Design and Simulation of Buck and Ćuk DC-DC Converters Using MATLAB/SIMULINK

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Abstract

This paper presents the design and simulation of two types of DC-DC converters, namely, Buck and Ćuk converters using Simulink in a MATLAB environment. The step-down modes of the two converters were compared and the result discussed. Both converters use 17V DC as the input voltage and 12V DC as the desired output voltage. The converters are mainly used in photovoltaic solar charge controllers to either step up or step down the fluctuating DC voltage from the solar panels for effective battery charging. The Buck converter type is popularly used in the solar charge controllers for the aforementioned purposes, but the need for further enhancing the charging process in order to extend the battery life requires the design of the Ćuk type converter. The Ćuk converter has several advantages over its Buck counterpart. The design and simulation of the two converters were carried out in order to determine, from their output responses, which of them has lower ripples, faster response, settling time, and moves closer to the desired output voltage value.

Keywords: Simulation, MATLAB, Photovoltaic, Charge Controller, Buck converter, Ćuk converter.

1. INTRODUCTION

A DC-DC converter is an electronic circuit which converts direct current (DC) supply from one voltage level to the other by changing the duty cycle of the main switches in the circuit [1]. The DC-DC converters are widely used in regulated switch-mode dc power supplies and in dc motor drives applications [2]. In most cases the input of these converters is an unregulated dc voltage, obtained by rectifying the line voltage, and hence it fluctuates due to changes in the line voltage magnitude [3]. Switch-mode DC-DC converters are used to convert the unregulated dc input into a regulated dc output for a desired voltage value [4]. The heart of maximum power point tracking (MPPT) hardware is a switch-mode DC-DC
converter [5]. MPPT uses the converter for a different purpose: regulating the input voltage at the PV MPP and providing load matching for the maximum power transfer [6] and [7]. The major advantages of Ćuk converter over the Buck type are that [7]:

- Both the input current and the current feeding the output stage of the Ćuk converter are reasonably ripple-free.
- Ćuk converter is also able to step up and down the voltage. It uses a capacitor as the main energy storage which results in a continuous output current.
- The Ćuk converter circuit has lower switching losses and higher efficiency.
- Ćuk converter does not allow electromagnetic interference like others.

In this paper, both converters were assumed to operate in a continuous conduction mode (CCM) and designed to function as step-down converters [8]. Thereafter, the model-based circuits will be simulated and the output voltage and current levels and response curves compared and discussed.

2. OPERATION PRINCIPLES OF THE PROPOSED DC-DC CONVERTERS

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 [9]. Many different types of converters with a variety of control schemes are used [10]. With the development in power electronics and improved technology, a more robust design and fast control is needed. This has led to the need for newer and more reliable design of DC-DC converters [11].

2.1 Buck Converter

A buck converter is the most basic switch-mode power supply (SMPS) topology. It is widely used throughout the industry to convert a higher input voltage into a lower output voltage [12]. The buck converter (voltage step-down converter) is a non-isolated converter, hence galvanic isolation between input and output is not given [13]. Figure 1(a) depicts the basic Buck converter topology consisting of low-pass filter and a diode, connected in parallel with a switch and equivalently with the DC source ($V_d$).

When the switch in Figure 1 is closed for the time duration $t_{on}$, the input voltage $V_d$ appears across the load R. For the time duration $t_{off}$, the switch remains open and the voltage across the load is zero as depicted from the waveform of Figure 1(b).
2.2 Ćuk Converter

The basic non-isolated Ćuk converter is shown in Figure 2. 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 [14]. It has the advantage of having higher efficiency and lower ripple currents and reduced switching losses.

![Schematic Diagram of Basic Ćuk Converter](image)

Figure 2: Schematic Diagram of Basic Ćuk Converter
Figure 3: Ćuk Converter Waveforms; (a) when switch T is off  (b) when switch T is on

The converter circuit operates in two different modes [14]. During mode 1, when the switch T is closed, as shown in Figure 3(b), 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 3(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.

3. DESIGN CONSIDERATIONS

3.1 Buck Converter

The average output voltage of the Buck converter is given in Equations (1) and (2)

$$V_o = \frac{1}{T_s} \left[ \int_{0}^{T_{on}} V_d \, dt + \int_{T_{on}}^{T_{s}} 0 \, dt \right] = \frac{T_{on}}{T_s} V_d = D V_d \quad (1)$$

Therefore,

$$V_o = D V_d \quad (2)$$

Where, $D$ is the switch duty cycle.

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

<table>
<thead>
<tr>
<th>Table 1: PV Panel Characteristics</th>
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<tbody>
<tr>
<td>Maximum power $P_{max}$</td>
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<tr>
<td>Voltage $V_{max}$</td>
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<tr>
<td>Maximum current, $I_{max}$</td>
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<tr>
<td>Open Circuit Voltage, $V_{oc}$</td>
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<td>Short circuit current $I_{sc}$</td>
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The design of Buck converter starts with the selection of one inductor and one capacitor with a resistive load.

Input voltage range: 12V – 17V

Output voltage and current: 12V, 10.8 Amp.

By using the equation; $V_o = D V_d$, the duty cycle is calculated to be 0.71.

The value of the inductance as calculated is given in Equation (3).

$$L = \frac{V_o(1-D)}{F_s \Delta I_{L_1}} = 43 \mu H \quad (3)$$

And the value of the capacitor is also calculated using Equation (4).

$$C = \frac{V_o(1-D)}{8P_2 \Delta V_{out}} = 135 \mu F. \quad (4)$$

Where, $\Delta I_{L_1} = 30\%$ of $I_{out}$ and $\Delta V_{out} = 10\%$ of $V_{out}$.

The switching frequency is chosen as $F_s = 25 kHz$ with a Time period $T = 0.04 ms$. 
3.2 Ćuk Converter

The Ćuk converter can step the voltage either up or down, depending on the duty cycle. The desired output voltage as in Buck converter design is 12V. The input is also assumed to be 17V and the duty cycle calculated as \( D = 0.41 \).

Output voltage and the duty cycle are related as shown in Equation (5).

\[
V_o = -V_d \left[ \frac{D}{1-D} \right]
\]  

(5)

The switching frequency is chosen as \( F_s = 120 \, kHz \) with a Time period \( T = 0.083 \, ms \).

Design equations for non-isolated Ćuk converter elements are as in Equations (6) through (9).

\[
L_{1\text{min}} \geq \frac{(1-D)R}{2DF_s} \quad \text{(6)}
\]

\[
L_{2\text{min}} \geq \frac{(1-D)R}{2F_s} \quad \text{(7)}
\]

\[
C_{1\text{min}} \geq \frac{D}{2F_s R} \quad \text{(8)}
\]

\[
C_{2\text{min}} \geq \frac{1}{8F_s R} \quad \text{(9)}
\]

The calculated values of the designed variables are; \( D = 0.41, L_1 = 1.8\,mH, L_2 = 1.2\,mH, \)

\( C_1 = 3.4\,\mu F, \quad C_2 = 21\,\mu F \) and \( R = 5\,\Omega \).

4. RESULTS AND DISCUSSION

The Buck and Ćuk converters circuit models are shown in Figures 4 and 5 respectively. The parameters calculated were used to simulate both circuit models in MATLAB/SIMULINK environment. The basic Buck converter type consists of a controlled switch, an uncontrolled switch (diode), an inductor and a capacitor, while the Ćuk converter has two inductors, two capacitors, a diode and a transistor switch. Both converters have pulsating or discontinuous input currents and continuous or non-pulsating output currents, because the output currents were supplied by the combination of both inductors and capacitors. Their respective output voltage and current responses are as shown in Figures 6, 7, 8 and 9.
Figure 4: Buck Converter Simulation in MATLAB

Figure 5: Ćuk Converter Simulation in MATLAB/Simulink
Figure 6: Output Voltage Response of Buck Converter

Figure 7: Output Current Response of Buck Converter

Figure 8: Ćuk Converter Output Voltage Response in Step-Down Mode

Figure 9: Ćuk Converter Output Current Response in Step-Down Mode

By comparison, it can be observed from Figures 6 and 8 that the output voltage response for Ćuk converter contains little or no ripples and also moves closer to the desired output voltage value of 12V, while the response for Buck converter type has ripples and less closer to the required output voltage value, at almost 11.7V. The settling time for Ćuk converter is less than that of its Buck counterpart with almost 0.003s.
Comparing Figure 7 with 9, it can be observed that, the output current for the Buck converter fluctuates with a lot of ripples between the values of 10A to 14A, while the Ćuk converter’s current response stays at -2.4A, having little or no ripples. However, the Buck converter’s current response is closer to the desired output current response.

5. CONCLUSION
The design and simulation of the DC-DC step down conversion of Ćuk and Buck converters have been carried out for constant voltage applications. Both converters have been designed to deliver 12V at their outputs. The step down capability of both converters is presented on the basis of simulation in MATLAB/SIMULINK. The design concepts were validated through simulation and the results obtained showed that step down conversion using Ćuk converter has higher efficiency and lower switching losses. Also it can be seen, from the result that, the Ćuk converter is reasonably ripple-free, whereas the Buck converter produces a lot of ripples at its output. The results further proved that Ćuk converter offers greater advantages over the Buck converter for constant voltage applications.
6. REFERENCES


## Authors

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