Reduction of Ripple and EMI in DC-DC Cuk Converter using Chaos Theory and Tuned Band Rejection Filter

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Abstract—In this paper, the effect of chaos-filter combination on the electromagnetic emissions and output ripple magnitude of a current-mode controlled Cuk converter is studied. When dc-dc cuk converter is operated in the chaotic region, electromagnetic interference is found to be minimized, because chaos spreads the spectrum of the converter output thereby reducing the interference power. Furthermore, by designing a tuned band reject filter and introducing the filter on the input side of the converter, in addition to the chaotic operation of the converter, the total conducted emission noise and ripple on the output voltage of the converter are reduced to a greater extent. The simulations are carried out in Matlab and are verified with the measured results.

Index Terms—Cuk converter, chaos, EMI, tuned band rejection filter, spectral analysis

I. INTRODUCTION

Recently, the use of chaos in reducing electromagnetic emissions in dc-dc converters has attracted great interest. Switched mode power supplies are known to be capable of chaotic behaviors [1]-[5]. Bifurcation and chaos in a current mode controlled cuk converter are analyzed extensively in the literature [6]-[9]. The distinct effect of chaos on reducing ripple and electromagnetic interference (EMI) in the cuk converter is largely explored.

In conventional power supplies, all the waveforms are periodic and hence most of the energy is concentrated in narrow spikes at the clock frequency and its harmonics [10]-[13]. With modulation, however, the energy is spread over a wide range of frequencies. The advantage is that the height of the spikes is now reduced, there by magnitude of ripple and EMI in output voltage of the converter is reduced [13]. The ripple and noise spikes are suppressed effectively with the help of various types of filter [15-18]. In [16], a tuned band reject filter (TBRF) is designed and introduced on the input side of the converter to reduce the interference noise.

In this paper, the current mode controlled cuk converter is operated in the chaotic state by chaotic parameter modulation method. In addition; a tuned band rejection filter has been designed and included in the circuit.

The effects on EMI reduction with chaos alone and with chaos-filter combination are studied using spectrum analysis. The simulated results are verified with the measured results.

II. CUK CONVERTER

The Cuk converter is a type of dc-dc converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude.

![Schematic of cuk converter](image)

Figure 1. Schematic of cuk converter

A non-isolated Cuk converter comprises of two inductors, two capacitors, a switch and a diode. Its schematic can be seen in figure 1. It is an inverting converter, so the output voltage is negative with respect to the input voltage.

Figure 2 shows the two operating states of a non-isolated Cuk converter. In this figure, the diode and the switch are either replaced by a short circuit when they are on or by an open circuit when they are off. It can be seen that in the off state, the capacitor C is being charged by the input source through the inductor L1. In the on state, the capacitor C transfers the energy to the output capacitor through the inductance L2.

The capacitor C is used to transfer energy and is connected alternately to the input and to the output of the converter through the commutation of the transistor and the diode as shown in figure 2.
The schematic diagram of current control Cuk Converter, operating in continuous conduction mode is shown in figure 3.

When \( i_{\text{sum}} \) is less than the reference of current \( i_{\text{ref}} \) and the comparator outputs a low level, \( S \) is on and \( i_{\text{sum}} \) increases. Once \( i_{\text{sum}} \) reaches the reference of current, the output of comparator turns to high, \( S \) transits from on to off, and \( i_{\text{sum}} \) begins to decrease. The circuit remains in this status until clock1 arrive to a flip. Then \( S \) returns to on with the above process. In order to make \( S \) off at least once in a period of clock, an OR gate is introduced to the circuit. If \( i_{\text{sum}} \) does not reach value of reference, the flip of clock2 will force the R of RS flip-flop to high, thus make the switch \( S \) to on.

Table 1 illustrates the above process [8]. Table 1 describes the ‘S’ status under all kinds of circuit conditions.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Switch ( S ) State</th>
</tr>
</thead>
<tbody>
<tr>
<td>clock1 flip</td>
<td>Off to On transition</td>
</tr>
<tr>
<td>clock1=0, clock2=0, ( i_{\text{sum}} &lt; i_{\text{ref}} ), ( \frac{di_{\text{sum}}}{dt} &gt; 0 )</td>
<td>Off</td>
</tr>
<tr>
<td>clock1=0, clock2=0, ( i_{\text{sum}} = i_{\text{ref}} )</td>
<td>On</td>
</tr>
<tr>
<td>clock1=0, clock2 flip, ( i_{\text{sum}} &lt; i_{\text{ref}} )</td>
<td>On to Off transition</td>
</tr>
<tr>
<td>clock1=0, clock2=0, ( i_{\text{sum}} &lt; i_{\text{ref}} ), ( \frac{di_{\text{sum}}}{dt} &lt; 0 )</td>
<td>Off</td>
</tr>
</tbody>
</table>

III. CHAOS IN CUK CONVERTER

The changes in the behavior of the cuk converter is analyzed by varying the parameter reference current \( i_{\text{ref}} \). The converter operates periodically at an \( i_{\text{ref}} \) of 0.2A. When the increase in the reference current \( i_{\text{ref}} \), the converter enters bifurcative regime and finally found to exhibit chaos. To this purpose, a detailed analysis for different values of \( i_{\text{ref}} \) has been carried out. For the value of \( i_{\text{ref}} \) as 0.5A the period 2 sub harmonic operation is found. When the value of \( i_{\text{ref}} \) is further increased, the converter enters chaotic operating regime. The chaotic behavior is obtained at \( i_{\text{ref}} = 0.8A \).

IV. TUNED BAND REJECT FILTER CONFIGURATION

The tuned band reject filter is a simple and low cost solution for conducted EMI [16]. It is a parallel combination of an inductor \( L \) and a capacitor \( C \) as shown in figure 4.

The resonant circuit offers negligible resistance at DC, and high impedance at parallel resonant frequency \( f = \frac{1}{2\pi\sqrt{LC}} \). The impedance \( Z_p \) at resonance is given by \( L/Cr \), where \( r \) is the ohmic resistance of the inductor including other stray ohmic resistances in the parallel resonant loop. The performance of the TBRF will depend on the quality of inductance and capacitance. Lower ‘r’ gives higher order of r
The inductor chosen should have high Q and should be able to carry the required load current [16]. Band reject filter has been designed and developed in several configurations depending on the insertion loss and skirt response requirements. The simple two element TBRF given in figure 4 is found to be more useful, since there is no need for good ground for this configuration. The tuned BRF is designed to offer high order attenuation. This band reject filter attenuation is independent of load and source impedances. This filter has been practically found to be simple low cost solution for EMI and ripple suppression.

The design values of the tuned band reject filter are $C=10\mu F$, $L=60\mu H$ and $f_r=2\text{KHz}$.

V. SIMULATION AND MEASURED RESULTS

The cuk converter has been designed with the specifications of $V_{in}=15\text{ volt}$, $L_1=L_2=16\text{mH}$, $C_1=C_2=47\mu\text{H}$, $R_L=75\Omega$ and Switching frequency $f_s=5\text{KHz}$. The simulation circuit of the cuk converter built using PSPICE is shown in figure 5. The simulation is carried out with $i_{ref}$ as the bifurcation parameter.

The spectrum is related to the Fourier transform of the signal, which transforms the signal into its frequency domain. The Fourier transform displays the signals in the frequency domain, and shows the frequency content of that signal. The power density spectrums of the output voltage during periodic state, chaotic state and chaotic state with TBRF included are simulated in PSPICE.

A. Period 1 operation of cuk converter

The output waveform of the cuk converter, while operating periodically is shown in figure 6.

B. Chaotic operation of the converter

By adjusting the reference current, the system is operated in the chaotic state. The corresponding output waveform and the spectrum of the converter are shown in figure 8 and figure 9.
It is found from figure 9 that the height of the spectral peaks have been reduced during the chaotic operation of the converter and the power has been spread over a wide range of frequencies and the electromagnetic emissions have been reduced.

B. Operation of the converter with chaos and TBRF combination

The tuned band rejection filter is introduced in the converter operating chaotically and the effect of the chaos and filter combination on the converter output is studied. The corresponding output waveform and spectrum are shown in figure 10 and figure 11.

Comparing figure 8 and figure 10, it is found that the ripples have been reduced to a greater extent with the chaos-TBRF combination.

It can be observed from figure 7 that the power density concentration of the periodic running cuk converter is very sharp and the height is 24mV at the fundamental frequency of 5 KHz. In figure 9, the fft analysis for chaotic operation of cuk converter shows the spectral peak is reduced to about 7mV at the fundamental frequency and the spectrum is spread. When the tuned band reject filter is inserted on the input side of the converter and the cuk converter is made to run chaotically the ripple and noise spikes are further widespread. From figure 11, it can be seen that the peak of the ripple voltage is reduced to about 0.1mV at the fundamental frequency and reduced to a greater extent at the harmonic higher frequencies, compared to the periodic operation and chaotic operation alone.

The simulated results are verified with the experimental results as shown in figure 12 and figure 13 respectively. Figure 12 shows the comparison of the periodic spectrum and the chaotic spectrum respectively.

Figure 12. Measured Spectrum comparison of periodic and chaotic operation of the converter

Figure 13 shows the power density spectrum measured during the implementation of chaos-TBRF combination in the converter. Comparing figure 12 and figure 13, it is found that the height of the power density peaks have been reduced drastically with the chaos-TBRF combination, compared with the density height reduction using only chaos.

Comparing figure 8 and figure 10, it is found that the ripples have been reduced to a greater extent with the chaos-TBRF combination.

The measured results are found to be in good agreement with the simulated results.

V. Conclusion

As a power converter system with four dimensions, Cuk has more complex structure and control procedure. In this paper, initially, the non-linear behavior such as chaos is used for EMI reduction in the current controlled cuk converter using reference inductor current as bifurcation parameter. Then in addition to chaos, TBRF is included in the circuit and the effect of chaos-TBRF combination in reducing EMI has been analyzed using FFT analysis. The simulation results prove that both ripple and EMI noise are suppressed to a significant level when the cuk converter is made to run in TBRF-chaotic mode operation combination. The simulation results are verified with the measured results and are found to be in good agreement.
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