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Nonlinear Oscillation of a Photovoltaic Cell Booster

Yushi Hasesaka†, Keisuke Mori†, Takuji Kousaka‡, Hirokazu Ohtagaki† and 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.
Email: {yushi,mori}@nonlineargroup.net, takuji@oita-u.ac.jp, {ohtagaki,asahara}@ee.ous.ac.jp

Abstract—In this study, we report fundamental characteristic of a photovoltaic cell booster. We show the circuit model, which is current-controlled DC/DC boost converter fed with photovoltaic module. Using the sampled data of the waveforms at the clock intervals, nonlinear oscillation of the circuit is investigated briefly. The circuit characteristic obtained in this report will help to control and design the photovoltaic cell booster in our future study.

1. Introduction

The clean energy technology is developing in recent years, and many power generation devices and its peripheral circuits are further along in development. The photovoltaic cell booster is a clean energy power generation system, which is a DC/DC converter fed with photovoltaic cell.

Because the photovoltaic cell is regarded as a current source, we often connect it to DC/DC converter, and control the current to track the maximum power point of the photovoltaic cell. There are many equivalent circuits of DC/DC converter fed with photovoltaic cell, and it is known that rich nonlinear phenomena are observed due to the switching events [1, 2]. From the viewpoints of circuit design and circuit theory, clarifying dynamic behavior of DC/DC converters fed with photovoltaic cell is important. However, circuit equation of DC/DC converter fed with photovoltaic cell have two or more dimensional topology and nonlinear characteristic, and its complexity makes the analysis difficult. Therefore, Ref. [3] proposed a simplified model, by assuming the photovoltaic cell to be a current source with piecewise smooth characteristic.

Now, we can design suitable circuit parameter based on tools, which are circuit model and its analysis technique, reported in Refs. [1, 2], and we can understand qualitative property based on the tools reported in Ref. [3]. This paper aims to propose an intermediate circuit model which has one-dimensional topology, and well simulate output characteristic of photovoltaic cell without using piecewise smooth characteristic.

First, we simulate output characteristic of photovoltaic cell based on Ref. [4]. Next, we show circuit dynamics of DC/DC convener fed with photovoltaic cell, and explain switching events. Finally, we discuss characteristics of the proposed circuit, and demonstrate nonlinear oscillation.

2. Photovoltaic Cell Booster

Table 1 shows output characteristics of the photovoltaic cell, which is used in this study. The output of the photovoltaic cell is calculated based on Ref. [4] as shown in Fig. 1.

Figure 2 shows DC/DC boost converter fed with photovoltaic cell, which we call photovoltaic cell booster. The circuit parameters are follows:

$$L = 1[\text{mH}],\ C = 100[\mu\text{H}],\ I_{\text{ref}} = 0.92[\text{A}],\ T = 17[\mu\text{s}]. \tag{1}$$

If the switch is ON, the circuit equations are given by

$$L\frac{di}{dt} = V_{\text{pv}} \tag{2}$$

and

$$C\frac{dv}{dt} = -\frac{v}{R}. \tag{3}$$

Likewise, if the switch is OFF, the circuit equations are given by

$$L\frac{di}{dt} = V_{\text{pv}} - v \tag{4}$$

and

$$C\frac{dv}{dt} = i - \frac{v}{R}. \tag{5}$$

Note that V_{pv} denotes output voltage from photovoltaic cell.

The drive circuit includes comparator and flip-flop. Using the current transformer, we sense the inductor current (i.e. output current of photovoltaic cell). The output of comparator, which compares inductor current and reference current, is input into flip-flop, and switching signal is generated. Note that we set reference current to the same value of the current at maximum power point of photovoltaic cell (i.e. $I_{\text{ref}} = I_{\text{pm}}$).

Table 1: Photovoltaic cell (BT432S-MRN).

Maximum Power P_m	14 [W]
Current at Maximum Power I_{pm}	0.92 [A]
Voltage at Maximum Power V_{pm}	15.3 [V]
Short Circuit Current I_{SC}	1.0 [A]
Open Circuit Voltage V_{OC}	18.6 [V]

3. Nonlinear oscillation observed in Equivalent circuit

We assume that capacitor voltage is constant value E_0. Therefore, the circuit equation is rewritten as follows:

$$L\frac{di}{dt} = \begin{cases} V_{\mathrm{pv}}, & \text{for ON} \\ V_{\mathrm{pv}} - E_0, & \text{for OFF} \end{cases} . \tag{6}$$

The transfer factor is described as

$$\begin{aligned} M &= \frac{E_0}{V_{\mathrm{pv}}} \\ &= \frac{1}{D'}, \end{aligned} \tag{7}$$

where $D' = 1 - D$. In addition, output current of photovoltaic cell is described as

$$\begin{aligned} I_{\mathrm{pv}} &= \frac{E_0}{R} \\ &= I_{\mathrm{pv}}D' \\ &= I_{\mathrm{pv}}\frac{V_{\mathrm{pv}}}{E_0}. \end{aligned} \tag{8}$$

Therefore, we get

$$\begin{aligned} E_0 &= \sqrt{I_{\mathrm{pv}}V_{\mathrm{pv}}R} \\ &\simeq \sqrt{I_{\mathrm{pm}}V_{\mathrm{pm}}R}. \end{aligned} \tag{9}$$

Note that we rewrite I_{pv} and V_{pv} by I_{pm} and V_{pm}. In the following, we use dimensionless values: $t = L\tau$, for the sake of the simplicity.

Figures 3 and 4 show waveform behavior of the capacitor voltage and inductor current; Fig. 3 is calculated using Eqs. (2)~(5), whereas Fig. 4 is calculated using Eq. (6). It is clear that the same waveforms are observed in the equivalent circuit. Therefore, we analyze nonlinear oscillation of the equivalent circuit in the following analysis.

There are two types of waveform behavior of the inductor current during clock interval. The switch keeps ON in the first case which we call case-1, whereas the switch changes its position from ON to OFF in the other case which we call case-2. We assume an initial value at $\tau = kT$, $k = 1, 2, 3, \cdots$, by i_k, and that of at $\tau = (k+1)T$ by i_{k+1}. We define the solution of Eq. (6) as follows:

$$i(\tau - kT) = \varphi(\tau - kT, i_k, \lambda) = \begin{cases} \varphi_1(\tau - kT, i_k, \lambda_1), & \text{for ON} \\ \varphi_2(\tau - kT, i_k, \lambda_2), & \text{for OFF} \end{cases}, \tag{10}$$

where λ, λ_1, and λ_2 are parameters.

In case-1, the i_{k+1} is defined as follows:

$$i_{k+1} = F(i_k) = \varphi_1(T, i_k, \lambda_1). \tag{11}$$

Likewise, the i_{k+1} is defined by following equation in case-2.

$$i_{k+1} = F(i_k) = P_2(P_1(i_k)), \tag{12}$$

where functions P_1 and P_2 in Eq. (12) are expressed by the following equations.

$$P_1(i_k) = \varphi_1(\tau_{\mathrm{on}}, i_k, \lambda_1) = I_{\mathrm{ref}} \tag{13}$$

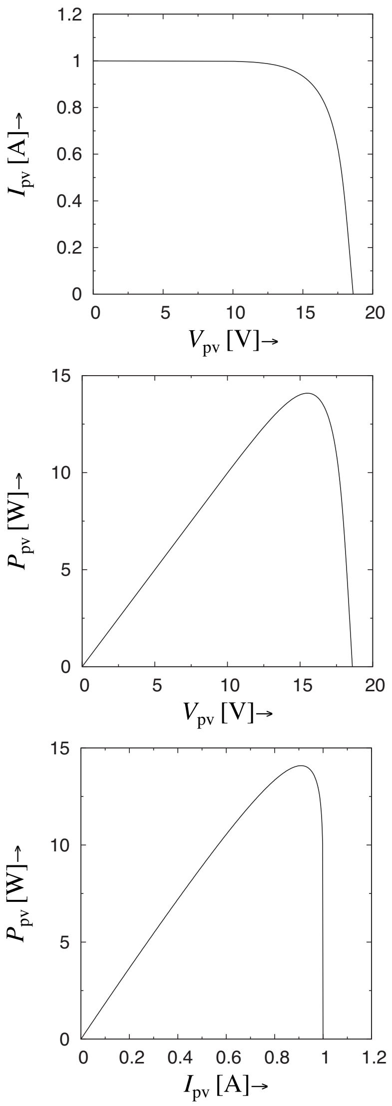


Figure 1: Output of BT432S-MRN.

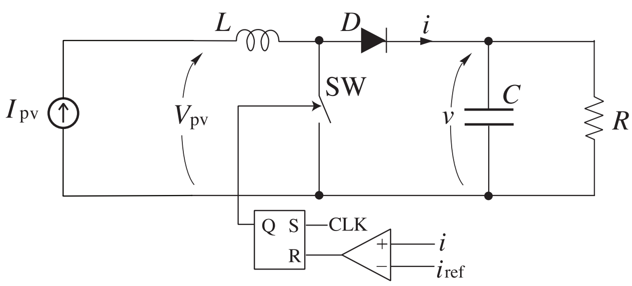


Figure 2: Photovoltaic cell booster.

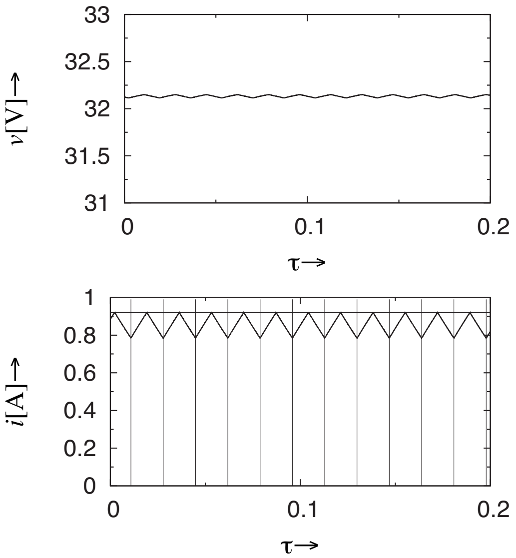


Figure 3: Numerical simulation of photovoltaic cell booster (R = 75).

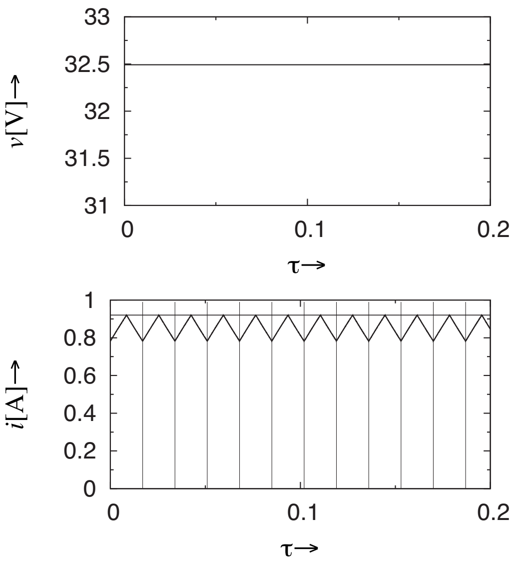
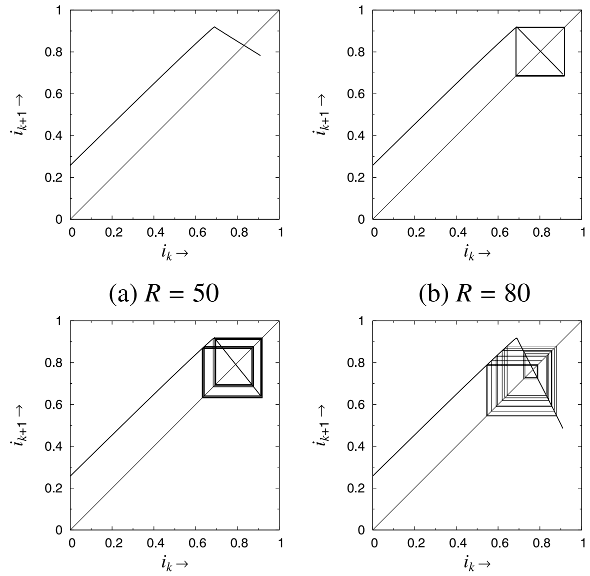


Figure 4: Numerical simulation of equivalent circuit (R = 75).

$$P_2(i_0) = \varphi_2(T - \tau_{\text{on}}, P_1(i_k), \lambda_2) \quad (14)$$

Note that τ_{on} denotes ON time during which the switch keeps ON, and i_0 is an initial value, which satisfies $i_0 = P_1(i_k) = I_{\text{ref}}$.

Figure 5 shows i_k versus i_{k+1} plane which we call return map. We change the resistance by $R = 50[\Omega]$, $R = 80[\Omega]$, $R = 100[\Omega]$, and $R = 175[\Omega]$. We can observe nonlinear phenomena in the circuit. For example, the fixed point is observed at $R = 50[\Omega]$, the period-2 orbit is observed at $R = 80[\Omega]$, the period-4 orbit is observed at $R = 100[\Omega]$, and aperiodic orbit is observed at $R = 175[\Omega]$.



(a) R = 50 (b) R = 80

(c) R = 100 (d) R = 175

Figure 5: Return maps.

4. Conclusion

We studied DC/DC boost converter fed with photovoltaic cell. First, we showed output characteristic of photovoltaic cell, and then we explained circuit dynamics. Finally, we proposed equivalent circuit, and demonstrated nonlinear phenomena observed in the equivalent circuit by using the return map. In future, we study this circuit in detail.

References

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