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 experimentally 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* voltage-controlled buck converter is depicted in Fig. 1 and is described by Eq. (1).

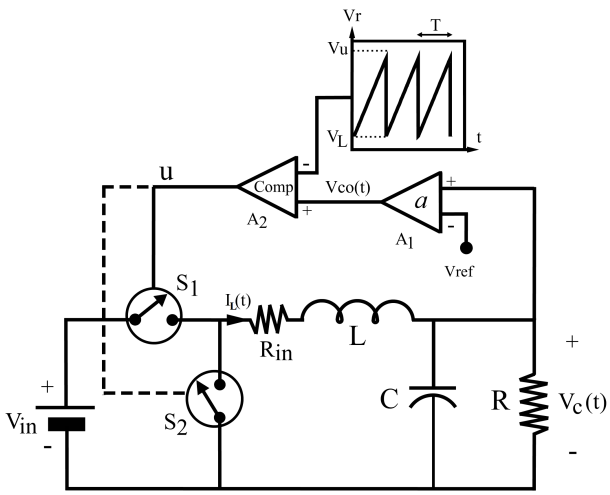

Figure 1: DC-DC buck converter controlled by a ramp.

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

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):

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

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 $Vref$ and 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:

$$Vco(t) = a\,(V_C(t) - Vref) \tag{3}$$

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

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:

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

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

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

The objective now is to find the values of V_{in} and k that will be replaced in Eq. (5) and will guarantee a $1T$-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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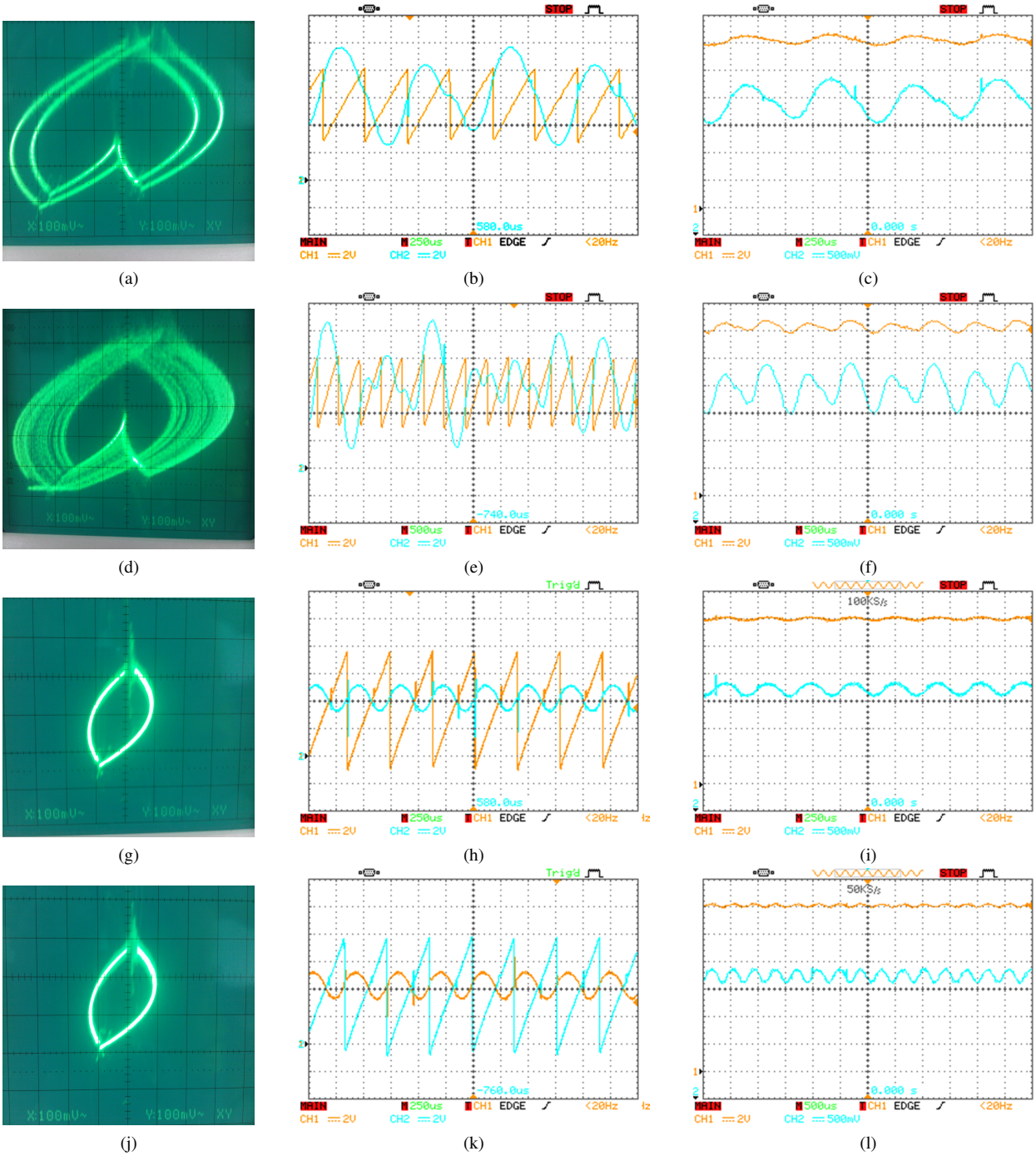

Figure 2: Experimental phase portrait and time responses for $Vr(t)$, $Vco(t)$ and V_C signals for the system controlled by a ramp. (a)-(c) for V_{in}=37V and (d)-(f) for V_{in}=38V.
Experimental phase portrait and time responses for $Vr(t)$, $Vco(t)$ and V_C signals for the system controlled by feed-forward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

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