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Optimization Parameter Design of SEPIC-Cuk Converter

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Abstract: This paper discusses the optimization parameters design of combined SEPIC-Cuk converter based on SEPIC and Cuk operation for dual output voltage polarities. The SEPIC-Cuk converter is designed to be operated in continuous conduction mode, the selection of passive components, i.e., inductor and capacitor are based on the switching frequency, the duty cycle and inductor current ripple. The range of duty cycle for buck operation is $0<D<0.5$, meanwhile for boost operation, the duty cycle range is $0.5<D<1$.The simulation and experimental results show a good agreement. Thus, the designed parameters of the converter are confirmed. The finding shows that during buck operation, the output voltages are +3.96 V and -3.96 V with duty cycle of 0.25 when the output voltage is 12 V. Meanwhile, during boost operation, the output voltages are +36 V and -36 V with the duty cycle of 0.75 when the output voltage is 12 V.

Keywords: SEPIC-Cuk converter, DC-DC converter.

1. Introduction

In recent years, portable electronic equipment has advanced from a power converter and has the advantages of high efficiency, small in size and possess a wide input and output voltage ranges [1]–[6]. On the other hand, the conventional power converter could not operate in a wide operation range with high efficiency; especially when the step up and step down voltage conversion has to be achieved [7], [3], [8]. Besides, battery voltage decreases as the battery discharges and will lead to various difficulties if there is no voltage control. Therefore, the most effective method of regulating voltage through a circuit is by using a DC/DC converter. SEPIC-Cuk converter can be applied in a battery because the voltage can be stepped up or stepped down depending on the regulator's preferred output. For example, two outputs of single input voltage sources are useful in various cases such as electrical machines, multi voltage DC micro grids, solar energy systems, data communication and telecom power systems [9]–[11].

SEPIC and Cuk converters have a different type of structure in the SEPIC-Cuk converter, where the SEPIC converter produces positive output polarity while Cuk converter produces negative output polarity. Basically, a SEPIC and Cuk converter is a buck-boost converter that can act as Buck or Boost converter depending on its duty cycle [7], [9], [10], [12]. The unique feature of the converter is that it has one switch only with the dual output polarities. The PWM switching signal can be designed using FPGA as in [13] and [14].

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This paper proposed a SEPIC-Cuk converter which can produce a regulated output voltage with positive and negative polarities. The output of this converter can be regulated by using a single switch which is PWM switching signal through FPGA board. The theoretical and simulation results have been verified and compared by a 50W experimental prototype. In addition, the optimization parameters for the passive components are discussed in detail in this paper. The proposed converter has the following advantages: two different outputs polarities, regulated output DC voltage and minimum number of power switch.

2. Principle of SEPIC-Cuk converter

Single-ended primary-inductor converter (SEPIC) is a type of DC-DC converter that allows the stepping-up and stepping-down of output voltage. Fig. 1 shows the SEPIC part that requires a larger current across the inductor L_2, meanwhile the Cuk part requires a larger voltage across the capacitor C_2. The operation of SEPIC is the same as the conventional buck-boost converter, where the output voltage is always positive polarity. However, the Cuk has only negative output voltage with buck and boost operations.

A dual output voltage DC/DC converter consists of a combination of SEPIC-Cuk converter with their respective characteristics. When SEPIC-Cuk characteristics are compared, the converter will have the same voltage conversion ratio but different in polarities. The performance of SEPIC and Cuk combination converter can be analyzed in terms of the size of magnetic components, low input ripple and device stress.

However, when the duty cycle approaches one, the DC gain moves towards zero [15]. To determine the optimization of parameter, the minimum value of frequency need to be considered. When the duty cycle increases, the value of frequency decreases which resulting the ripple current on the inductor to decrease.

Fig. 2 shows the DC gain characteristics for the SEPIC-Cuk converter. This structure on Fig. 1 consists of buck and boost operation in which the buck operation has less than 0.5 duty cycle compared to the boost operation that has more than 0.5 duty cycle.

Fig. 3 shows the relationship between switching frequency and the duty cycle. It shows the boundary of CCM and DCM in terms of the minimum selection of switching frequency versus duty cycle. Besides, the appropriate inductance can be determined from the boundary of CCM and DCM. On the other hand, the middle point of duty cycle of buck and boost operation modes are 0.25 and 0.75, respectively.

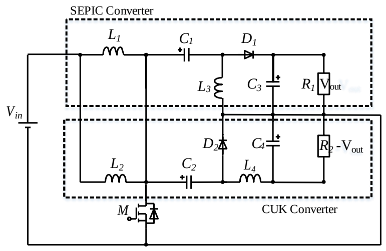


Fig. 1 - Circuit of SEPIC-Cuk converter [7]

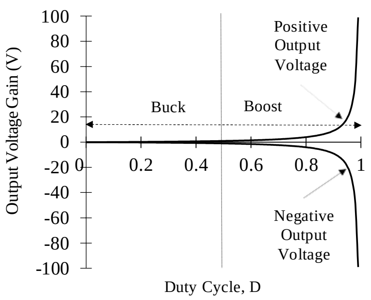


Fig. 2 - DC gain characteristics

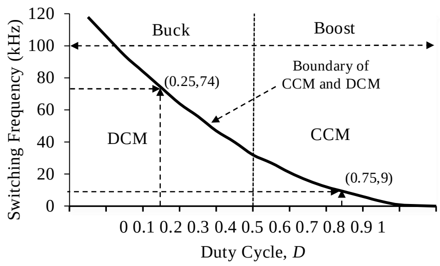


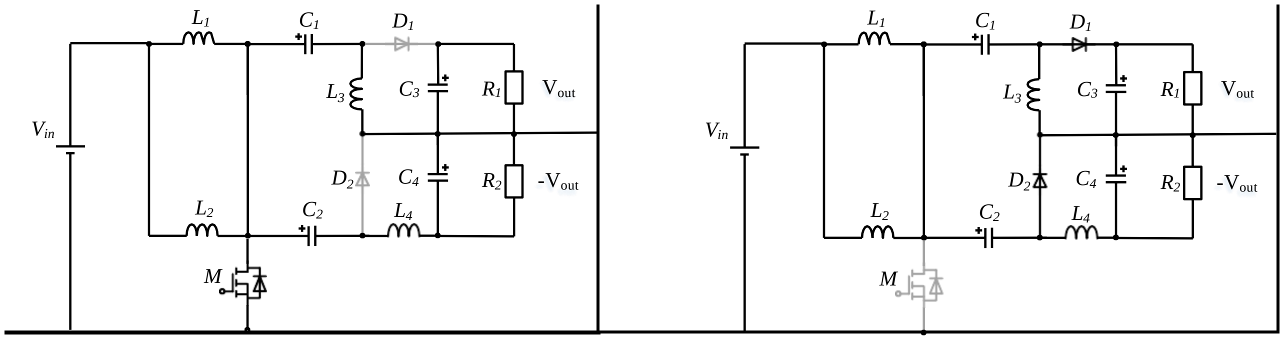
Fig. 3 - Boundary of CCM and DCM

3. Operation of SEPIC-Cuk converter

In topology [7], the circuit of combination SEPIC-Cuk converter is controlled by a single switch as shown in Fig. 1. This circuit can be divided into two operating modes.

Mode 1: The equivalent circuit of SEPIC-Cuk converter in mode 1 operation is shown in Fig. 4 (a). When the switch M is turned-ON, the energy is stored in L_1. Initially, L_1 is equivalent to two inductors ($2L_1$). At the same time, inductors L_2 and L_3 stored energy due to the discharge of C_1 and C_2. During this interval, the freewheeling diodes (D_1 and D_2) are turned-off and the power is supplied to the loads.

Mode 2: The equivalent circuit of SEPIC-Cuk converter in mode 2 operation is shown in Fig. 4 (b). When the switch M is turned-off, the inductors recharge the capacitors C_1 and C_2 through the freewheeling diodes and supply power to the loads.



(a) (b)

Fig. 4 - Equivalent circuit of SEPIC and CUK converters in (a) mode 1 and (b) mode 2 [7]

4. SEPIC-Cuk Converter design parameter

The main function of SEPIC-Cuk converter is to increase and decrease the output voltage with a different polarity. The initial specification is considered in order to determine the parameters of the converter. The converter specifications are shown in Table 1.

Table 1 - Initial specification of SEPIC and CUK converters parameters

Parameters	Values				
Input Voltage, V_{in}	12 V				
Switching Frequency, F_{SW}	50 kHz				
Output Resistor, R	200 Ω				
Duty Cycle, D	25%	40%	50%	60%	75%
Boost ratio, β	0.33	0.67	1.00	1.50	3.0

4.1 Output Voltage

Based on the input voltage specification, Table 1, the output voltage of SEPIC and Cuk can be expressed in Eqn. (1) and Eqn. (2) respectively as follows:

$$\text{SEPIC: } V_1 = \frac{D \cdot V_{in}}{1-D} \quad (1)$$

$$\text{CUK: } V_2 = -\frac{D \cdot V_{in}}{1-D} \quad (2)$$

4.2 Inductors Selection

Next, the input inductors (L_1 and L_2) and other inductors (L_3 and L_4) can be expressed in Eqn. (3). Theoretically, the larger the inductance, the lower the inductor current ripple. However, the appropriate selection of the inductance is an important aspect to be considered.

$$L_x = \frac{V_{in} \cdot D}{\Delta I \cdot L_x \cdot f_s} \quad (3)$$

where, $Lx = L_1 = L_2 = L_3 = L_4$

4.3 Link Capacitor Selection

The third step to calculate the link capacitors (C_1 and C_2), Eqn. (4). The role of the link capacitor is to transfer the energy to the output side.

$$C_x = \frac{I_{in}(1-D)}{\Delta V \cdot C_x \cdot f_s} \quad (4)$$

where, $C_x = C_1 = C_2$

4.4 Output Capacitor Selection

The fourth step is the estimation of the output capacitors (C_3 and C_4). The output capacitors such that the ripple at the output voltage is less than 1% of the DC output voltage. Therefore, the output voltage ripple can be expressed as follows:

$$\Delta V_{out} = \frac{V_{out}\left(1-D\right)}{8 \cdot R \cdot C} T_s^2 \qquad (5)$$

4.5 Parameters Estimation

After all the parameters are determined, the SEPIC-Cuk converter specifications are listed as shown in Table 2. The output voltage depends on the duty cycle.

Table 2 - SEPIC and CUK converters calculation parameters

Parameters	Values				
Input Voltage, V_{in}	12 V				
Switching Frequency, F_{SW}	50 kHz				
Output Resistor, R	200 Ω				
Duty Cycle, D	25%	40%	50%	60%	75%
Boost ratio, β	0.33	0.67	1.00	1.50	3.0

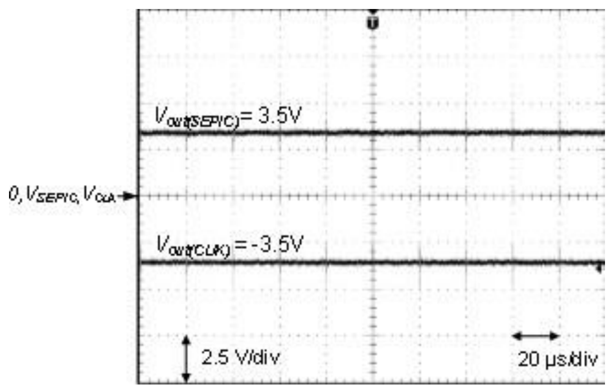
5. Experimental Results

Table 3 shows the output voltage based on the duty cycle of the SEPIC-Cuk converter. It can be observed that for the calculation results, the estimated output voltages are based on the ideal condition. Due to the parasitic elements on the non-ideal components, there are errors between the design values and the experimental results. But the errors are small and can be considered acceptable. Thus, all the results between calculation, simulation and experiment are in a good agreement, Table 3.

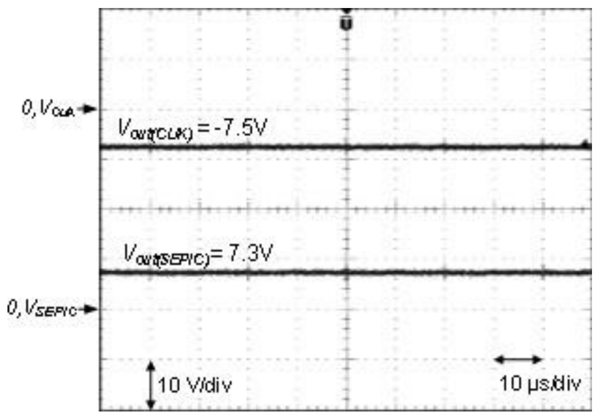
Figs. 5 (a), (b), (c), (d), and (e) shows the output voltage waveform of the SEPIC-Cuk converter with several duty cycles, i.e., 25%, 40%, 50%, 60% and 75%. The switching frequency and the input voltage are fixed at 50 kHz and 12 V, respectively for all the duty cycle operations. The switching frequency of 50 kHz is selected for CCM operation and the values for all the inductances are fixed at 3.3 mH. The operation for buck and boost of the SEPIC-Cuk converter are verified by these experimental results. Thus, the design parameters of the converter are confirmed.

Table 3 - All result output voltage of SEPIC-Cuk converter

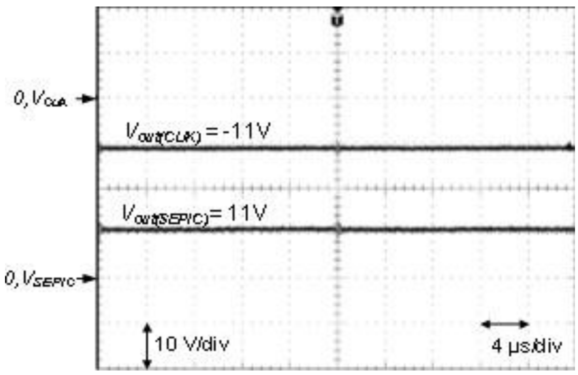
Duty Cycle (%)	Calculation		Simulation		Experimental	
	SEPIC (V)	CUK (V)	SEPIC (V)	CUK (V)	SEPIC (V)	CUK (V)
25 (buck)	3.96	-3.96	3.90	-3.90	3.5	-3.5
40 (buck)	8.04	-8.04	7.30	-7.30	7.3	-7.5
50 (V_{in}=V_o)	12.0	-12.0	11.30	-11.30	11	-11
60 (boost)	18.0	-18.0	17.30	-17.30	17	-18
75 (boost)	36.0	-36.0	35.50	-35.50	32	-34



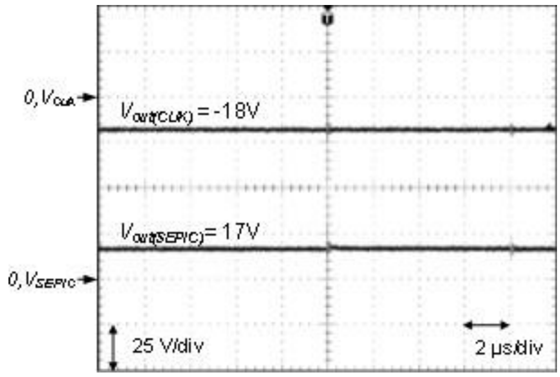
(a)



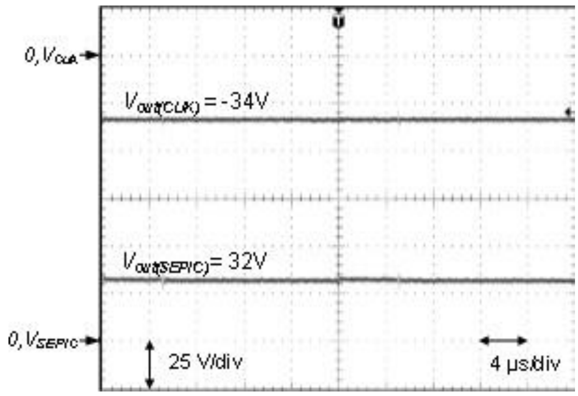
(b)



(c)



(d)



(e)

Fig. 5 - The output voltage of SEPIC-Cuk converter with duty cycle (a) 25% (b) 40% (c) 50% (d) 60% (e) 75%

6. Conclusion

This paper discussed the designed parameters and operation of the SEPIC-Cuk converter with dual polarities of the output voltages and single switch consideration. In addition, structure uses only single switch (MOSFET) in order to control both circuits, positive (SEPIC) and negative (Cuk) polarities. Based on the experimental results, the designed parameters of the converter have been confirmed.

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