Conduction Loss Reduction in Three-level Flying Capacitor DC/DC Converters Applying Trapezoidal Current Mode

Yoshimune Hirai*, Ryohei Higashide[1], Hiroki Watanabe[1], Jun-ichi Itoh[1]
1 Nagaoka University of Technology, Nagaoka Niigata, Japan
*s243165@stn.nagaokaut.ac.jp

***Abstract*— Triangular current mode (TCM) has been applied to a three-level flying capacitor converter (FCC) for high power density power conditioners in photovoltaic systems. TCM enables a significant reduction in boost inductance; however, it increases RMS current and conduction losses. Trapezoidal Current Mode has been proposed as an alternative control strategy, but it's ideal operating condition has not been fully clarified. This paper investigates the ideal operating condition of the trapezoidal current mode for an FCC. It is shown that setting the output voltage to twice the input voltage and the flying capacitor voltage to half the output voltage produces a constant-current interval in the inductor current, thereby minimizing RMS current. The effectiveness of the proposed method is verified through simulation and experimental results. The proposed method reduces conduction loss compared with TCM and achieves high efficiency over the entire operating range, reaching 98.4% efficiency at 1 kW operation.**

***Keywords*— Flying capacitor converter, Triangular Current Mode, Trapezoidal Current Mode, Conduction loss**

I. INTRODUCTION

In recent years, research on photovoltaic power generation systems has been actively conducted in response to environmental issues such as global warming. In grid-connected photovoltaic systems, a power conditioner (PCS) composed of a boost chopper circuit and a grid-connected inverter is generally required. High power density and high efficiency are required for PCS, and in particular, the inductor in the boost chopper circuit occupies a large volume, making size reduction an important issue. Previous studies have proposed a method applying triangular-current mode (TCM) to a three-level flying capacitor converter (FCC). TCM can significantly reduce the inductance of the boost inductor; however, it increases the RMS inductor current, resulting in higher conduction losses in semiconductor devices[1]. In addition, trapezoidal current mode has been proposed as an alternative control method to TCM. The trapezoidal current mode reduces the current peak compared with TCM, thereby reducing the RMS current [2] [3]. This paper investigates the ideal operating condition of the trapezoidal current mode and demonstrates its effectiveness through experimental results.

II. TRAPEZOIDAL CURRENT MODE

A. Condition for Minimizing RMS Current

Fig. 1 shows the operating modes of the FCC. The FCC operates in Mode I and Mode IV, in which energy is stored in the inductor for voltage boosting, and in Mode II and Mode III, in which energy is stored in both the inductor and capacitors. The trapezoidal current mode is realized by switching among these modes within one switching period.

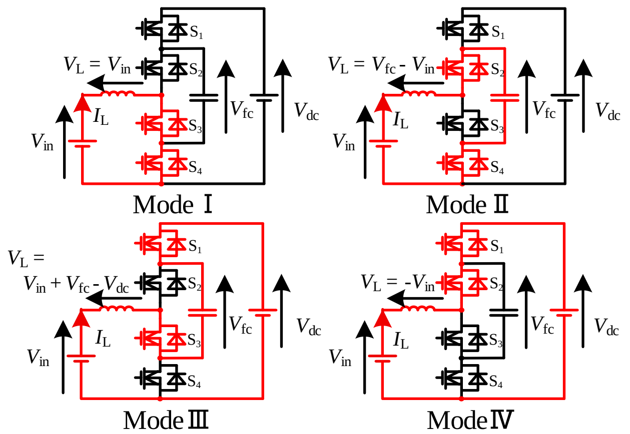

Fig. 1. Operation Modes of flying capacitor converter.

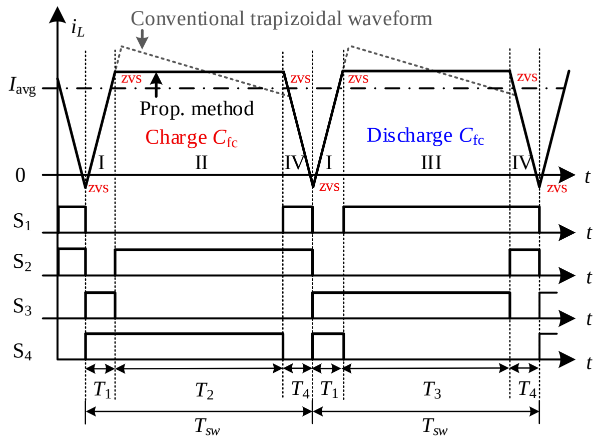

Fig. 2. Schematic of the trapezoidal current mode.

Fig. 2 shows a schematic of the trapezoidal current mode. The RMS current increases with an increase in the peak current. Therefore, under the ideal condition, the upper flat region of the trapezoidal current becomes constant. To form a constant-current interval, the condition di/dt=0 must be satisfied. Since the inductor voltage is expressed as $V_L = L$ di/dt, the voltage across the inductor must be zero in Mode II and Mode III by appropriately balancing the circuit voltages.

The voltage conditions in Modes II and III are given in (1) and (2), respectively. The solution is shown in (3).

$$V_L(\text{mode II}) = V_{fc} - V_{in} = 0 \quad (1)$$

$$V_L(\text{mode III}) = V_{in} + V_{fc} - V_{dc} = 0 \quad (2)$$

$$V_{in} = V_{fc} = 2V_{dc} \quad (3)$$

From (3), it is found that the condition for minimizing the RMS current is that the FCC output voltage V_{dc} is twice the input voltage V_{in}, and the flying capacitor voltage V_{fc} is half of V_{dc}. In addition, to achieve ZVS, a negative bottom current must be applied during the transition between Mode IV and Mode I.

B. Formulation of RMS Current

The RMS currents of the TCM and the trapezoidal current mode are expressed in (4) and (5), respectively.

$$I_{rms\_TCM} = \frac{1}{\sqrt{3}}\left(\frac{2I_{avg}T_{sw} + 2I_{bot}T_{bot}}{T_{sw}}\right) \simeq 1.15 I_{avg} \quad (T_{bot} \ll T_{sw}) \; ....(4)$$

$$I_{rms\_trap} = \frac{2T_{sw}I_{avg} + T_{bot}I_{bot}}{2\left(T_{sw} - T_r - T_{bot}\right)}\left\{\left(1 - \frac{2T_r + T_{bot}}{T_{sw}}\right) + \frac{1}{\sqrt{3}}\frac{2T_r}{T_{sw}}\right\} + \frac{1}{\sqrt{3}}\frac{T_{bot}I_{bot}}{T_{sw}}$$

$$\simeq 1.00 I_{avg} \quad (T_{bot} < T_r \ll T_{sw}) \; ....(5)$$

Denotes the rising and falling time of the trapezoidal current, T_{sw} denotes the switching period, I_{bot} denotes the bottom current value, and T_{bot} denotes the bottom current interval. From (4) and (5), when the average current I_{avg} is identical, the RMS current of the trapezoidal current mode is approximately 13% lower than that of the TCM.

III. Analysis of Conduction Loss by Simulation

Table I summarizes the experimental conditions. In the TCM case, an input voltage of 200 V and an output voltage of 300 V are assumed. On the other hand, when the trapezoidal current mode is operated under the same voltage conditions as TCM, a constant-current interval cannot be achieved. Therefore, in the ideal condition of the trapezoidal current mode, the condition that the FCC output voltage V_{dc} is always twice the input voltage V_{in} is applied, and an input voltage of 200 V and an output voltage of 400 V are used for investigation.

Fig. 3 shows a comparison of conduction losses obtained by simulation for each current mode. The proposed trapezoidal current mode under the ideal condition (proposed method) achieves lower conduction loss than both the TCM and the trapezoidal current mode under the TCM voltage condition (conventional trapezoidal waveform) over the entire output range. In particular, at 1 p.u. (1 kW) operation, conduction loss is reduced by 38.6% compared with TCM and by 18.2% compared with the trapezoidal current mode under the TCM condition.

IV. Experimental Results

Fig. 4 shows the operating waveforms of the proposed method at 1 p.u. (1 kW) operation. It is confirmed that a constant-current interval is achieved in the proposed trapezoidal current mode. In addition, A bottom current of approximately 2.0 A is applied to achieve ZVS.

Fig. 5 shows the efficiency comparison between the proposed method under the ideal condition and the TCM. The proposed method achieves higher efficiency than the TCM over the entire output range. In particular, in the light-load region, the TCM suffers from efficiency degradation due to increased switching losses caused by an increase in switching frequency. In contrast, the proposed method maintains a constant switching frequency by adjusting the duration of the constant-current interval, enabling high efficiency even under light-load conditions. Furthermore, a peak efficiency of 98.4% is achieved at 1 p.u. operation.

Table. 1. Experimental parameters.

Parameter	TCM	Prop. method
Input voltage V_{in}	200 V	200 V
Flying capacitor voltage V_{fc}	150 V	200 V
Output voltage V_{dc}	300 V	400 V
Boost inductor L	20 μH	20 μH
Flying capacitor C_{fc}	186 μF	186 μF
Switching frequency f_{sw}	Variable	50 kHz

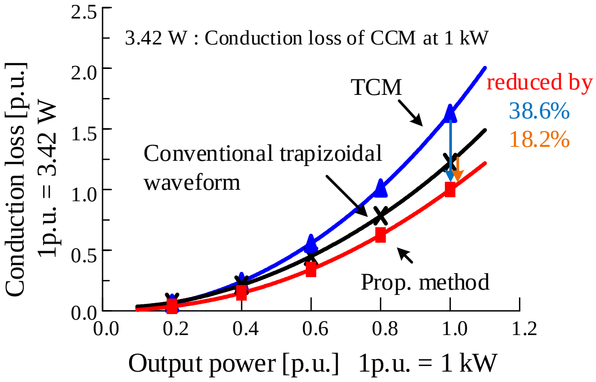

Fig. 3. Conduction losses in each current mode. (sim)

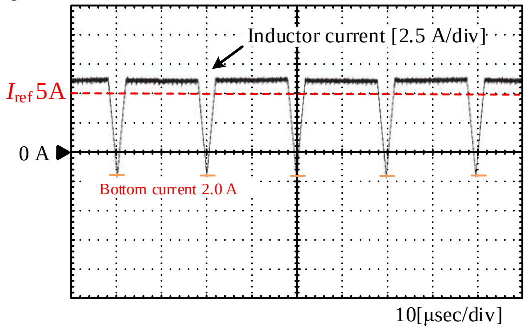

Fig. 4. Operating Waveforms of Trapezoidal Current Mode

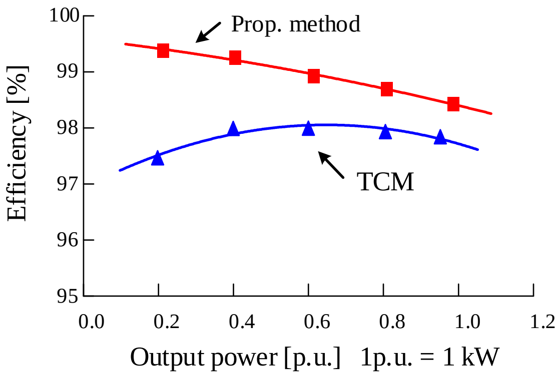

Fig. 5. Comparison of Converter Efficiency

References

[1] H. N. Le, J. Itoh: "Wide-Load-Range Efficiency Improvement for High-Frequency SiC-Based Boost Converter with Hybrid Discontinuous Current Mode", IEEE Transactions on Power Electonics, Vol. 33, No. 2, pp. 1843-1854 (2017)

[2] J. Itoh, R. Ishibashi, H. N. Le, N. Takaoka, K. Kusaka, K. Tanabe: "Control Method of Flying Capacitor Converter Operated in Discontinuous Current Mode and Critical Current Mode", Energy Conversion Congress Exposition 2018, Vol. , No. , pp. 155-161 (2018)

[3] J. Liu, Z. Yao, J. C. Z. Wei, and Y. Tang, "A trapezoidal modulation for three-level flying capacitor converters," Energy Conversion Congress and Exposition, 2024, Vol. , No. pp. 4088-4092(2024)