

# Feed-forward Chaos Control of a Buck Converter

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Abstract-In this paper, a computationally-based methodology to obtain chaos controllers for PWM buck power converters is proposed, developed and proven. The mathematical model of a PWM is highly nonlinear (and non-smooth) and simulations show rich phenomena. The technique is based on a feed-forward control, where the offset of the T-periodic sawtooth signal is modified continuously. Basically, the sawtooth is redefined as a function of the output and reference voltages. The controller is easy to implement with an analog circuit, and it improves the performance of the system. Additionally, it reduces the percentage of regulation error and eliminates non-desired orbits. Computational and experimental results validate the controller design. Due to space restrictions a few pictures are included in this document, but many will be presented at the conference and in the final version of this paper.

## 1. Introduction

Many techniques have been developed to counteract chaotic regimes and other undesired behaviors [1-5]. To eliminate high-period orbits and chaos, mainly two techniques have been proposed: *OGY* [6] and *TDAS* [7]. Both methods eliminate chaos and high-periodic orbits in the buck converter, and an example can be found in [8]. However, these techniques require complex schemes to be implemented, and they require digital devices such as FPGA-s, DSP-s, microcontrollers and so on.

With the aim to develop a control technique that is simple to implement, a control scheme that suppresses chaotic bands and orbits with a period greater than one is proposed in this paper. The control has very good performance in a wide range of power sources, reference voltages and load values. Essentially, this method, which is based on feed-forward action, consists of adapting the ramp waveform (Vr(t)) to the control signal (Vco(t)) in such a way Vr(t) becomes similar to Vco(t). In this way, the ramp signal changes its offset voltage over the time. In addition, with this control technique, the frequency of the ramp signal is not altered. After developing the proposed technique, the performance of the system was numerically and exper-

imentally proven. It was proven that 1T-periodic orbits remain stable within the  $V_{in}$  range [13, 70]V. This result was validated experimentally for  $V_{in} \in [20, 40]V$ .

The main contribution of this paper is the development of a methodology to compute a chaos controller using bifurcations diagrams.

#### 2. Model of a Buck Converter

A simplified schematic diagram of the PWM voltagecontrolled buck converter is depicted in Fig. 1 and is described by Eq. (1).



Figure 1: DC-DC buck converter controlled by a ramp.

$$\begin{bmatrix} \dot{V}_C \\ \dot{I}_L \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC} & \frac{1}{C} \\ -\frac{1}{L} & -\frac{R_{in}}{L} \end{bmatrix} \begin{bmatrix} V_C \\ I_L \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{V_{in}}{L} \end{bmatrix} u \quad (1)$$

 $V_C$  and  $I_L$  are the state variables and correspond to the capacitor voltage and the inductor current, respectively. Switches  $S_1$  and  $S_2$  operate in a complementary way. R, L and C are the load resistance, the inductor and the capacitor, respectively, and  $R_{in}$  is the equivalent resistance of the current sensor and the inductor internal resistance.  $V_{in}$  is the value of the power source. u is the control signal

and takes values in the discrete set  $\{0, 1\}$ ; its value is given according to the based-ramp controller.

The buck converter controlled by a ramp consists of a control signal Vco(t) that is compared with a *T*-periodic sawtooth waveform Vr(t), which is given by Eq. (2):

$$Vr(t) = V_L + (V_u - V_L) \operatorname{mod}\left(\frac{t}{T}\right)$$
(2)

where  $V_L$  and  $V_u$  are the lower and upper constant voltage values, respectively, and *T* is the switching period. The control signal Vco(t) is proportional to the output error, which is the difference between the reference voltage Vrefand the output voltage  $V_C$ . The amplifier  $A_1$  with gain *a* is used to obtain Vco(t), and  $A_2$  is an infinite gain comparator, which is used to obtain the control action *u*. Vco(t) and *u* are computed according to the following equations:

$$Vco(t) = a \left( V_C(t) - Vref \right)$$
(3)

$$u = \begin{cases} 1 & if Vco(t) < Vr(t) \\ 0 & if Vco(t) > Vr(t) \end{cases}$$
(4)

# 3. Controlling Chaos

The analysis of the signal Vco(t) shows that, as  $V_{in}$  increases, Vco(t) also increases, and Vco(t) is unable to interact with the voltage of ramp Vr(t), which induces the bifurcation scenario. Then, the main idea is to change the Vr(t) value depending on the Vco(t) value without changing the slope of the ramp. When the slope of the ramp remains fixed and undesired behaviors are avoided, it is possible to obtain fixed frequency switching and a simple circuit design. However, the design of the final controller is based on the bifurcation diagram when the slope changes. In this way, the basic feed-forward controller (Var(t)) in which k and  $V_{in}$  vary is defined as:

$$Var(t) = \frac{Vco(t)}{k} + \frac{V_{in}}{k} \operatorname{mod}\left(\frac{t}{T}\right)$$
(5)

where Var(t) corresponds to the signal that will replace Vr(t), k is a constant to be computed, and  $V_{in}$  will be fixed to a constant value. The values of  $V_{in}$  and k are computed in such a way that undesired behaviors are avoided. According to Eq. (5), a change in Vco(t) immediately updates *Var*. The term Vco(t) causes the ramp Var(t) to change its offset voltage. Now, the control signal is described by

$$u = \begin{cases} 1 & if \ Vco(t) < Var(t) \\ 0 & if \ Vco(t) > Var(t) \end{cases}$$
(6)

The objective now is to find the values of  $V_{in}$  and k that will be replaced in Eq. (5) and will guarantee a 1*T*-periodic solution with good regulation performance. Bifurcation diagrams are then used to find suitable values for  $V_{in}$  and k. Initially, a two-dimensional bifurcation diagram is computed using  $V_{in}$  and k as bifurcation parameters. The aim of

this diagram is to find a region where the system presents a stable 1T-periodic solution, which is obtained if k is properly chosen.

After that, we used these values in Eq. (5), and we obtained the experimental results shown in Fig.2

## 4. Conclusions

A new technique for chaos control applied to a *PWM* voltage-controlled buck converter has been proposed. The design approach is based on the analysis of bifurcation diagrams to compute the constant parameters that define the controller. The methodology provides a feed-forward controller. The proposed control is easy to implement, does not require many components and yields excellent results.

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Figure 2: Experimental phase portrait and time responses for Vr(t), Vco(t) and  $V_C$  signals for the system controlled by a ramp. (a)-(c) for  $V_{in}$ =37V and (d)-(f) for  $V_{in}$ =38V. Experimental phase portrait and time responses for Vr(t), Vco(t) and  $V_C$  signals for the system controlled by feed-forward technique. (g)-(i) for  $V_{in}$ =37V and (j)-(1) for  $V_{in}$ =38V.

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