Voltage Ripple Comparisons of some DC-DC Converters and their Interleaved Versions

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Abstract. *In order to achieve high efficiency when boosting and lowering voltage, DC-DC converters are used. A large amount of di/dt and du/dt of switching circuits causes unwanted electromagnetic noise, which disturbs both the input and output parts of the circuit. The paper presents interleaved design of DC-DC converters. In cases where output voltage quality is important, this simple concept can be used as a replacement for some conventional electronic switching systems. In this paper, the operation of existing DC converters is analyzed and comparations with interleaved (canonical) DC converters are given. The application of interleaved converters can be useful for consumers who require as stable voltage signals as possible. In addition, better stabilization of the output voltage of DC converters can contribute to the application of low-cost filter elements in circuits.*

1 Introduction

Switching power converters have been replacing linear power converters for a long time. The reason for this is higher efficiency, lower mass and volume, and smaller costs [1]. Although today's converters have a high efficiency of energy conversion, they also have disadvantages related to fast switching on and off of input and output currents. As a result, electromagnetic interference occurs, [2], so it is necessary to use additional filters, which again increases the cost of the converter and reduces efficiency.

The proposed interleaved converters use all the advantages of conventional switching DC converters, whereby a better quality of the output voltage is enabled at lower switching frequencies compared to conventional DC converters.

2 The overwiev of DC-DC converters

2.1 Linear voltage regulator

In a linear voltage regulator, the transistor operates in the linear region as a variable resistance, so that the output voltage can be regulated from zero to the value of the source voltage (Figure 1).

This simple way of converting a DC source voltage to a lower DC voltage has a serious disadvantage in terms of efficiency, as part of the source power is absorbed by the load, so it has limited application.

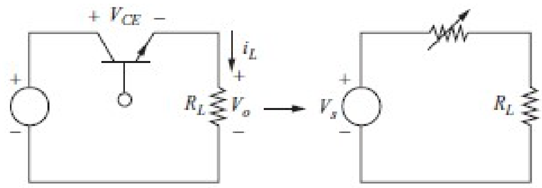

Figure 1. A basic linear regulator

2.2 The switching converters

An effective alternative to a linear voltage regulator is a switching converter, which can work as a buck, boost or buck-boost, giving its output a lower or higher voltage compared to the input voltage [3].

In a switching converter circuit, the transistor operates in switching mode by being either fully on or fully off. If the switch were ideal, the output voltage would be equal to the input one when the switch is closed, and the output voltage would be zero when the switch is open. However, the voltage drop on real switches is not equal to zero when they are conducting, so during the transition from one state to another, the switch goes through a linear state, which results in losses.

2.3 Simulation model of the buck converter

A buck converter is a DC/DC converter that steps down the voltage from its input (source) to its output (load). In continuous conduction mode (the current through the inductor never drops to zero), the theoretical transfer function of this converter is:

$$V_0 = V_S \cdot D \tag{1}$$

In the buck converter model, the diode in the parallel branch conducts when the MOSFET switch in the series branch is off (Figure 2). In this model, the inverter supplies the RC load from a 24 V source. The output voltage cannot be constant because a real capacitor has a finite capacitance. Therefore, there is a ripple in the output voltage which is measured from peak to peak of the output voltage:

$$\Delta V_{out} = \frac{V_{out}(1-D)}{8LCf^2} \tag{2}$$

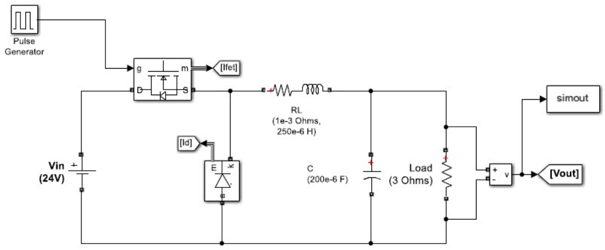

Figure 2. Buck converter model

2.4 Simulation model of voltage booster

A voltage booster is a DC-DC converter that steps up the voltage from its input to its output (Figure 3). The theoretical gain transfer function of the converter is:

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \tag{3}$$

The final value of the capacitance results in output voltage fluctuation, or voltage ripple. The peak-to-peak voltage ripple value in this case is:

$$\Delta V_{out} = \frac{V_{out} D}{RCf} \tag{4}$$

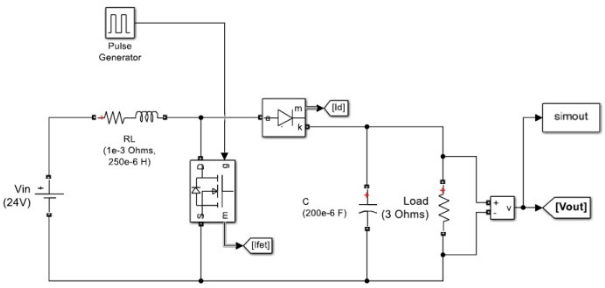

Figure 3.Booster model

2.5 Simulation model of buck boost converter

A buck-boost converter is a DC/DC converter where the output voltage is greater or less than the input voltage, depending on the factor D. The theoretical transfer function of the buck converter is:

$$abs(V_{out}) = \frac{D}{(1-D)} \cdot V_{in} \tag{5}$$

An inverting buck-boost topology produces an output voltage that is opposite in polarity to the input voltage. The output voltage is determined by the duty cycle of the MOSFET transistor (Figure 4). The output voltage fluctuation is determined by:

$$\Delta V_{out} = \frac{D \cdot V_{out}}{RCf} \tag{6}$$

2.6 Simulation model of Cuk DC-DC conveter

A non-isolated Ćuk converter is a DC/DC power converter that can produce an output voltage (V_{out}) which is greater or less than input voltage (V_{in}). This is an inverting topolgy, so the output voltage is of the opposite polarity compared to the input voltage.

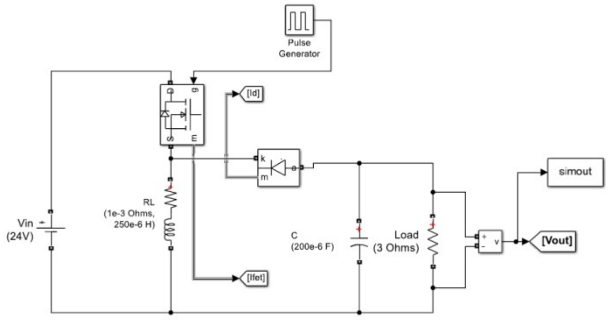

Figure 4. Buck. boost pretvarač

Capacitor C1 acts as the primary means of storing and transferring energy from the input to the output (Figure 5). The advantage of this converter is that both the input current (I_{L1}) and the current feeding the output stage (I_{L2}) are relatively ripple-free (unlike a buck-boost converter where both of these currents are very discontinuous).

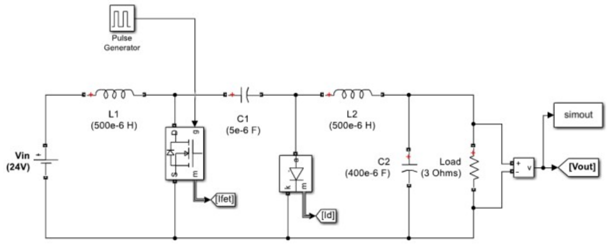

Figure 5. Ćuk model DC-DC converter

Assuming there is a constant voltage across C1, the theoretical transfer function of the Ćuk converter is:

$$\frac{V_{out}}{V_{in}} = -\frac{D}{1-D}$$

2.7 Simulation model of interleaved converter

The interleaving is a useful technique for reducing filter components. This converter is equivalent to a parallel connection of two switches where the diode and the choke are connected to a common C filter and load [4]. The operation of the switch is phase shifted by 180 degrees, so the choke currents are also shifted by 180 degrees. This model is known as canonical as well. The current entering the capacitor and load resistance is the sum of the inductor currents, has less peak-to-peak variation and twice the frequency of the individual inductor currents. This results in less current capacitor variation compared to one achieved with a single buck converter, and less capacitor for the same output voltage ripple. Interleaving can be done with two or more converters, where the phase shift is 360°/n, n being the number of paralel converters. Figure 6 shows the scheme for an interleaved buck converter. Other types of converters are interleaved in a similar way.

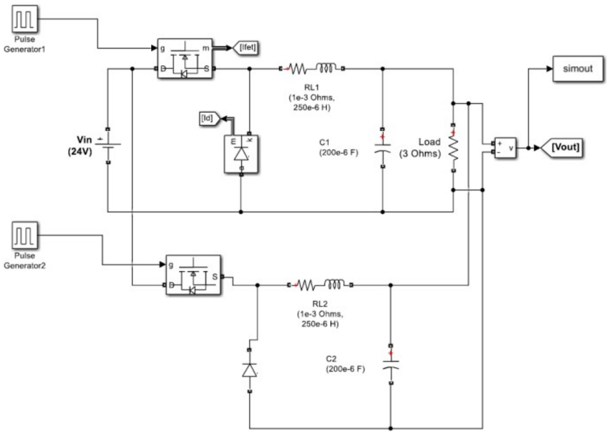

Figure 6. Interleaved buck converter model

3 Comparison of the output voltage ripple of classic DC-DC converters and their interleaved versions

Input parameters of all simulation modes are:

$$V_{in} = 24V, R_{out} = 3\Omega, C_1 = 200\mu F$$

$$R_1 = 10^{-3}\Omega, L_1 = 250 \cdot \mu H$$

The secondary circuit is phase shifted relative to the primary control circuit throughout the observation period. The minimum and maximum value of the output voltage at discrete time points has been measured during the entire observation period. The ripple value of the output voltage is observed from the stationary state.

The absolute value of the difference between the maximum and the minimum value is used to modify the phase shift between the control clock of pulse generators. The smallest calculated phase shift becomes the new shift of the secondary circuit relative to the primary circuit in the next time interval. This achieves minimal ripples. The cases of classic converters and their interleaved versions for frequencies, 10 kHz and 20 kHz, with duty factor of 10% and 90% were examined. A comparison of each converter with its interleaved version (canonic) are shown (Figures 7-12).

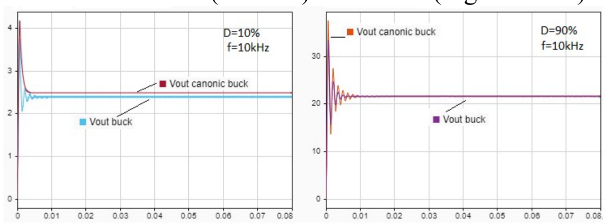

Figure 7. Output voltages comparision of classic buck and interleaved buck converters, frequency 10 kHz

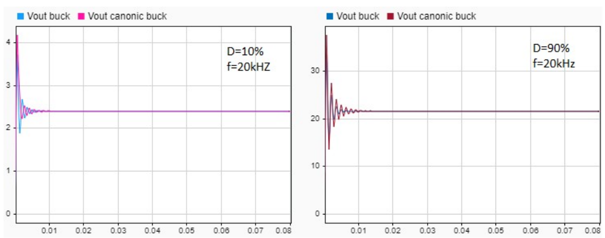

Figure 8. Output voltages comparison of classic buck and interleaved buck conveters, freqeuncy 20 kHz

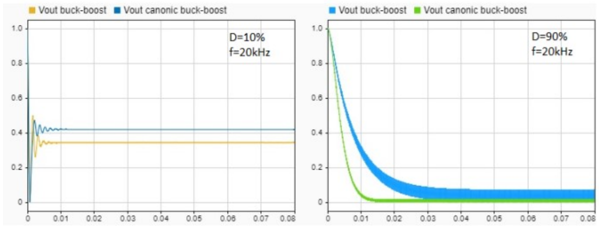

Figure 9. Output voltages comparisions of classic buck_boost and interleaved buck_boost converters, frequency 20 kHz

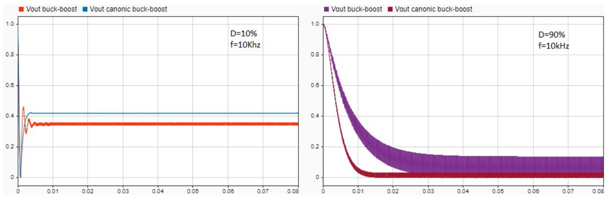

Figure 10. Output voltages comparisions of classic buck_boost and interleaved buck_boost converters, frequency 10 kHz

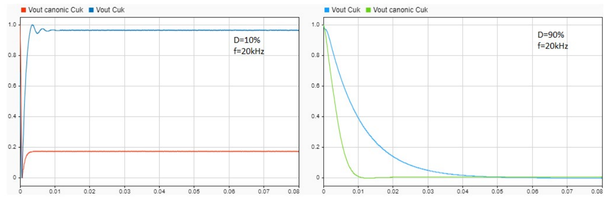

Figure 11. Output voltages comparisions of classic Cuk and interleaved Cuk converters, frequency 20 kHz

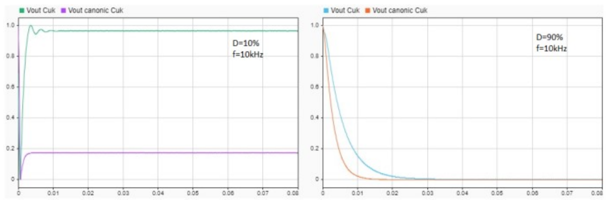

Figure 12. Output voltages comparisions of classic Cuk and interleaved Cuk converters, frequency 10 kHz

In the case of a duty factor of 10% and f=10 kHz, the output voltage of the interlevaed buck converter in the stationary state has 6 times less oscillation compared to the ordinary buck converter, and comes to a steady state much faster than a classic buck converter (Figures 7,13,14).

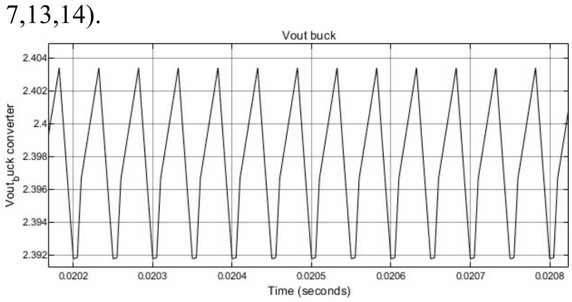

Figure 13. The segment of the buck conveter output voltage

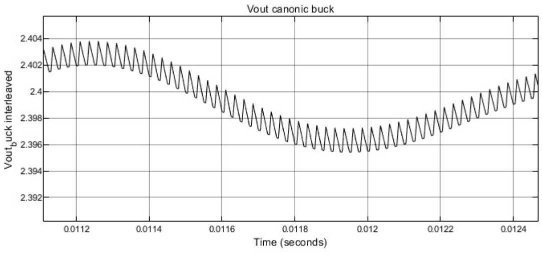

Figure 14. The segment of the interleaved buck converter output voltage

Output voltage of interleaved buck-boost conveter has 5.3 times less oscillation (Figures 10, 15, 16) while Ćuk has 1.4 times less oscillation, compared to their interleaved versions (Figures 11,12,17,18).

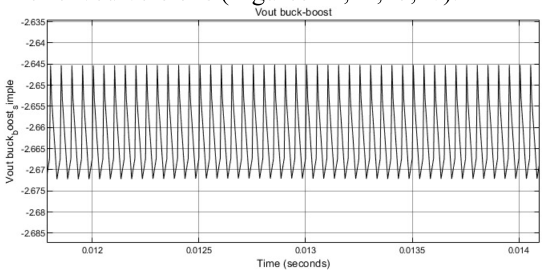

Figure 15. The segment of the buck-boost converter output voltage

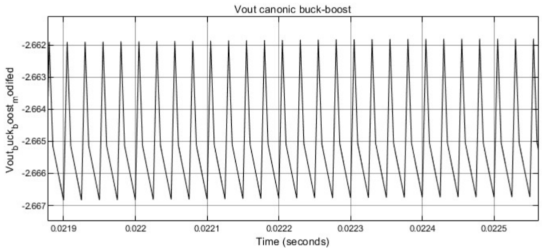

Figure 16. The segment of the interleaved buck-boost converter output voltage

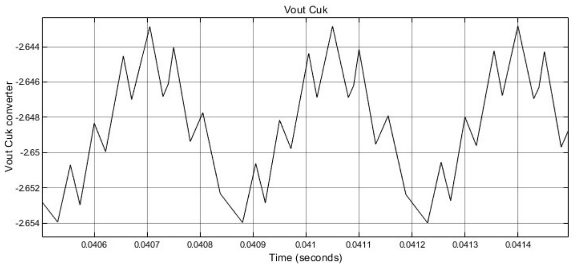

Figure 17. The segment of the Cuk converter output voltage

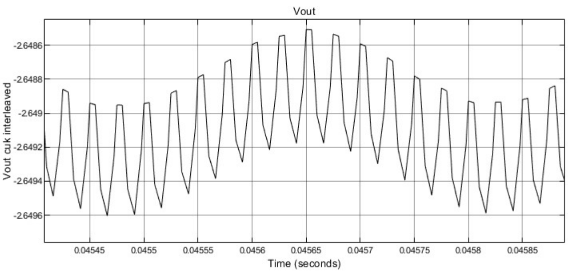

Figure 18. The segment of the interleaved Cuk converter output voltage

A detailed overview of the ripple values of the output voltages of classic and interleaved DC-DC converters are shown in the Table 1.

Table 1. Voltage ripple comparisons

Converter type	Voltage ripple V_{out}			
	Frequency 20 kHz		Frequency 10 kHz	
	D=10%	D=90%	D=10%	D=90%
buck	0.0116	0.0108	0.0462	0.0464
Interleaved-buck	0.0018	0.0018	0.077	0.0073
boost	0.222	16.96	0.4434	33.78
Interleaved-boost	0.0494	3.87	0.0992	7.74
buck_boost	0.0269	15.2709	0.0782	30.4047
Interleaved buck_boost	0.0049	3.4924	0.0147	7.0013
Cuk	0.0116	0.6719	0.0157	0.4809
Interleaved Cuk	0.0229	0.0467	0.0108	0.1798

4 Conclusion

The desired performance of the converter in terms of fast switching transitions of the switching elements and the greater ability to store electrostatic and electromagnetic energy requires higher costs. The point of this work was to achieve the most stable possible output voltage of the converter with the control structure while limiting the costs related to the switching frequency of the circuit and the costs related to the energy storage elements. Aside from the mentioned advantages of the interleaved converters compared to the conventional ones, the interleaved converters are also characterized with the advanages regarding the ways of interrupting the current, so that the value of the possible overvoltage on inductive elements is reduced. The interleaved mode of converter control can easily be applied to bidirectional inverters.

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