2016 International Symposium on Nonlinear Theory and Its Applications,
NOLTA2016, Yugawara, Japan, November 27th-30th, 2016

A Switching Ripple Reduction Technique for Current-Controlled 1-Dimensional DC/DC Boost Converter

Hiroyuki Fukue† Takuji Kousaka‡ Tetsushi Ueta* Daisuke Ito** Hirokazu Ohtagaki† Hiroyuki Asahara†

†Faculty of Engineering, Okayama University of Science,
1-1 Ridai-cho, Kita-ku, Okayama-shi, Okayama 700-0005, Japan.
‡Faculty of Engineering, Oita University, 700 Dannoharu, Oita-shi, Oita 870-1192, Japan.
∗ Center for Administration of Information Technology, Tokushima University,
2-1, Minami-Josanjima-cho, Tokushima-shi, Tokushima 770-8506, Japan.
∗∗ Faculty of Engineering, The University of Shiga Prefecture,
2500, Hassaka-cho, Hikone-shi, Shiga 522-8533, Japan.
Email:fukue@nonlineargroup.net, takuji@oita-u.ac.jp, ueta@tokushima-u.ac.jp,
ito.d@e.usp.ac.jp, ohtagaki@ee.ous.ac.jp, asahara@ee.ous.ac.jp

Abstract—In this paper, we demonstrate a switching ripple reduction technique for current-controlled one-dimensional DC/DC boost converter. First, we show the circuit model, and then we explain behavior of the waveform. Next, we define the discrete map by sampling the inductor current at clock interval. Based on the discrete map, we derive a controlling gain. Finally, we try to reduce switching ripple of inductor current, and confirm the effectiveness of our controlling method.

1. Introduction

Power conversion circuits including switching devices have an interrupted characteristics due to the switching events, and rich nonlinear phenomena can be observed depending on the circuit parameter [1, 2]. It is important to analyze the bifurcation parameter for designing suitable circuit parameter.

In this study, we focus on the current-controlled DC/DC boost converter. The switching action depends on its own state and a time interval. This circuit exhibits rich nonlinear phenomena including chaotic behavior depending on the circuit parameter, and it is known that the switching ripple becomes minimum when it behaves with period-one oscillation. Therefore, we can say that we should to design the suitable circuit parameters for making the circuit behave with period-one oscillation. On the other hand, even if the circuit exhibits chaotic behavior, we can control the chaotic behavior to the unstable period-one oscillation by using the chaos controlling technique. There are many chaos controlling techniques [3, 4, 5, 6], and one of which is our proposed technique [6].

This paper addresses to demonstrate application of our proposed chaos controlling technique to DC/DC converter. First, we show the circuit model, and then we explain behavior of the waveforms. Next, we define the discrete map, and derive a controlling gain. Finally, we try to reduce switching ripple of inductor current.

2. DC/DC boost converter and its control algorithm

Figure 1 shows the DC/DC boost converter, where the circuit parameters are

$$\begin{array}{l} R = 70[\Omega],\ L = 1[\text{mH}],\ C = 100[\mu\text{F}], \\ r = 1[\Omega],\ T = 17[\mu\text{s}],\ I_{\text{ref}} = 0.92[\text{A}],\ E = 15[\text{V}]. \end{array} \tag{1}$$

Note that the capacitor voltage is constant under this circuit parameter, and we show the capacitor voltage as E_0 in the following. Therefore, the circuit equation is described as follows.

$$L\frac{di}{dt} = \begin{cases} E - ri, & \text{for switch is ON} \\ E - E_0 - ri, & \text{for switch is OFF} \end{cases} \tag{2}$$

The solution of Eq. 2 is

$$i(t) = \begin{cases} \left(i_0 - \frac{E}{r}\right)e^{-\frac{r}{L}t} + \frac{E}{r}, & \text{for switch is ON} \\ \left(i_0 - \frac{E - E_0}{r}\right)e^{-\frac{r}{L}t} + \frac{E - E_0}{r}, & \text{for switch is OFF} \end{cases}, \tag{3}$$

where i_0 is an initial value at $t = 0$. Here, i_R is given by

$$i_R = \frac{E_0}{R}. \tag{4}$$

The transfer factor is

$$M = \frac{E_0}{E} = \frac{1}{D'}. \tag{5}$$

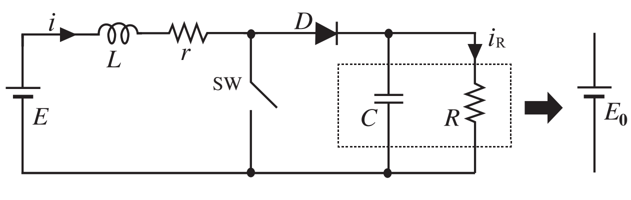


Figure 1: DC/DC boost converter

Therefore, we have

$$D' = \frac{E}{E_0}, \tag{6}$$

where $D + D' = 1$, and D is duty ratio. In addition, it holds the following equation:

$$i = \frac{E_0}{RD'} = \frac{E_0}{R}\frac{1}{D'} = \frac{i_R}{D'}, \tag{7}$$

and we get

$$i_R = iD'. \tag{8}$$

Based on Eq. (4), Eq. (6), and Eq. (8), i_R is rewritten as follows:

$$i_R = iD' = \frac{E_0}{R} = i\frac{E}{E_0}. \tag{9}$$

By solving Eq. (9), we get

$$E_0 = \sqrt{iER}. \tag{10}$$

In the following, we assume $i = I_{ref}$, where I_{ref} is a reference value.

We now explain switching rule and its control algorithm. The current-control is applied to turn on, or turn off, the switch. We assume that the switch is ON at first position at $t = 0$, and inductor current increases. If the inductor current reaches the reference value I_{ref} at $t = t_{on}$, the switch turns off and inductor current decreases. When the clock pulse is applied at $t = T$, the switch turns on.

We control the switching action based on the algorithm proposed in Ref. [6]. Therefore, the switch turns on at $t = nT + t_{on} + \Delta t_{on}$, where $n = 1, 2, 3, \cdots$, and Δt_{on} is defined as follows:

$$\Delta t_{on} = k\Delta i_n. \tag{11}$$

In Eq. (11), k is a controlled gain described by

$$k = -\frac{\dfrac{di_{n+1}}{di_n}}{\dfrac{di_{n+1}}{dt_{on}}}, \tag{12}$$

and Δi_n is a perturbation described by

$$\Delta i_n = i_n - i_n^*, \tag{13}$$

where i_n is inductor current at $t = nT$, i_{n+1} is inductor current at $t = (n+1)T$, and i_n^* is fixed point.

3. Demonstration of application

Using the algorithm proposed in Ref. [6], and controlling the inductor current to unstable period-one oscillation, we try to reduce switching ripple smaller.

The discrete map is needed for deriving control gain, and it is illustrated in Fig. 3. In case-1, the switch keeps ON during clock interval, and the discrete map i_{n+1} is described as follows:

$$i_{n+1} = \left(i_n - \frac{E}{r}\right)e^{-\frac{r}{L}T} + \frac{E}{r} \tag{14}$$

On the other hand, switch turns off at $t = nT + t_{on}$ in case-2. Therefore, the discrete map i_{n+1} is described as follows:

$$i_{n+1} = \left(i_n - \frac{E - E_0}{r}\right)e^{-\frac{r}{L}(T - t_{on})} + \frac{E - E_0}{r}. \tag{15}$$

The differentials of Eq. (14) and Eq. (15) with respect to i_n are described as follows:

$$\frac{di_{n+1}}{di_n} = \begin{cases} e^{-\frac{r}{L}T}, & \text{for case-1} \\ \dfrac{I_{ref} - \dfrac{E - E_0}{r}}{I_{ref} - \dfrac{E}{r}} e^{-\frac{r}{L}T}, & \text{for case-2} \end{cases}. \tag{16}$$

Likewise, the differentials of Eq. (14) and Eq. (15) with respect to t_{on} are described as follows:

$$\frac{di_{n+1}}{dt_{on}} = \begin{cases} 0, & \text{for case-1} \\ \dfrac{r}{L}I_{ref} - \dfrac{E - E_0}{r}e^{-\frac{r}{L}(T - t_{on})}, & \text{for case-2} \end{cases}. \tag{17}$$

Because the fixed point satisfies $i_n = i_{n+1} = i_n^*$, it is defined from Eq. (15) as follows:

$$i_n^* = \frac{E_0}{r}\frac{I_{ref} - \dfrac{E}{r}}{\left(I_{ref} - \dfrac{E - E_0}{r}\right)e^{-\frac{r}{L}T} - \left(I_{ref} - \dfrac{E}{r}\right)} + \frac{E}{r} \tag{18}$$

Therefore, the control gain k is given by

$$k = -\frac{\dfrac{I_{ref} - \dfrac{E - E_0}{r}}{I_{ref} - \dfrac{E}{r}}e^{-\frac{r}{L}T}}{\dfrac{r}{L}I_{ref} - \dfrac{E - E_0}{r}e^{-\frac{r}{L}(T - t_{on})}}. \tag{19}$$

Figure 3 shows waveform of inductor current; (a) is overall view, where we start to control around $t = 0.9$[ms], (b) is enlarged view of uncontrolled waveform, (c) is enlarged view of controlled waveform, and (d) is Δt_{on}. We observe period-two oscillation under the circuit parameter shown in Eq. (1) (see Fig. 3(b)). On the other hand, if we apply the

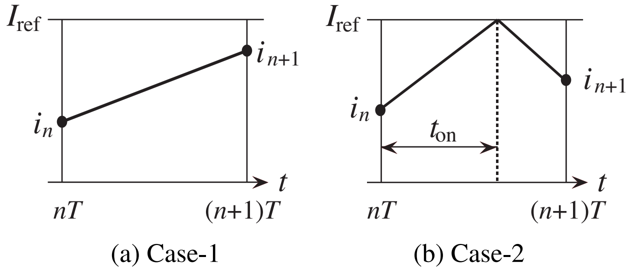
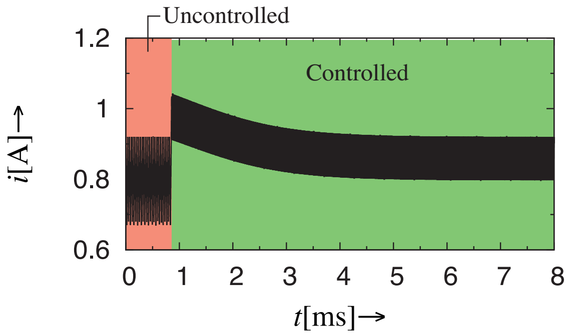
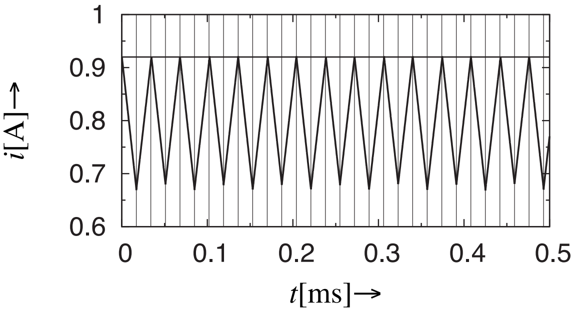


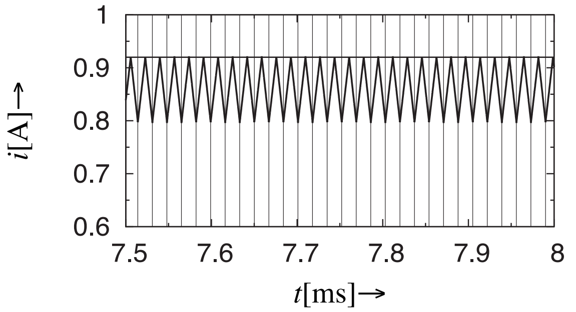
Figure 2: Inductor current observed in clock interval.



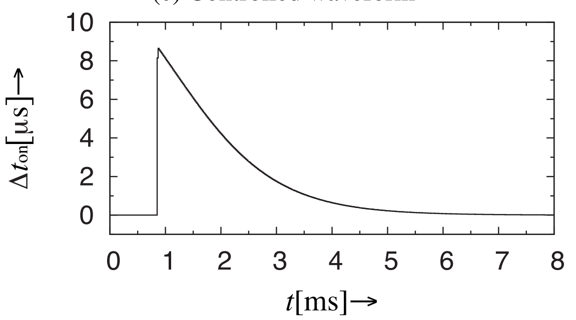
(a) Waveform



(b) Uncontrolled waveform



(c) Controlled waveform



(d) Δt_{on}

Figure 3: Inductor current.

control method discussed in Sec. 2, the period-two oscillation is controlled to unstable period-one oscillation (see Fig. 3(c)). It is clear from Fig. 3(d) that the control is completed around $t = 6$[ms], because $\Delta t_{\mathrm{on}} = 0$. We observe that the switching ripple is reduced by using the control method. We know that the circuit exhibits rich nonlinear phenomena by changing the circuit parameter. The switching ripple reduction technique proposed in Ref. [6] is applicable period-two or more oscillation including chaos, and can reduce the switching ripple.

4. Conclusion

We demonstrated a switching ripple reduction technique for current-controlled one-dimensional DC/DC boost converter. First, we showed DC/DC boost converter, and then we explain the switching events. Next, we introduced a control method of switching action reported in Ref. [6]. Using discrete map, which is a sampling inductor current at clock interval, we derive a control gain. Finally, we tried to reduce the switching ripple of inductor current, and confirmed the effectiveness of the method.

The control algorithm is effective only for one-dimensional DC/DC converters. In future, we improve the control algorithm for *n*-dimensional interrupted circuits, and confirm validity of the method.

References

[1] M. di. Bernardo and C. K. Tse, "Chaos in power electronics: an overview," Chaos in Circuits and Systems, vol. 16, pp. 317-340, 2002.

[2] C. K. Tse, "Complex behavior of switching power converters," *CRC Press*, 2003.

[3] J. Chen, A. Prodić, R. W. Erickson and Dragan Maksimović, "Predictive Digital Current Programmed Control," *IEEE Trans. Power Electron.*, vol. 18, no. 1, pp. 411–419, 2003.

[4] T. Kousaka, T. Ueta and H. Kawakami, "Controlling Chaos in a State-dependent Nonlinear System," *Int. J. Bifurcat. Chaos*, vol. 12, no.5, pp. 1111–1119, 2002.

[5] D. Ito, T. Ueta, T. Kousaka, J. Imura and K. Aihara, "Controlling Chaos of Hybrid Systems by Variable Threshold Values," *Int. J. Bifurcat. Chaos*, vol. 24, no. 10, pp. 1450125-1–1450125-12, 2014.

[6] T. Sasada, D. Ito, H. Ohtagaki, T. Kousaka, H. Asahara., "Controlling Unstable Orbits via Varying Switching Time in a Simple Dynamical Systems." *Proc. of 2015 International Symposium on Nonlinear Theory and Its Applications*, pp.475-478, 2015.