Chaotic triangle wave generator implementing Chua circuit towards DC/DC converter control

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Summary. In this paper, an investigation of how the nonlinear Chua circuit can be useful to control a buck converter is carried out. The comparison between a reference voltage and a triangle wave produces the classic PWM control. The chaotic PWM utilizes a chaotic triangle wave generator. The impact of these two carriers was compared and it was proved via simulations and experimental methods that the switching harmonics during chaotic control were reduced. This kind of chaotic carrier frequency modulation control can bring great advantages in electromagnetic compatibility and interference.

Introduction

Research about chaos in power electronics and especially power converters is vast such as in [1] and nonlinear techniques are promising because they can offer widespread frequency spectrums resulting in higher efficiencies [2]. However, most of the research papers are consumed towards presenting how the converter exhibits these nonlinear oscillations by introducing bifurcation diagrams and phase portraits with high amplitudes [3]. This kind of oscillations may be harmful for commercial applications, since the majority of loads requires steady voltage supply with minimum voltage ripple.

In this work, we are aiming towards using chaos as a means to maintain the widespread frequency spectrums but in the meantime restrict voltage ripple. Among many chaotic oscillators (Duffing, Colpitts etc.), Chua oscillator was chosen for the purpose of this work. Figure 1 shows the layout of the Chua circuit. R_1 is a variable resistance and by changing its value, steady state operation, periodic and chaotic oscillations are possible to take place. The signals of interest are V_1 and V_2 (shown at Fig. 2) and the famous chaotic attractor is produced by plotting against each other.

The nonlinear dynamics effect on carrier signals has already been studied such as in [4] where a chaotic carrier frequency modulation scheme can further reduce the conducted EMI. In [2], a complex triangle generator using two comparators and one RS flip-flop is presented where the conducted EMI was again further suppressed. An alternative way to reduce the switching harmonics was studied in [5] by another chaotic carrier frequency modulation scheme.

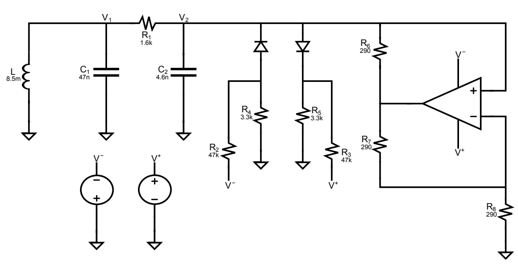

Figure 1: Chua circuit.

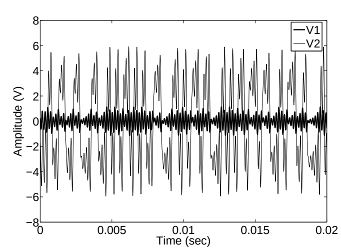

Figure 2: V_1 and V_2 chaotic signals.

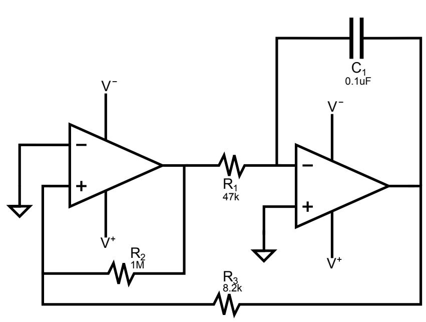

Figure 3: Triangle wave generator.

Triangle wave generator

A triangle wave generator based on [6] is presented in Fig. 3. R_2 can be considered as the responsible resistor for the signal peak to peak amplitude while R_1 for tuning the switching frequency (f_s). The output of the second amplifier is the triangle wave signal. The rails of the two amplifiers are fed with ±9V. Actually, the RC parameters create two thresholds wherein the capacitor is charging and discharging according to the switching frequency set up.

The idea of the chaotic triangle wave is based on the insertion of a small perturbation at the operational amplifier input voltage sources. In other words, the few mV of signal V_1 of the Chua circuit are added to the ±9V DC signals. The

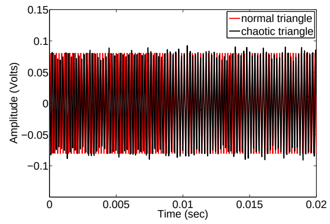

Figure 4: Chaotic and normal triangle waves.

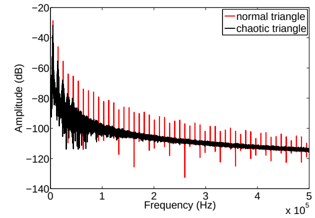

Figure 5: Fig. 4 equivalent spectrums.

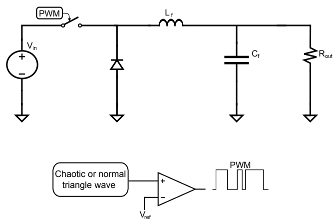

Figure 6: Buck converter layout.

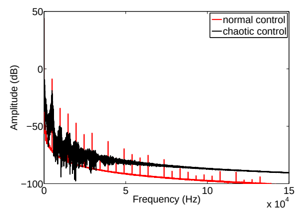

Figure 7: V_{out} FFT when f_s=5kHz.

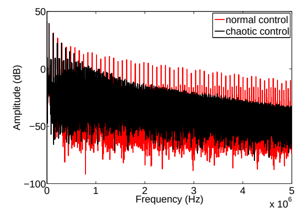

Figure 8: V_{DS} FFT when f_s=34kHz.

resulting chaotic triangle wave is compared with a simple one at Fig. 4. It is clear that in the chaotic solution the charging and discharging of the capacitor doesn't oscillate between two DC values but it rather oscillates around these values in a chaotic motion. This small perturbation creates a significant impact into the harmonic generation. The harmonic FFTs are shown in Fig. 5. While the harmonics are gathered in multiples of switching frequency with high amplitudes in the normal triangle, there is a distributed frequency spectrum in the chaotic triangle with reduced harmonic amplitudes. This advantage is achieved because of the chaotic insertion.
This control can be considered as a new chaotic carrier frequency modulation as in [5] but with a simpler design. However, as it might not be desired to feed the operational amplifiers with a chaotic voltage source, another method is possible based on the same triangle generator circuit. The chaotic perturbation from Chua circuit is inserted to the inverting input and the non-inverting input of the first and second amplifier equivalently. The sources $V^{\pm}$ are constant $\pm$9V. The results are similar with the previously mentioned configuration.

Converter operation

Figure 6 shows the converter layout. An input voltage source is feeding with power a semiconductor switch which is a SiC MOSFET during experiment. Then, a freewheeling diode, an LC filter ($L_f = 5mH$ and $C_f = 100uF$) and an electronic load constitute the rest of the buck converter. A normal triangle carrier is then compared with a reference voltage to produce a pulse which actually will be boosted by the drive circuit. This comparison can be achieved by a single op-amp where the output is an oscillating pulse between the positive and negative rail voltages. An appropriate voltage divider and a diode to cut off the negative part can create the correct pulse for the input of drive circuit. The output of the drive circuit is an isolated from the input side pulse that is applied to MOSFET's gate. After obtaining the steady state of the converter, the chaotic triangle replaces the normal one in order to capture the chaotic control operation.
The first fourier spectrum at Fig. 7 is for the output voltage between normal and chaotic control. The output ripple actually is indeed a little higher in the chaotic operation but in contrary, the harmonic spectrum appears in a widespread area during chaotic control. In the equivalent experimental results, 26% reduction was observed at the switching frequency harmonic (5kHz), while there was a 31.2% reduction at 10kHz. The second spectrum at Fig. 8 presents the comparison for the MOSFET V_{DS} (drain to source voltage) in a different simulation where the switching frequency is 34kHz. It is obvious that several dB of harmonic reduction can be achieved during chaotic control. In particular, there is a 70.7% reduced peak at the switching frequency harmonic during chaos and harmonics around 1MHz have been reduced more than 90%. Practically, the harmonic peaks are not even clear during chaos in higher frequencies due to widespread spectrum.
Experimental results confirmed the Chua circuit based triangle wave generator and also an experimental power converter was tested for the application and verification of this kind of control.

References

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