

Three – Stage Solar Battery Charge Control Using Cuk Dc – Dc Converter

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Abstract

This paper presents the design and simulation of a three-stage solar battery charge controller using Ćuk DC-DC converter, functioning as the major interface between the solar PV module array and the battery bank. The charging current and voltage curves for the three – stage charge controller were obtained and discussed. The simulation curves for the converter in open – loop and closed – loop modes with and without PID controller, respectively, were also compared and discussed. The commonly used converters in solar charge controllers normally step down the non-linear DC voltage supplied by the PV module array to a stabilized desired DC voltage value, required to charge the battery bank. The Ćuk DC-DC converter used in this paper has the capability of stepping down as well as stepping up the supplied DC voltage among other advantages, which include, minimum ripples at the output stage, faster rise and settling time and getting closer to the desired output value.

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1. Introduction

A DC-DC converter is a power electronic circuit that changes the level of its input by altering the pulse width modulation (PWM) waveform through adjusting the ON-OFF timings thereby keeping the output at the desired value [1].

The minimum controllable ON-time of a converter is the narrowest achievable pulse width of the pulse width modulation (PWM) circuit. While the duty cycle of a converter is the percentage of the time that the FET is on during a switching cycle [2].

Solar panel output is affected by the cell temperature. Panels are rated at a nominal temperature of 25 degrees Celsius. The output of a typical solar panel can be expected to vary by 2.5 % for every 5 degrees. With this in mind, it is worth noting that, if the panels are very cool due to cloud cover, and the sun bursts through the cloud, it is possible to exceed the rated output voltage of the panel [3].

The battery's efficiency and life time affects significantly the overall PV system performance and economy. Batteries specified especially for use in PV systems have to be distinguished with standing of a very deep discharge rate and high cycling stability, meaning that they can be discharged and recharged continuously for long period [4]. There are three conventional solar battery charge control techniques namely; constant current (CC), two stage constant current constant voltage (CC-CV) and three stage constant current constant voltage constant current charging techniques [5].

In the proposed three-stage charging, the battery is charged in three stages, which are known as bulk, absorption and float charging stages [6]. In the bulk stage, the current is maintained constant at a relatively high value. During the absorption stage, the voltage supplied to the battery is kept constant which consequently lowers the current flow. In the float charging stage, the voltage is lowered to a float level and the battery draws small maintenance current [7].

1.1 Operation Principles of Ćuk Converter

The Ćuk DC-DC converter type is proposed in this research due to its ability to step down as well as step up the voltage supplied from the PV module array. Among its advantages, the Ćuk converter contains little or no ripples at its output stage and prevents electromagnetic interferences.

Despite the aforementioned advantages, the Ćuk converter also has the following limitations:

- The Ćuk converter provides a negative polarity regulated output voltage with respect to the common terminal of the input voltage.
- There is need for an additional capacitor at the converter's input stage with a large ripple current-carrying capability which increases the cost of the converter design.
- The excess ripples at the output stage are not completely eliminated but are minimized considerably.

The Ćuk converter can step the voltage either up or down, depending on the duty cycle. The basic non-isolated Ćuk converter is shown in Figure 1. It is one of the basic DC-DC converters that have negative voltage at its output which can be higher or lower than the input [8].

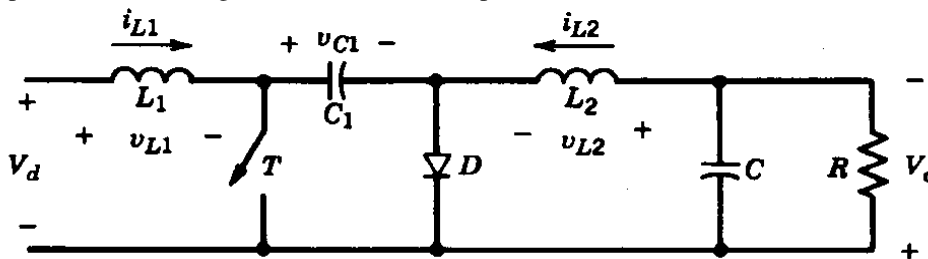


Figure 7-25 Ćuk converter.

Figure 1: Schematic Diagram of Basic Ćuk Converter
 Source: Bastos (2008)

The converter circuit operates in two different modes [8]. During mode 1, when the switch T is closed, as shown in Figure 2(a), the current through inductor L_1 increases. At the same time the voltage of capacitor C_1 reverse biases diode D and turns it off. The capacitor C_1 discharges its energy to the circuit formed by C_1 , C, L_2 and the load.

During mode 2, when the switch T is open, as can be seen in Figure 2(b), the diode D is forward biased and

capacitor C_1 is charged through L_1 , input supply V_d and D. The energy stored in the inductor L_2 is transferred to the load [9].

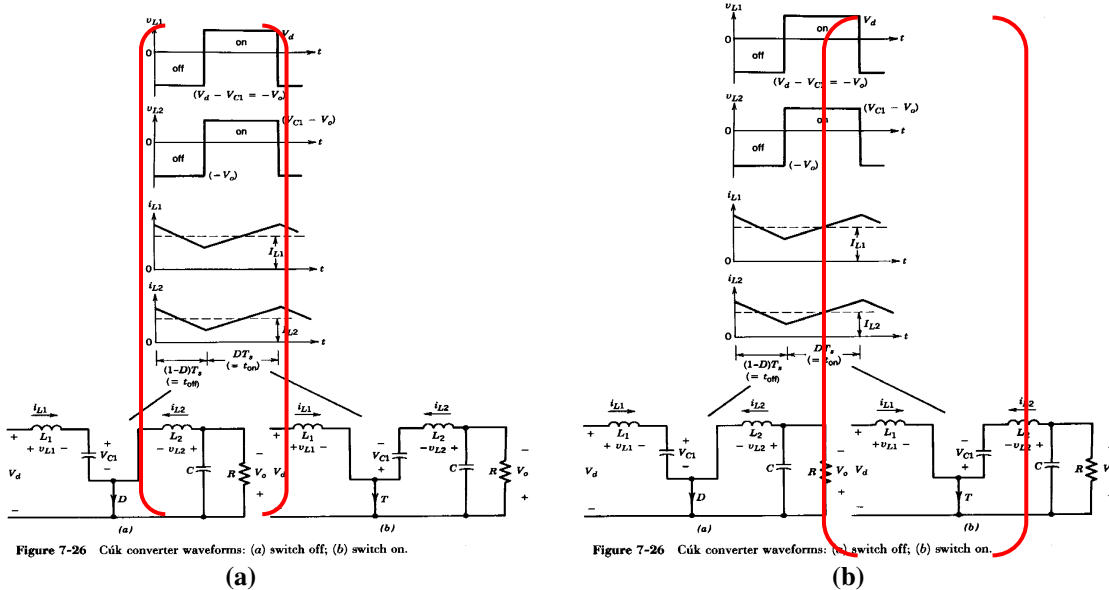


Figure 2: Ćuk Converter Waveforms; (a) when switch T is off (b) when switch T is on

2. Design Considerations

The PV panel used as a source of input for the DC-DC converter has the characteristics as shown in Table 1.

Table 1: Technical Specifications of a 12V, 60W PV Module

Parameter	Value
Maximum Power	60 W
Maximum Power Voltage	18.2 V
Maximum Power Current	3.3 A
Short Circuit Current	3.56 A
Open Circuit Voltage	22.2 V

2.1 Ćuk Converter in Step-Down Mode

The output voltages generated by Solar panels vary with cell temperatures. Panels are rated at a nominal temperature of 25 degrees Celsius. The output of a typical solar panel varies by 2.5 % for every 5 degrees. With this assertion, it is worth to note that, if the panels are very cool during cloudy weather conditions, and the sun bursts through the cloud, it is possible to exceed the rated output voltage of the panel [3].

Based on the aforementioned characteristics of the solar panel and with the aid of Table 1, the converter's input voltage range of 8V – 17V was used in the design. For the step-down operation of the Ćuk converter, the converter's input voltage was assumed to be 8V.

Output voltage and the duty cycle are related in Equation (1) [9].

$$V_o = V_d \left[\frac{D}{1-D} \right] V_o = V_d \left[\frac{D}{1-D} \right] \quad (1)$$

Where D is the duty cycle and $V_d V_d$ is the input voltage of the converter.

It is a good practice to always check the DC-DC converter datasheet for a guaranteed minimum controllable ON-time in selecting a switching frequency. Typical switching frequencies of converters lie in the range of 1kHz to 1MHz, depending on the speed of the semiconductor devices [13]. The switching frequency is chosen as $F_s = 120 \text{ kHz}$ with a Time period $T = 0.083 \text{ ms}$. Design equations for non-isolated Ćuk converter elements are shown in Equations (2) to (5) [8].

$$L_{1\min} \geq \frac{(1-D)^2 R}{2DF_s} L_{1\min} \geq \frac{(1-D)^2 R}{2DF_s} \quad (2)$$

$$L_{2\min} \geq \frac{(1-D)R}{2F_s} L_{2\min} \geq \frac{(1-D)R}{2F_s} \quad (3)$$

$$C_{1\min} \geq \frac{D}{2F_s R} C_{1\min} \geq \frac{D}{2F_s R} \quad (4)$$

$$C_{2\min} \geq \frac{1}{8F_s R} C_{2\min} \geq \frac{1}{8F_s R} \quad (5)$$

Where R is the load resistance of the converter

D is the duty cycle of the converter, calculated from Equation (1) with input voltages ($V_d V_d$) of 8V and 17V for step down and step up modes respectively. The load resistance was chosen to be 16.67Ω .

Thus, for Ćuk converter in step down mode (with $V_d = 8V$), Equation (1) was used;

$$\begin{aligned} V_o &= V_d \left[\frac{D}{1-D} \right] V_o = V_d \left[\frac{D}{1-D} \right] \\ 12 &= 8 \left[\frac{D}{1-D} \right] 12 = 8 \left[\frac{D}{1-D} \right] \\ \rightarrow D &= 0.6 \rightarrow D = 0.6 \end{aligned}$$

For the Ćuk converter operation in step up mode (with $V_d = 17V$), Equation (1) was used;

$$\begin{aligned} V_o &= V_d \left[\frac{D}{1-D} \right] V_o = V_d \left[\frac{D}{1-D} \right] \\ 12 &= 17 \left[\frac{D}{1-D} \right] 12 = 17 \left[\frac{D}{1-D} \right] \\ \rightarrow D &= 0.41 \rightarrow D = 0.41 \end{aligned}$$

The calculated values of the designed elements for the Ćuk converter using Equations (2) to (5) were found as shown in Table 2.

Table 2: Calculated Parameters' Values for Ćuk Converter in Step-down Mode

Parameter	Value
Duty cycle, D	0.41
Inductor, L_1	1.8 mH
Inductor, L_2	1.2 mH
Capacitor, C_1	3.4 μF
Capacitor, C_2	5 μF

2.2 Ćuk Converter in Step-Up Mode

For the step-up operation of the Ćuk converter, the module's least output voltage was chosen to be 8V with the desired output voltage of 12V [10].

The values for the circuit elements in Table 2 were used in the simulation. Only the duty cycle's value was recalculated using Equation (1), since the corresponding converter's input value has changed. The value of D used was calculated to be 0.6.

3. Results and Discussion

3.1 Open-Loop Ćuk DC-DC Converter

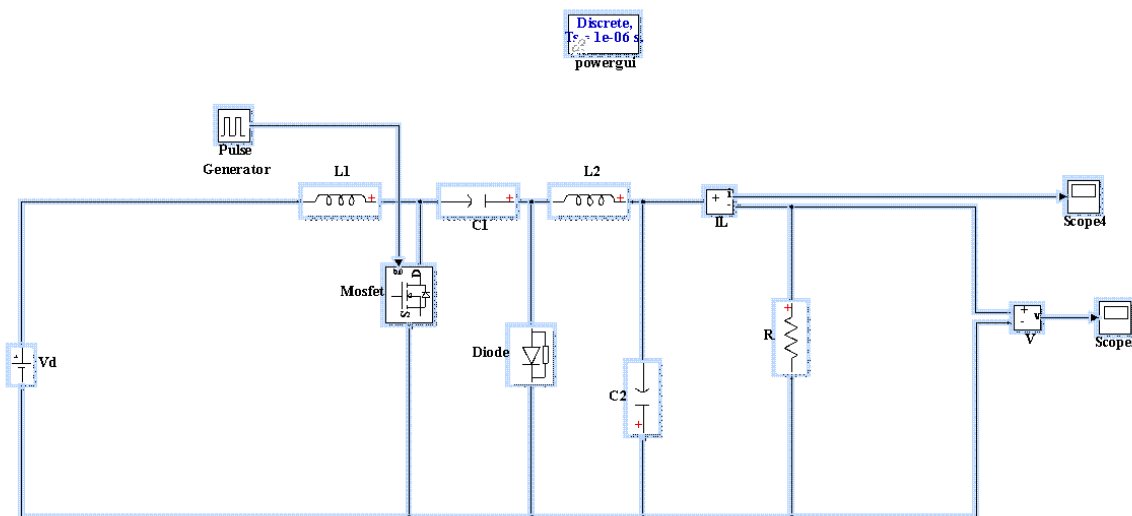


Figure 3 shows the corresponding open loop circuit model used in the simulation of the Ćuk DC-DC converter in MATLAB/Simulink environment. The Ćuk converter has two inductors, two capacitors, a diode and a transistor switch.

Figure 3: Ćuk Converter Simulation in MATLAB/Simulink

3.2 Closed-Loop Ćuk Converter

To design a controller for the Ćuk converter, a small signal conversion function is required in order to obtain the converter's transfer function. This can be obtained by either using the canonical model of the Ćuk converter derived from small signal A.C model of the converter or by using state space averaging technique. By using the state space averaging technique, the control to output transfer function of the Ćuk converter is derived as shown in Equation (6) [11].

$$G_{vd}(s) = \frac{V_d}{D'^2} \frac{s^2 \frac{L_1 C_1}{D'} - s \frac{D^2 L_1}{D'^2 R} + 1}{s^4 \frac{L_1 C_1 L_2 C_2}{D'^2} + s^3 \frac{L_1 C_1 L_2}{D'^2 R} + s^2 \left(\frac{L_1 C_1 L_2}{D'^2} + L_2 C_2 + \frac{D^2}{D'^2} L_1 C_2 \right) + s \left(\frac{L_2}{R} + \frac{D^2 L_1}{D'^2 R} \right) + 1}$$

$$G_{vd}(s) = \frac{V_d}{D'^2} \frac{s^2 \frac{L_1 C_1}{D'} - s \frac{D^2 L_1}{D'^2 R} + 1}{s^4 \frac{L_1 C_1 L_2 C_2}{D'^2} + s^3 \frac{L_1 C_1 L_2}{D'^2 R} + s^2 \left(\frac{L_1 C_1 L_2}{D'^2} + L_2 C_2 + \frac{D^2}{D'^2} L_1 C_2 \right) + s \left(\frac{L_2}{R} + \frac{D^2 L_1}{D'^2 R} \right) + 1} \quad (6)$$

Where $D' = 1 - D$ and $DD' = 1 - D$

The denominator of the converter's transfer function needs to be factored from fourth order to second order polynomials for proper implementation in the MATLAB's M-file. The approximation of the fourth order polynomials in the denominator is required for optimal placement of poles and zeros in order to optimize the stability of the loop gain.

The Ćuk converter's factorization of the denominator for the fourth order transfer function $G_{vd}(s)G_{vd}(s)$ is separated into two second order factors as shown below [11].

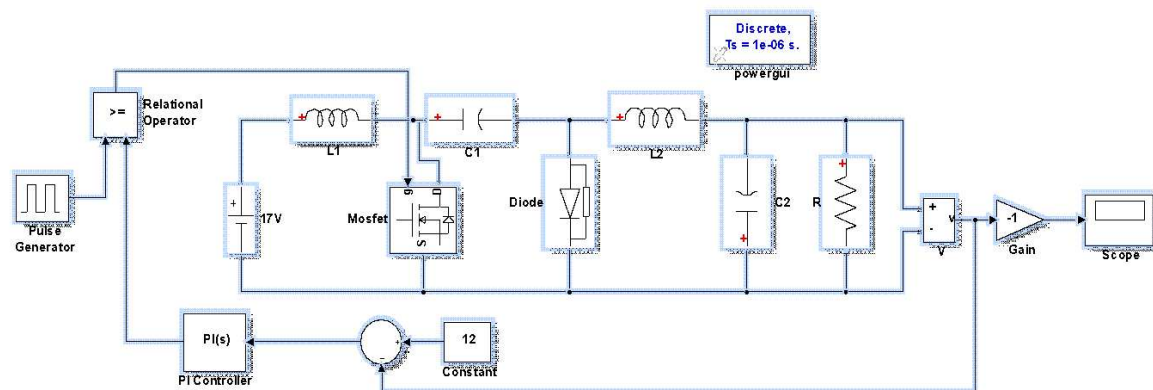
$$\left(s^2 \frac{L_1 C_1}{D'^2} + s \frac{D^2 L_1}{D'^2 R} + 1 \right) \left(s^2 L_2 C_2 + s \frac{L_2}{R} + 1 \right) \left(s^2 \frac{L_1 C_1}{D'^2} + s \frac{D^2 L_1}{D'^2 R} + 1 \right) \left(s^2 L_2 C_2 + s \frac{L_2}{R} + 1 \right)$$

The control-to-output transfer function was used in the MATLAB's M-file to obtain the controller parameters and the system's step response for the closed-loop converter in both step-up and step-down modes.

3.2.1 Closed-loop Ćuk converter in step-down mode

The Simulink model of the closed-loop Ćuk DC-DC converter is shown in Figure 4. The calculated duty cycle of 0.41 was used for the step down operation of the DC-DC converter.

The



parameter values of Table 2 were used in the closed-loop simulation of the converter.

Figure 4: Simulink Model of a Closed-loop DC-DC Ćuk Converter

3.2.2 Closed-loop Ćuk converter in step-up mode

The parameter values of Table 2 were used for the simulation of the closed-loop Ćuk converter in step-up mode with the exception of the duty cycle. The duty cycle was calculated using Equation (1) and the converter's input voltage was assumed to be 17V [10]. The Simulink circuit of Figure 4 was used for the simulation, with the calculated duty cycle of 0.6 replacing the 0.41 value used in the step-down mode.

3.3 Three Stage Charge Control Logic

The flowchart for the three stage charge control logic is shown in Figure 5 and the equivalent MATLAB/Simulink block implementation is shown in Figure 6.

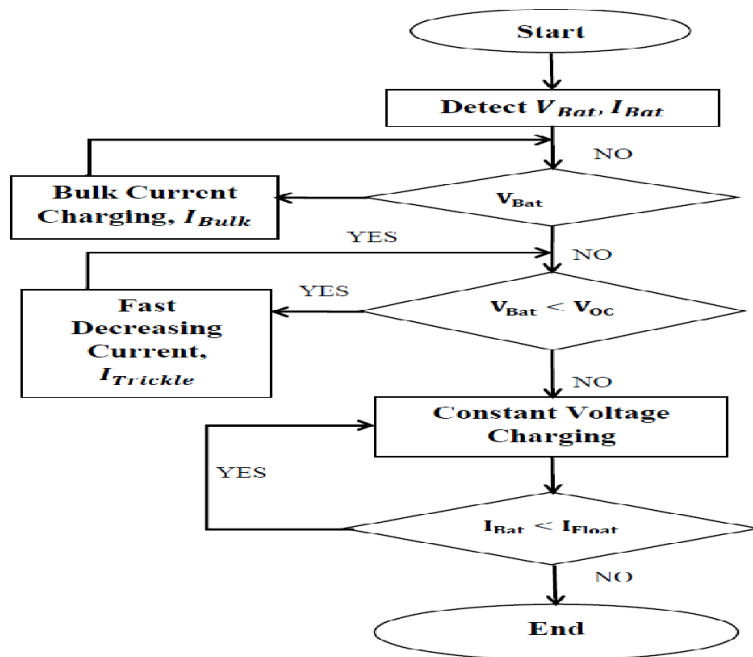


Figure 5: Three Stage Charge Control Flowchart

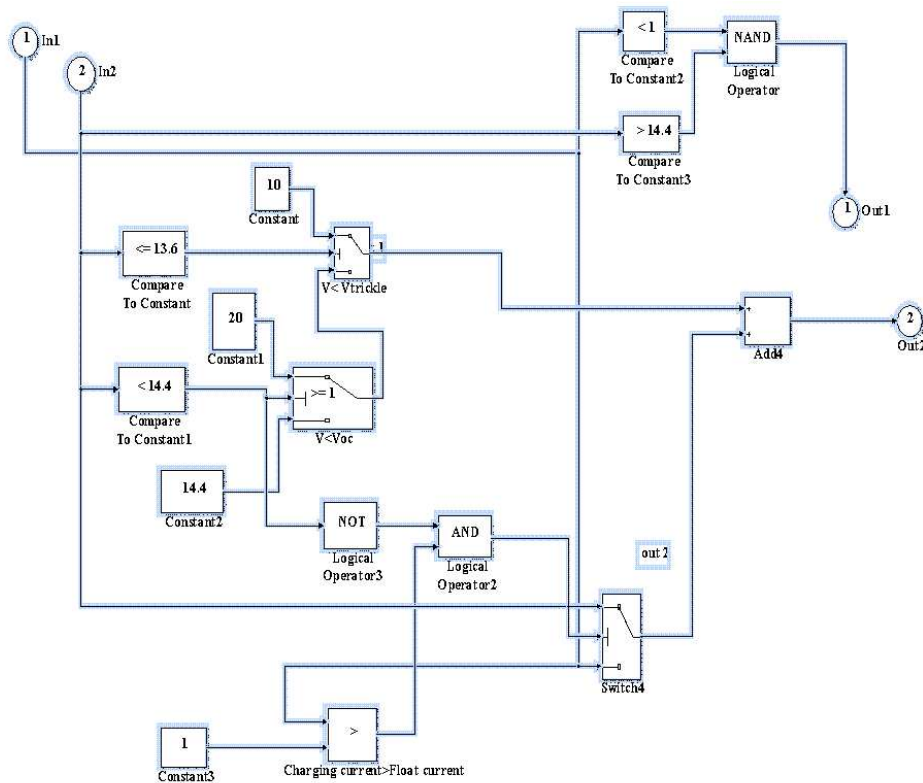


Figure 6: Simulink Model of Control Logic for Three Stage Battery Charging

The two inputs to the control logic subsystem *In1* and *In2* are the converter's output current and output voltage respectively. The capacity of the battery used for the simulation is 100 Ah. The time normally taken to charge the battery from full discharge using algorithm is between 8 to 12 hours. A 12 V lead-acid battery was used in the simulation. The first switch checks if the battery voltage is up to the trickle voltage value which is set at 13.6 V. If this condition is false, then the Bulk charging stage is enabled. The three – stage charge algorithm initially uses the maximum solar panel current available to charge the battery up to the Bulk level of 14.4 V. During the Absorption stage, the second switch $V < V_{oc} V < V_{oc}$, compares the battery voltage with the Bulk voltage value, if this condition is met, then the voltage is maintained at Bulk level for a specified time (up to about an hour) while the current gradually decreases as the battery charges up. In the last charging phase, which is the float charging stage, the voltage is lowered to float level of 13.6 V and the battery draws a small maintenance current until the next cycle [5].

3.4 Three – Stage Charging using Ćuk Converter

The charge control logic Simulink block for the Ćuk converter is the same as the control logic block shown in Figure 6. The same charge control algorithm employed on Buck converter was also used on the Ćuk DC-DC converter. The three – stage battery charging algorithm implemented in Simulink environment using Ćuk DC-DC converter is shown in Figure 7.

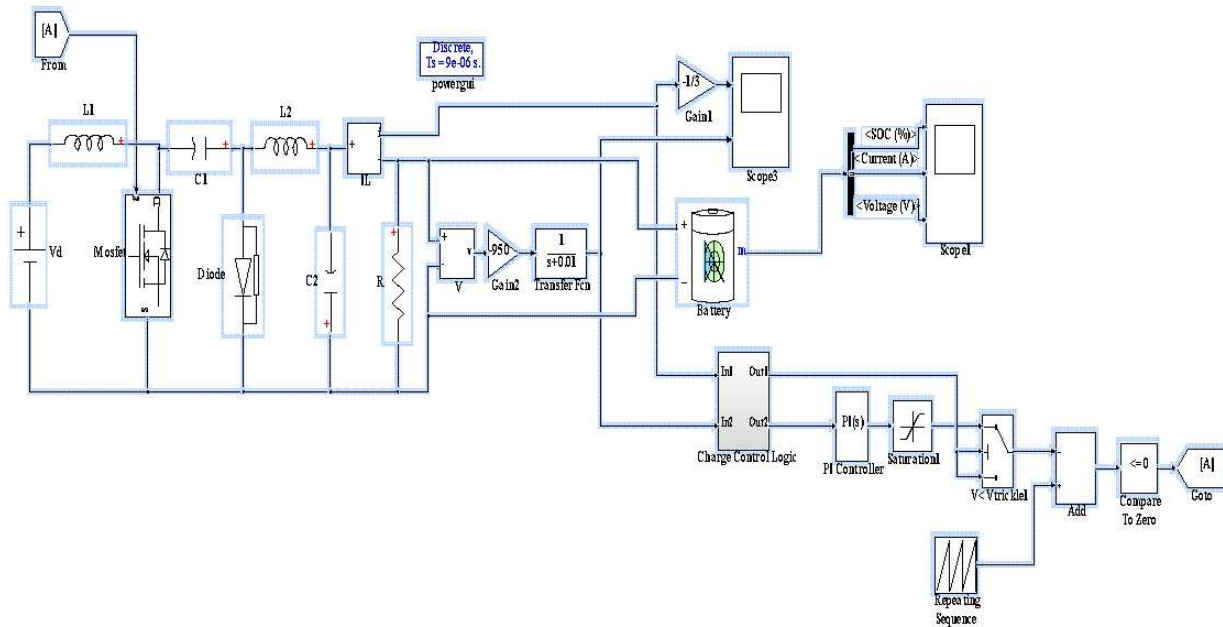
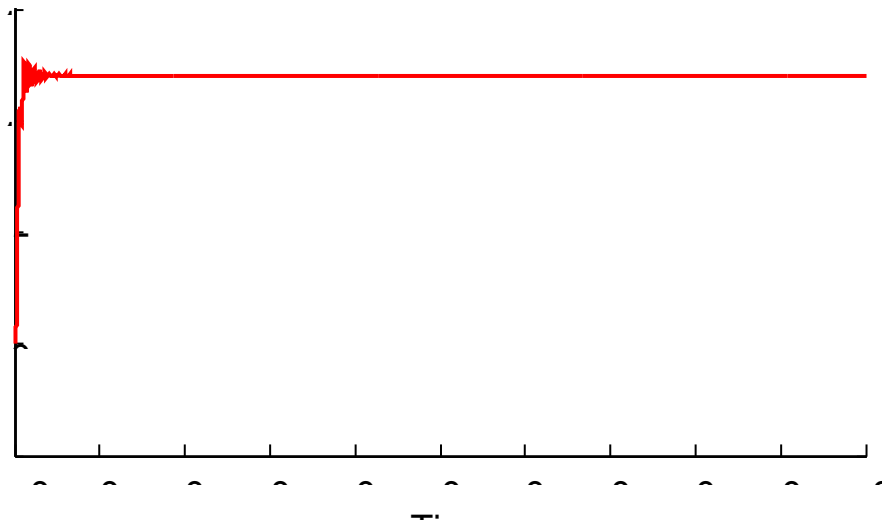
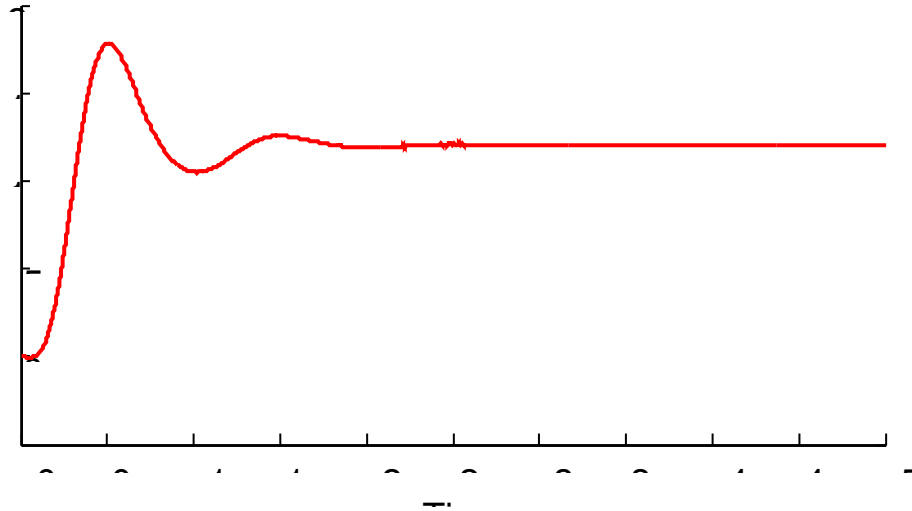


Figure 7: Simulink Model of a Three Stage Battery Charge Controller Using Ćuk Converter

The open- and closed-loop output voltage responses for Ćuk DC-DC converter with and without PID feedback control are depicted in Figures 8(a), (b) and 9(a), (b) respectively.

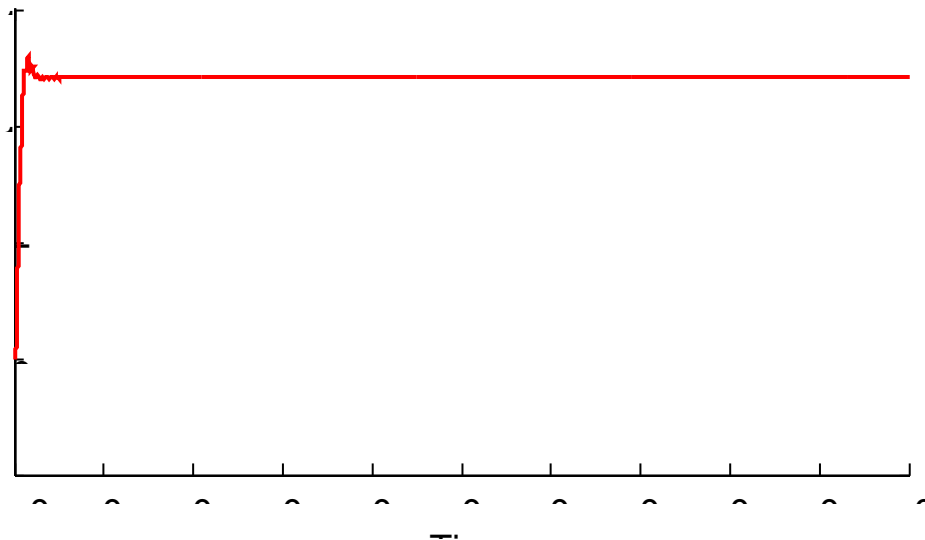


(a) Open-loop Voltage Response

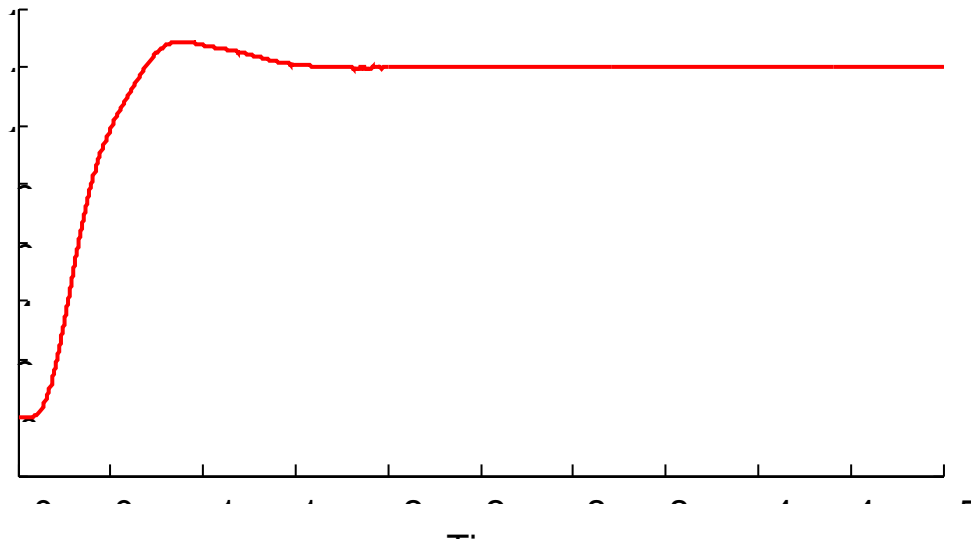


(b) Closed-loop Voltage Response

Figure 8: Open and Closed-loop Voltage Response for Ćuk DC-DC Converter in Step-Down Mode



(a) Open-loop Voltage Response

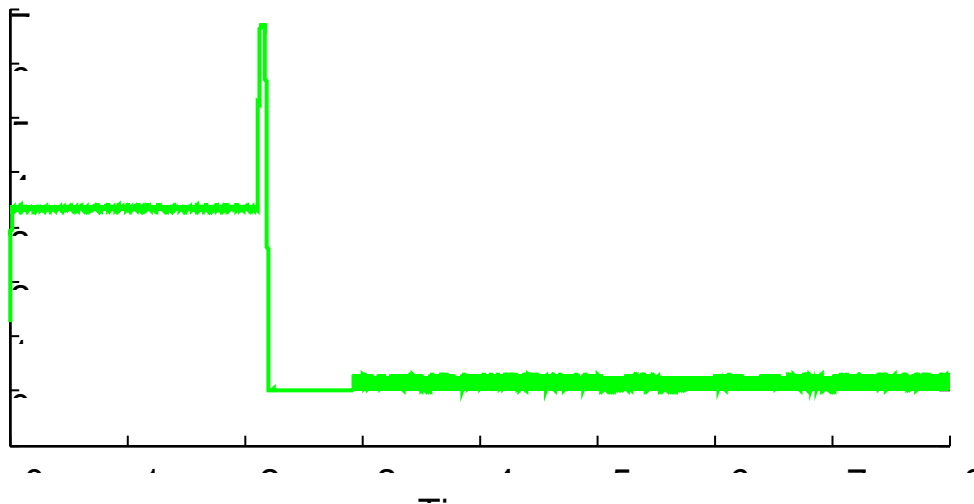


(b) Closed-loop Voltage Response

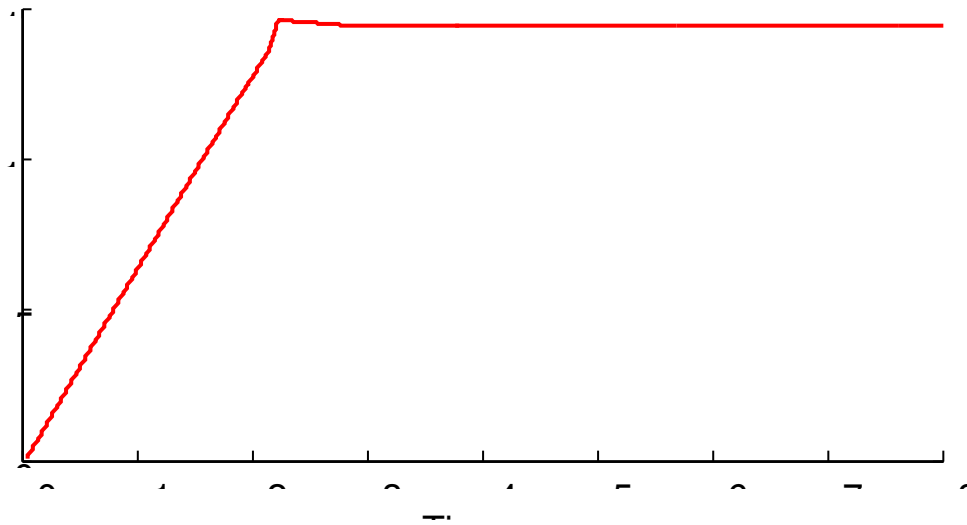
Figure 9: Open-Loop and Closed-Loop Voltage Response for Ćuk DC-DC Converter in Step Up Mode

3.5 Simulation Results of Three – Stage Battery Charge Control using Ćuk Converter

The charging current and voltage curves for the three – stage charge control using Ćuk DC-DC converter are depicted in Figures 10(a) and 10(b) respectively.



(a) Output Current Response



(b) Output Voltage Response

Figure 10: Three Stage Output Voltage and Current Responses Using Ćuk Converter

4. Conclusion

This paper has presented the results that emerged from the simulation of a three-stage battery charge control technique using Ćuk DC-DC converter. The outcome of the simulation results using the Ćuk DC-DC converter depicts a typical characteristic of an interrupted charge control algorithm. At the initial stage, the battery is charged with constant current to an upper threshold value. This current is maintained until the next stage where it reduces to 0A. In the third stage, the battery is charged with very small continuous pulses of charge current. Although, the interrupted charge control technique charges the battery with lower operating temperature which prolongs the battery life, it has the limitation of being less effective at returning the battery to full state of charge at a fast rate [12].

5. References

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