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Clock pulse modulation for ripple reduction in buck-converter circuits

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DC–DC switching converters which are frequently treated as hybrid dynamical systems exhibit complex behavior due to nonlinear and interrupt characteristics. For synchronous buck-converters, we propose a method to control chaotic behavior by pulse–frequency modulation. An input voltage, a duty ratio of PWMs, and so on, affect to the regulation characteristics of converters directly, but a frequency of PWMs is determined by the frequency characteristics of the converter and is set as a fixed value. The proposed chaos-control method suppresses chaotic responses by slightly perturbing the pulse frequency alone, therefore our method can stabilize unstable periodic orbits without influence on the voltage regulation scheme. To simplify the feedback controller, the condition of dimension reduction for the controlling gain vector is derived. The proposed controller achieves the stabilization without a current sensor. Numerical simulation and circuit implementation demonstrate the validity of this method.

1. Introduction

Electrical circuits with switches are frequently treated as hybrid dynamical systems [1,2]. They occur in many engineering fields [3,4]. Hybrid dynamical systems have some deterministic flows and flip these flows in a non-smooth manner with discrete events. This nonlinearity causes rich complex behavior such as bifurcation phenomena and chaotic attractors [3]. Saito et al. have found chaotic attractors in one-dimensional *piecewise linear* systems [5–7], and they have validated the presence of bifurcation phenomena and chaotic attractors with explicit solutions.

High-power circuits can inevitably be treated mathematically as hybrid systems since the electrical switches, relays, and MOSFETs may cause non-smooth and interruptive characteristics determined by discrete events [8,9]. DC–DC converters are practically used as DC voltage converters, in fact, such switching converters are also categorized as hybrid systems, and their bifurcations and chaotic attractors have been analyzed thoroughly [10,11]. Waveforms of these circuits looks noisy [12], indeed, they show pseudo-random and continuous-spectrum characteristics. From the viewpoint of converter performance, the noise-like responses increase ripple voltages and electromagnetic interference.

While, controlling chaos is an effective method to suppress the chaotic responses [13,14]. In recent studies, various control schemes have been proposed [15–18]. These authors achieved ripple reduction by stabilizing previously unstable periodic orbits (UPOs). Yan-Li et al. proposed a control method for buck converters that varies the source voltage [19]. The frequency domain information is applied for the controlling chaos for boost converters by Rodríguez et al. [20], and suppressing chaotic behavior is successfully achieved. In the stability analysis utilizing Monodromy matrices [21], it suggests that an interrupt characteristic is important for the circuit behavior. Poddar et al. [22] proposed the controlling chaos method utilizing the switching characteristics of a buck converter circuit, and we also proposed the method that varies switching threshold values as reference voltages [16]. As these studies, the stabilization schemes using switching characteristics for converter circuits have achieved good controlling performance, but they require the load current value, which is difficult to measure precisely for the state-feedback, and treated only simple circuit models, indeed, an inductor is often omitted in a mathematical model. Additionally, circuit configurations including input and output voltages, loads, and reference values are not easy to be changed dynamically because they are determined by the converter specifications and usage.

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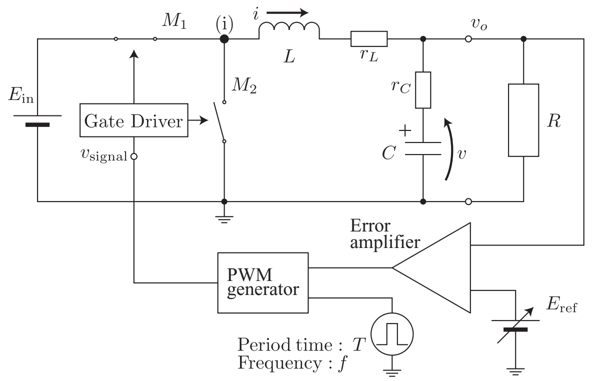

Fig. 1. Synchronous buck-converter circuit with a voltage-mode controller.

On the other hand, a pulse width modulation (PWM) input is often used to drive the converter circuit. Its duty ratio depends on requested values and the output voltage, whereas the optimum period of the pulse is determined by the frequency characteristics of a converter. An output voltage controller for a DC–DC converter adjusts the duty ratio to deal environmental, source voltage, and requested output voltage changes. In contrast, the frequency is usually considered as a fixed value, while it composes a PWM generator; we mean that it is independent on the converter circuits, so it is easy to adjust by other controllers. The chaos control with small-signal inputs has also been proposed [23–25], and Kikuchi et al. proposed a frequency modulation method that offers the possibility of controlling chaos in practical systems for a semiconductor laser [26]. On the viewpoint of a DC–DC converter, the controller with pulse frequency modulation can suppress chaotic phenomena with the small frequency perturbation of PWMs. For all of these reasons, a frequency modulation for the controlling chaos will be available in combination with an output voltage controller, and it can reduce ripple voltages without influence for the performance of the voltage conversion.

In a previous study, we proposed chaos control in a buck converter with PWM [27]. However, target circuit is an identical model that omits an inductor and operates under light-loads. In this paper, we expand our method for an actual circuit model and propose a simplification of the controller. We report our attempt to suppress chaotic phenomena in a synchronous buck-converter circuit through pulse width (frequency) modulation of a clock. The frequency of the PWM is perturbed based on feedback control. The controlling gain was designed with a pole-assignment method [28], and the stability of circuits with the proposed controller can be proved accordingly. To achieve the voltage feedback controller without current measurements, we employ the condition for poles on which controlling gain vectors degenerate. Whereas, it is unclear the relationship between responsiveness and robustness and the controller designed by a pole-assignment method, but this problem will avoid by using optimal control theory. First, we explain the circuit model and the design procedure for the feedback gain. Next, we demonstrate the performance of the proposed method with numerical simulations, and the simulated results reveal the robustness of the proposed method. Finally, to confirm feasibility of the method and applicability to real circuits, a prototype controller is configured for a sample buck-converter. We show its laboratory experiment results.

2. Circuit model and analytic results

Let us consider the synchronous buck-converter circuit diagrammed in Fig. 1. Two switches have zero resistance when ON and infinite resistance when OFF, without a time delay. The switches are flipped according to a rule that depends on the output voltage v_o and the clock with the period time T. The PWM generator and the error amplifier comprise a general voltage-mode controller. If we assume that v and i are state variables, the normalized equation is given in Eq. (1).

$$\begin{aligned} \frac{dx}{dt} &= -\beta x + \alpha y \\ \frac{dy}{dt} &= -\alpha x - \gamma y + e \end{aligned} \tag{1}$$

where

$$t = \frac{1}{\sqrt{LC}} t', \quad x = \sqrt{\frac{C}{L}} v, \quad y = i \tag{2}$$

and

$$\rho = \frac{1}{\sqrt{LC}} T, \quad \alpha = \frac{R}{R + r_c}, \quad \beta = \frac{1}{R + r_c}\sqrt{\frac{L}{C}},$$
$$\gamma = \left(r_L + \frac{R r_c}{R + r_c} \right) \sqrt{\frac{C}{L}}, \quad e_{\rm in} = \sqrt{\frac{C}{L}} E_{\rm in}, \quad e_{\rm ref} = \sqrt{\frac{C}{L}} E_{\rm ref}. \tag{3}$$

Note that the symbol e in Eq. (1) is the normalized voltage at point (i) in Fig. 1 and is set to $e_{\rm in}$ or zero for the two switches. The

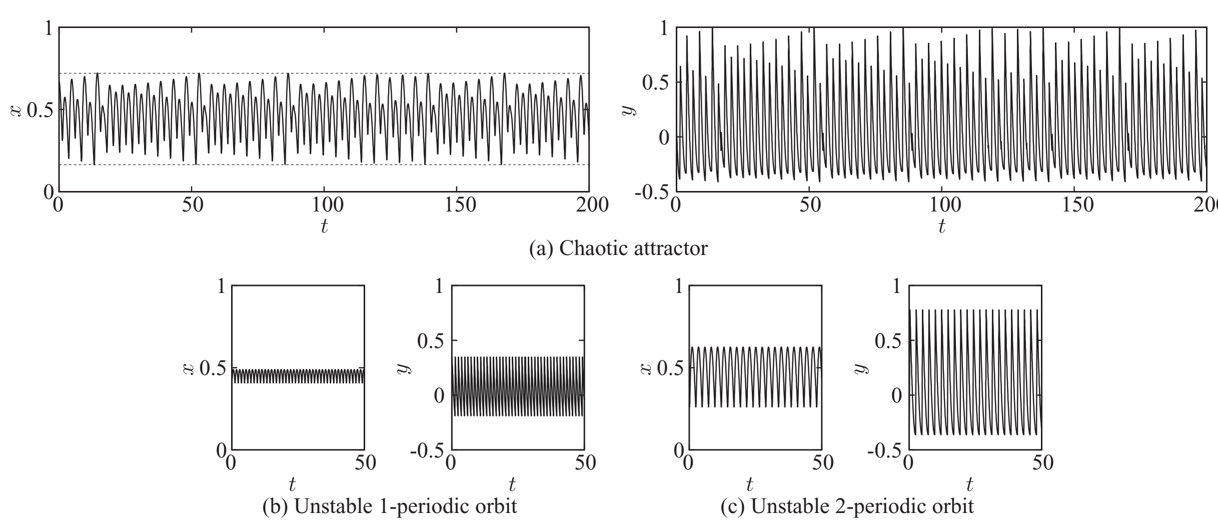

Fig. 2. Chaotic attractor and unstable periodic orbits. The ripples of capacitor voltages and inductor currents on UPOs are obviously smaller than the chaotic attractor. ($\alpha = 0.995$, $\beta = 0.1$, $\gamma = 0.7281$, $e_{\rm in} = 5.372$, $\rho = 1.2$, $a = -0.2238$ and $b = 0.517$).