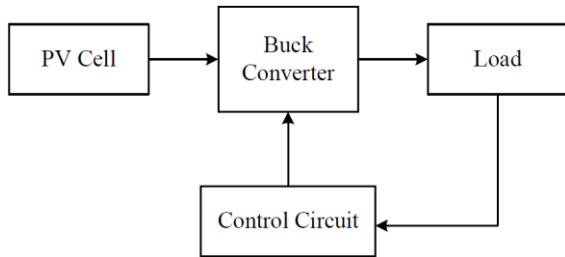


Figure 6. Block Diagram of PV Installation System.

III. DESIGN A TYPE-3 VOLTAGE CONTROLLER

The type-3 voltage control board has the schematic shown in Figure. 7.

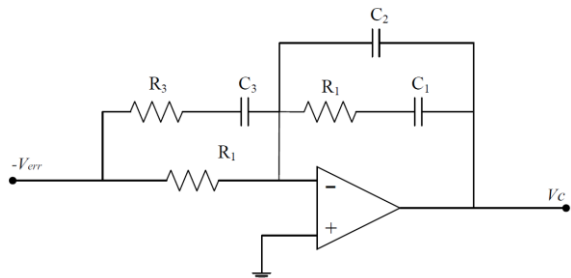


Figure 7. Voltage Control.

Also, the transfer function in a forward converter operating in a continuous-conduction mode for Figure. 6, can be written as [8] :

$$T_p(s) = \frac{v_o^{\sim}(s)}{d^{\sim}(s)} = v_d \cdot \frac{1 + s r_c C}{LC \left(s^2 + \left[\frac{r_c + r_L}{L} \right] s + \frac{1}{LC} \right)} \quad (5)$$

The Bode plots for the transfer function $\frac{v_o^{\sim}(s)}{d^{\sim}(s)}$ are calculated by Matlab and given in Figure. 8.

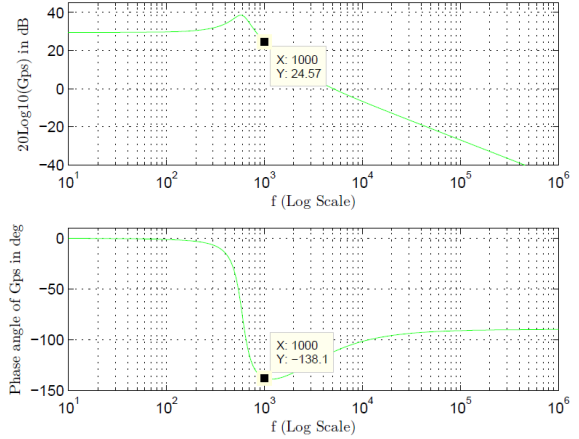


Figure 8. Gain and Phase plot of the forward converter.

The frequency $f_c = 1kHz$ will be chosen as the crossover frequency of the open-loop transfer function $G_L(s)$ [8], see also [12, 13]. This ensure that the phase angle of the loop remains greater than -180° at all frequencies below f_c . The desired phase margin is specified as $\phi_{PM} = 60^\circ$. The required phase boost ϕ_{boost} at the crossover frequency is calculated as follows :

$$\phi_{boost} = -90^\circ + \phi_{PM} - \angle G_{PS}(s)|_{f_c}$$

Noting that G_{PWM} and k_{FB} produce zero phase shift [8]. From Figure. 8, $\angle G_{PS}(s)|_{f_c} = -138^\circ$. Yields the required phase boost is $\phi_{boost} = 108^\circ$.

The Bode plot of the transfer function $G_c(s)$ of the controller is shown in Figure. 9.

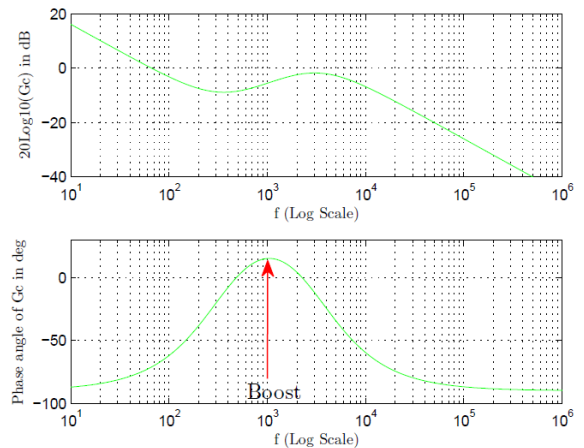


Figure 9. Bode plot of $G_c(s)$.

The values of physical components (the resistors and capacitors) of the voltage control board are given in the table below [8]:

Table 1. VOLTAGE OF CONTROL BOARD COMPONENT VALUES

No.	Component	Calculated Value
1	R1	98.9 KΩ
2	R2	19 KΩ
3	R3	11.9 KΩ
4	C1	22 μF
5	C2	3 nF
6	C3	4.7 μF

IV. EXPEREMENTAL WORK, SIMULATION AND RESULTS

The solar cells system represented by the block diagram of Fig. 6, is implemented in the laboratory as shown in the photo given in Fig. 10.

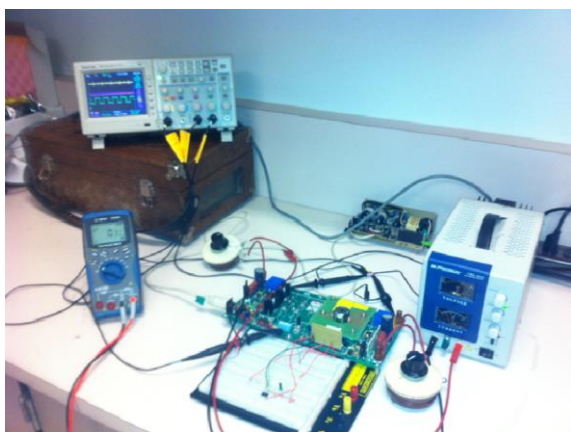


Figure 10. Photograph of the Experiment.

Equally, the solar cells system represented by the block diagram of Figure.6, reconstructed using Matlab/Simulink simulation environment [14]. The Matlab/Simulink model of Buck converter for solar cells system is given in Figure. 11.

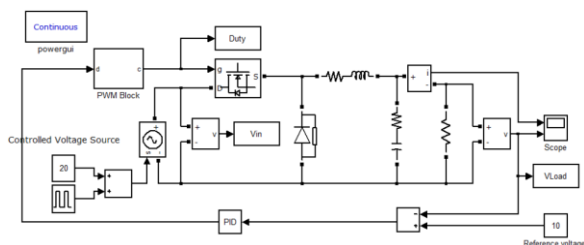


Figure 11. Simulink Circuit of Solar Cells System.

Furthermore, the driving pulses of the MOSFET are shown in Figure. 12. The main experimental parameters in Figure. 4, and Figure. 5, are taken as follows [8]: $V_s = 20V$, $0 < R_1 < 25\Omega$, $R_2 = 10\Omega$, $C = 680\mu F$, $L = 105.2\mu H$, and $F_{sw} = 100kHz$.

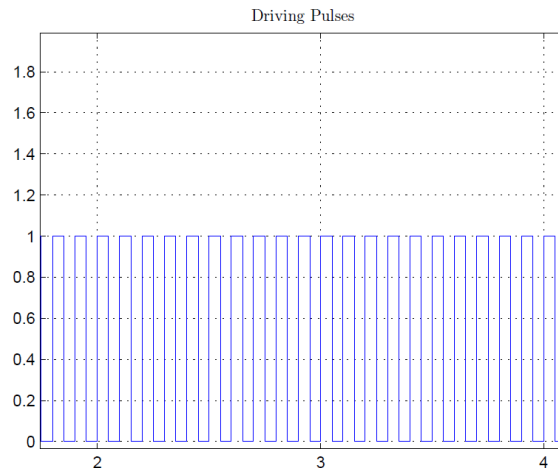


Figure 12. Driving Pulses.

A. Simulation Results

As mentioned earlier, the simulation of the solar cells system is accomplished using Matlab/Simulink and the simulation results are presented in this section as follows. Firstly, for the Open-loop system with disturbance at the input, an external disturbance signal of step rise in input voltage of magnitude of 1V is applied at ($t = 0.03sec$) as shown in Figure. 13. As a consequence, the system responds to this disturbance and its output voltage increases from 9.55V to 10.08V as shown in Figure. 14.

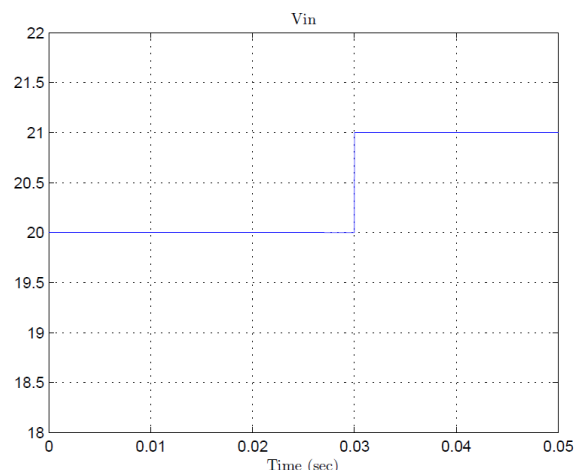


Figure 13. Input Voltage with Disturbance of Open Loop System.

In the open-loop configuration, It is clear that any disturbance or noise signal that effects the input will have a direct consequence at the output and the system cannot eliminate completely its effects, as shown in the system's response in Figure. 14.

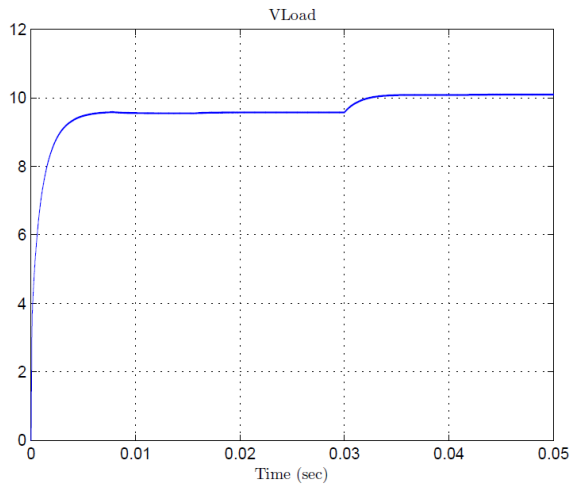


Figure 14. Output Voltage with Disturbance of Open Loop System.

Secondly, for the closed loop DC to DC buck converter case, the input and output voltage signals are shown in Figure. 15, and Figure. 16, respectively. It can be clearly seen that the input has a disturbance at ($t=0.03\text{sec}$) where a step change of a magnitude $1V$ is presented. Consequently, at ($t=0.03\text{sec}$) the input signal rises from $20V$ to $21V$, Fig. 15. The response is then given in Figure. 16.

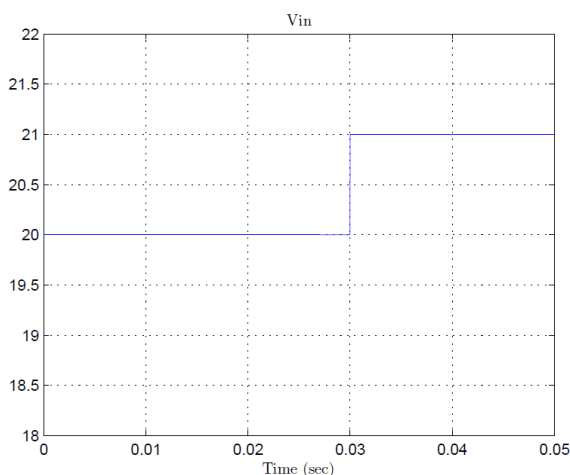


Figure 15. Input Voltage with Disturbance of Close Loop System.

In this case, contrasted to the open-loop case, the error is processed by the controller which adjusts the PWM to maintain the output voltage constant at $10V$. This result is clearly presented in Figure. 16, where the effect of the disturbance appears as a small oscillations in the response starts at ($t=0.03\text{sec}$).

In the closed-loop configuration, It is clear that the system have eliminated the effect of the disturbance presented at the input and it can maintain the output voltage at a desired value despite the changes in the operating conditions.

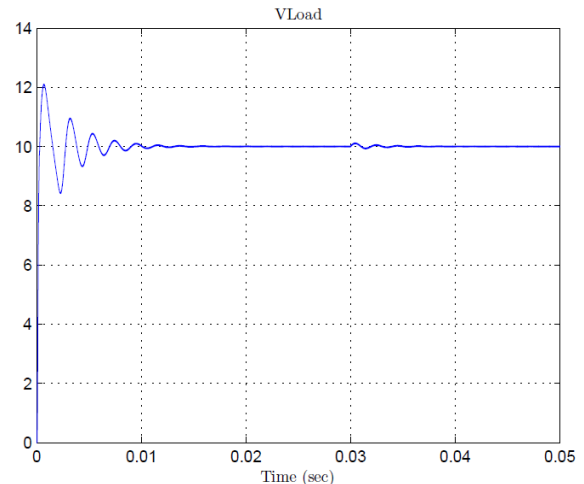
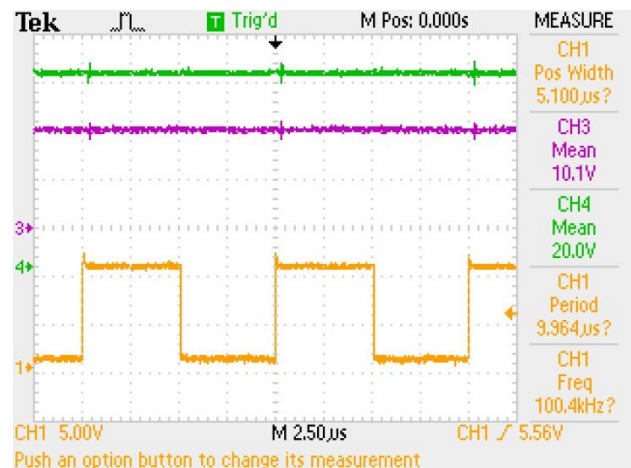


Figure 16. Output Voltage with Disturbance of Close Loop System.

B. Experimental Results

According to the experimental implementation shown in Figure. 10, and the circuit configuration given in Figure. 4, the input voltage of the buck converter can be changed by adjusting the resistance (rheostat) R_1 , Figure. 4. The control system automatically adjusts its duty ratio so that the output voltage of the converter can be maintained fixed even with changes at the input voltage. However, when the input voltage is smaller than the reference voltage, which is $10V$, the output voltage will change to be less than the desired voltage because the buck converter cannot accomplish the job in this case.

Figure 17. Input & Output Voltages with Duty Ratio at $V_{in} = 20V$.

In Figure. 17, and Figure. 18, the output is maintained fixed at $10.1V$ even with the changes in the input voltages; the input voltage is equal to $20V$ in Figure. 17, and equal to $15V$ in Figure. 18. From the results given in Fig. 17, and Figure. 18, the duty ratio in changed from 0.51 to 0.67 to keep the output voltage constant at $10.1V$.

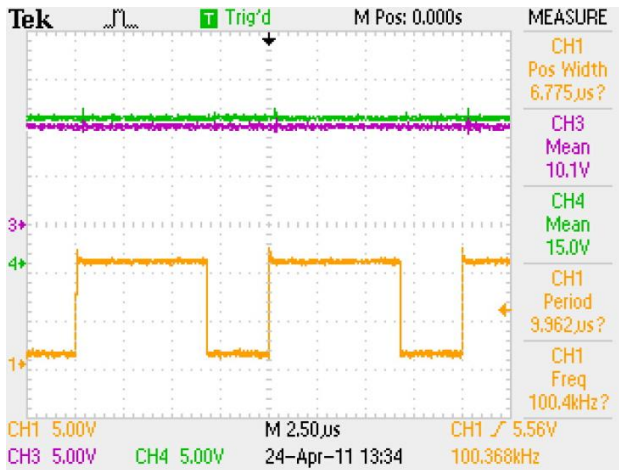


Figure 18. Input & Output Voltages with Duty Ratio at $V_{in} = 15V$.

Moreover, in Figure. 19, the output voltage decreases where the input voltage was less than the reference voltage because the output voltage must always be less than the input voltage; this is inherited from the buck converter physical characteristics. This can be clearly noted in Figure. 19, where the input voltage is about 8V gives an output voltage of about 7.91V.

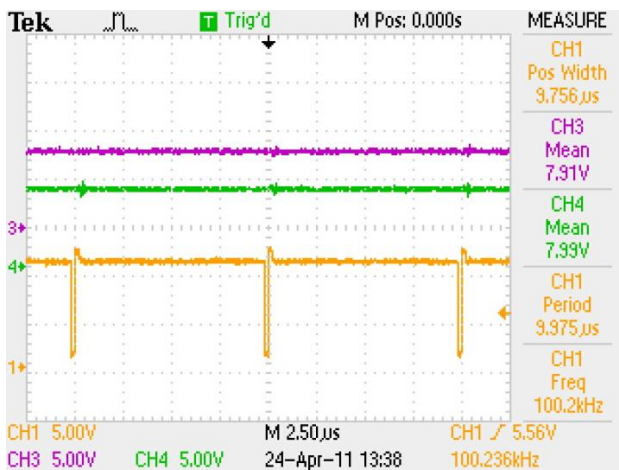


Figure 19. Output & Output Voltages with Duty Ratio at $V_{in} \approx 8V$.

Finally, the crossover frequency f_c , of the open-loop gain which is 1 KHz, was high enough to response fast and the response in the closed-loop system settles quickly without big oscillations as a result as you can see in Figure. 20.

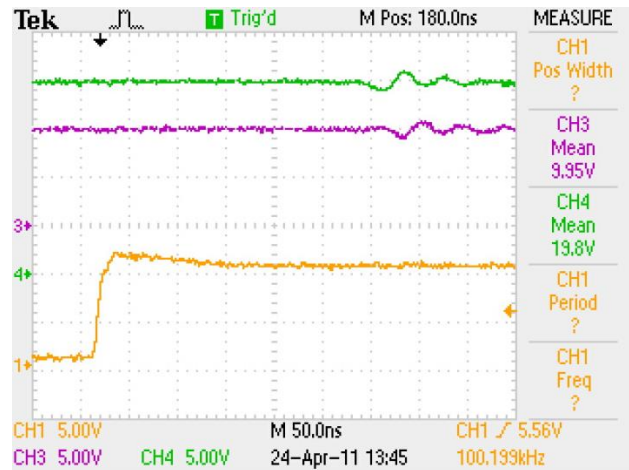


Figure 20. The Response of the Converter.

V. CONCLUSION

This paper presents open-loop and closed-loop controlled buck converter system for solar panel system. Matlab models for open loop and closed loop systems are developed using the blocks of Simulink simulation environment. The closed-loop system is able to maintain an output constant voltage. The simulation results for the closed loop system are in good agreement with the experimental results.

In addition, DC power supply with variable resistor can be used to simulate the solar cells to do Maximum Power Point Tracking (MPPT). However, The Buck circuit's input current is not continuous, which will result in some of the energy losses in photovoltaic power. Therefore, the boost converter is better than buck converter in the applications that do MPPT. Also, the output voltage of the buck converter is always less than or equal the input voltage.

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