

Trapezoidal Current Mode Control for Loss Reduction in Active Power Decoupling of a Single-/Three-Phase Compatible T-Type Converter

Ryohei Higashide
Dept. of Electrical, Electronics, and
Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
s235027@stn.nagaokaut.ac.jp

Hiroki Watanabe
Dept. of Electrical, Electronics, and
Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
hwatanabe@vos.nagaokaut.ac.jp

Jun-ichi Itoh
Dept. of Electrical, Electronics, and
Information Engineering
Nagaoka University of Technology
Nagaoka, Japan
itoh@vos.nagaokaut.ac.jp

Abstract— This paper proposes a trapezoidal current mode-based loss reduction method for a single-phase and three-phase compatible T-type converter with active power decoupling (APD). In conventional APD using this converter, a two-level voltage is applied to the APD inductor. This increases the APD inductor current ripple, causing efficiency degradation under light-load conditions. To address this issue, the proposed trapezoidal current mode clamps the inductor voltage to zero by using a bidirectional switch in the APD circuit. By applying a zero-voltage period, the inductor voltage waveform is changed from a two-level waveform to a three-level waveform, thereby reducing both the iron loss and the current ripple. The optimal zero-voltage period that minimizes the total loss is determined through loss analysis. Experimental results show that the proposed loss reduction method improves the efficiency at 500 W from 87.5% to 89.2% and reduces the total loss by 15.2% compared with the conventional modulation method. In addition, the proposed loss reduction method reduces the second-order harmonic component by 97.7%.

Keywords—on-board charger, T-type converter, single-phase and three-phase compatible, active power decoupling

I. INTRODUCTION

The circuit configurations of on-board chargers (OBCs) for various charging systems have been actively researched [1]–[6]. Among them, the circuits in [1]–[4] operate with both single-phase and three-phase power systems by switching the operating mode based on the connected grid. In addition, control methods based on the active power decoupling (APD) have been proposed for single-phase and three-phase compatible OBCs [7]–[10]. These methods compensate for ripple power using an energy buffer. As a result, OBCs with APD reduce converter size and extend converter lifespan by replacing electrolytic capacitors with smaller film or ceramic capacitors.

Reference [9] proposes an APD method based on an interleaved totem-pole power factor correction (PFC) converter. During single-phase operation, the unused leg is utilized as a half-bridge APD circuit. This approach eliminates the need for an additional APD circuit. However, the neutral point current required for APD is not supplied properly to the buffer capacitor because of interference between the PFC control and the neutral point current control. Consequently, the pulsating component of the power fluctuation remains on the DC side. Reference [10] proposes another APD method using the LCL filter of a three-phase PWM rectifier. This method also avoids the use of an additional APD circuit. In contrast to [9], this APD method does not exhibit residual power ripple. However, the power factor and total harmonic distortion (THD) of the grid current deteriorate significantly because the AC-side filter capacitor is utilized for APD.

To solve these problems, the authors have proposed a single-phase and three-phase compatible T-type converter that employs the APD method [11]. This circuit configuration uses the unused leg as a half-bridge APD circuit during single-phase operation. Thus, no additional APD circuit is required as in [8]–[10]. Furthermore, this approach allows the single-phase T-type converter and the APD circuit to be controlled almost independently. Consequently, this approach eliminates residual DC-side power ripple while avoiding significant deterioration in the grid-current THD. On the other hand, the APD circuit employs a modulation method that controls the neutral point current using only the half-bridge leg. As a result, a two-level voltage is applied to the APD inductors L_{gw} and L_{fw} , unlike the inductor on the single-phase T-type converter side. This causes a significant ripple in the APD inductor current. This ripple is the main reason for the efficiency reduction under light-load conditions.

This paper proposes a loss-reduction method based on the trapezoidal current mode for a single-phase and three-phase compatible T-type converter. In trapezoidal current mode, a bidirectional switch integrated into the APD circuit clamps the inductor voltage to zero. This increases the number of voltage levels applied to the APD inductors and reduces iron loss. In addition, the APD inductor current ripple is reduced by setting a zero-voltage period at the current peak within each switching cycle. However, the APD inductor current does not flow through the DC-side capacitor during the clamping period. Therefore, a compensation current is required during the zero-voltage period in order to achieve APD. This indicates a trade-off between the zero-voltage period and the conversion loss in the APD circuit. Thus, the zero-voltage period that minimizes the APD circuit loss is designed based on loss analysis. Experimental results show that the proposed loss reduction method improves efficiency at 500 W from 87.5% to 89.2% and reduces the total loss by 15.2%. In addition, the proposed loss reduction method reduces the second-order harmonic component by 97.7%. This indicates that it maintains an APD performance comparable to that of the conventional method.

II. CIRCUIT CONFIGURATION AND CONTROL STRATEGY

A. Circuit Configuration

Fig. 1 shows the circuit diagram of a single-phase and three-phase compatible T-type converter. The three-phase grid is connected to T_u , T_v , and T_w during three-phase operation. In this case, the mechanical relays R_u and R_v are connected to the LCL filter section. The W-phase mechanical relay R_w and the LCL mechanical relay R_n are changeover contact relays. These relays are connected to the LCL filter section during three-phase operation. Consequently, the circuit functions as a three-phase T-type converter in this operating mode.

In single-phase operation, the single-phase grid is connected to terminals T_u and T_v , as shown in Fig. 1(b). The mechanical relays R_u and R_v are connected to the LCL filter section as in the three-phase operation. The W-phase mechanical relay R_w is connected to terminal T_{fw} on the filter inductor L_f side of the LCL filter section. In addition, the mechanical relay R_n of the LCL filter section is connected to the neutral point of the DC-side capacitor. As a result, the circuit functions as both a single-phase T-type converter and a half-bridge APD circuit during single-phase operation.

B. Principle of the Active Power Decoupling

Fig. 2 shows the principle of the active power decoupling method. The APD method maintains constant DC-side power by compensating for the ripple component of the AC-side instantaneous power using an energy buffer. Assuming that the single-phase grid operates at unity power factor, the instantaneous power on the AC-side, p_{in} is expressed as

$$p_{in} = v_g i_g = V_g I_g - V_g I_g \cos(2\omega_g t) \quad (1)$$

where v_g and i_g are the input voltage and current, V_g and I_g are their RMS values, and ω_g is the grid angular frequency. The second term in (1) represents the pulsating component of the power fluctuation. To compensate for this pulsating component, the split capacitors C_1 and C_2 are used as an energy buffer in a T-type converter without an additional circuit. Thus, each capacitor voltage is controlled to form a sinusoidal waveform with an amplitude of V_c , centered at half the DC voltage V_{dc} . These voltages are expressed as

$$\begin{cases} v_{c1} = \frac{V_{dc}}{2} + V_c \sin\left(\omega_g t - \frac{\pi}{4}\right) \\ v_{c2} = \frac{V_{dc}}{2} - V_c \sin\left(\omega_g t - \frac{\pi}{4}\right) \end{cases} \quad (2)$$

where V_{dc} is the DC voltage, and V_c is the amplitude of the capacitor voltage, which must be less than half of V_{dc} . From (1) and (2), the neutral point current i_n flowing through the leg consisting of DC-side capacitors is derived as

$$i_n = 2\omega_g C V_c \sin\left(\omega_g t + \frac{\pi}{4}\right) \quad (3)$$

where C is the capacitance of C_1 and C_2 . In this case, the capacitances of C_1 and C_2 are assumed to be equal. By shaping the neutral point current i_n according to (3), the T-type converter achieves the APD function without an additional circuit.

C. Control Strategy

Fig. 3 shows the control block diagram for single-phase operation using the conventional modulation method. The T-type converter side consists of output voltage control and grid current control. The modulation method is a conventional phase-disposition PWM technique. The voltage balancing control on the APD circuit side compensates for imbalances caused by the neutral point current flowing into the T-type converter side. Switches S_5 and S_6 operate based on the APD circuit output voltage command v_{APD} from the PIR controller. The inductors L_{gw} and L_{fw} , through which i_{n_LW} flows,

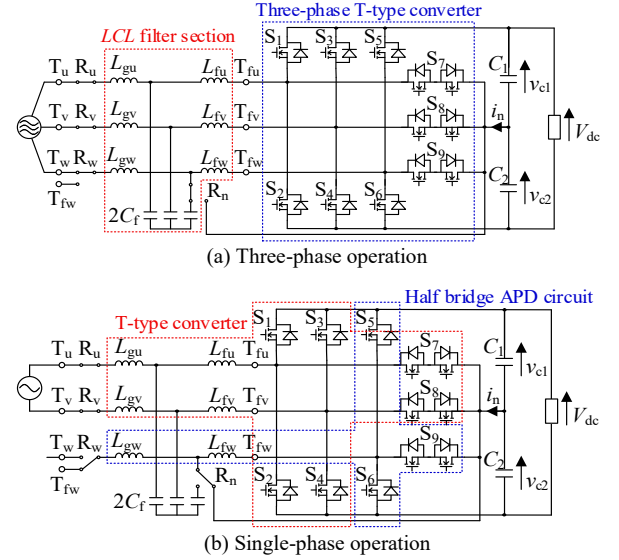


Fig. 1. Circuit diagram of a single-phase and three-phase compatible T-type converter.

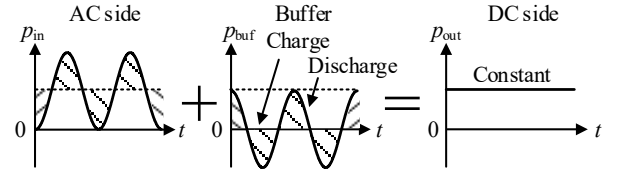


Fig. 2. Principle of the active power decoupling method.

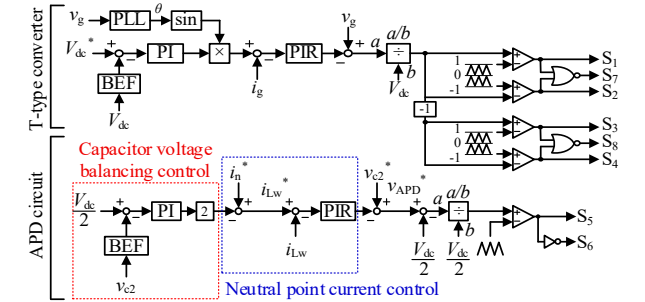


Fig. 3. Control block diagram for single-phase operation using the conventional modulation method.

correspond to the W-phase in three-phase operation. Since a current sensor is already installed in this phase, no additional sensor is required for the APD circuit.

In the conventional modulation method for the APD circuit, the neutral point current is controlled by switches S_5 and S_6 as shown in Fig. 3. As a result, a two-level voltage is applied to the APD circuit inductors L_{gw} and L_{fw} , unlike the inductors on the single-phase T-type converter side. Furthermore, under light-load conditions, the iron loss in the APD inductors L_{gw} and L_{fw} becomes the dominant loss component because the two-level inductor voltage causes a large high-frequency flux swing even when the load current is small.

III. TRAPEZOIDAL CURRENT MODE

A. Loss Reduction Method

Fig. 4 shows the operating waveforms of the proposed trapezoidal current mode. The trapezoidal current mode utilizes the bidirectional switch S_9 in the APD circuit in order to clamp the inductor voltage to zero. The zero-voltage period

reduces the peak magnetic flux in the APD inductor during the switching cycle. This reduction enables iron loss to be reduced. However, the APD inductor current does not flow through the DC-side capacitor during the clamping period. Therefore, a compensation current is required during the zero-voltage period in order to maintain APD operation.

The compensation current affects the conduction losses in the W-phase inductor and bidirectional switch S9. These losses depend on the application range of the trapezoidal current mode and the zero-voltage duty ratio. This indicates a trade-off between the zero-voltage period of the trapezoidal current mode and the conversion loss in the APD circuit. The compensation current varies depending on the phase of the neutral point current within the range of the trapezoidal current mode. In particular, the compensation current required at the peak of (3) is maximized. For this reason, the trapezoidal current mode is applied near the zero-crossing point of the neutral point current in order to minimize conduction losses caused by the compensation current. In addition, the zero-voltage duty ratio d_9 during the switching cycle also affects conduction losses. Thus, it is necessary to consider both the range of the trapezoidal current mode and the zero-voltage duty ratio d_9 simultaneously.

Fig. 5 shows the relationship between the neutral point current and the zero-voltage period parameters. The parameter k determines the application range of the trapezoidal current mode. This parameter represents the offset applied to the full-wave-rectified waveform $|\cos(\omega_g t + \pi/4)|$, which reaches its maximum at the zero crossing of the neutral point current command, where $0 < k < 1$. This parameter adjusts Region A in which the trapezoidal current mode is applied. Note that the trapezoidal current mode is not applied in Region B. The zero-voltage duty ratio d_9 is expressed as

$$\begin{cases} d_9 = d_{\text{zero_peak}} \frac{|\cos(\omega_g t + \frac{\pi}{4})| - k}{1 - k} & \text{when } |\cos(\omega_g t + \frac{\pi}{4})| - k \geq 0 \\ d_9 = 0 & \text{when } |\cos(\omega_g t + \frac{\pi}{4})| - k < 0 \end{cases} \quad (4)$$

where $d_{\text{zero_peak}}$ is the parameter that determines the maximum value of the zero-voltage duty ratio d_9 . In this paper, $d_{\text{zero_peak}}$ and the parameter k are determined based on loss analysis in order to minimize the APD circuit loss under various load conditions. Conduction losses and switching losses in each switching device are calculated using a thermal model. The copper losses in each inductor are calculated based on the RMS values of the currents and the measured series parasitic resistance. In addition, iron losses are calculated using the improved generalized Steinmetz equation (iGSE) [12].

B. Loss Analysis Result

Table I shows the conditions for the loss analysis. The parameter k is varied from 0.3 to 0.95 in increments of 0.05, whereas $d_{\text{zero_peak}}$ is varied from 0.05 to 0.8 in increments of 0.025. The output power P_{out} is varied from 500 W to 3 kW in increments of 500 W. Loss analysis is then performed for each parameter combination.

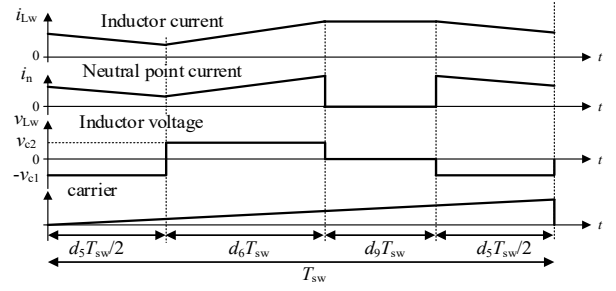


Fig. 4. Operating waveforms of the proposed trapezoidal current mode.

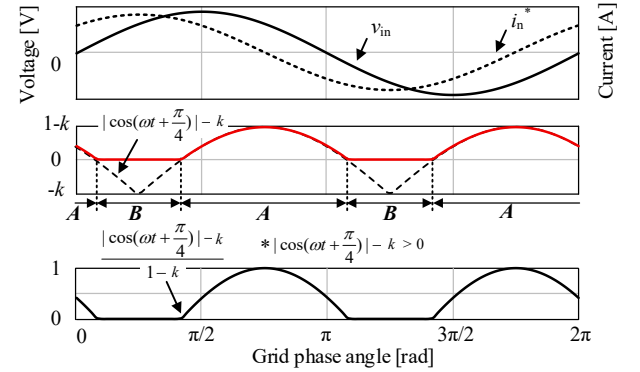
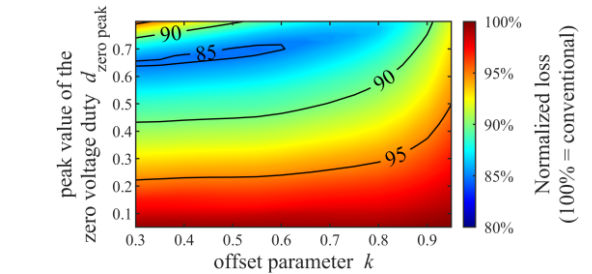


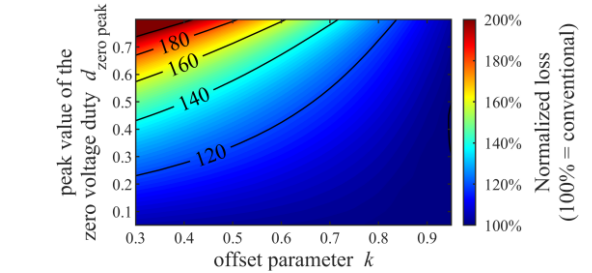
Fig. 5. Relationship between the neutral point current and the zero-voltage period parameters.

TABLE I. PARAMETER CONDITIONS FOR LOSS ANALYSIS

Symbol	Range	Step
k	0.3 ~ 0.95	0.05
$d_{\text{zero_peak}}$	0.05 ~ 0.8	0.025
P_{out}	500 ~ 3000	500



(a) Light-load condition (500 W)



(b) Rated-load condition (3 kW)

Fig. 6. Loss analysis results under different conditions.

Fig. 6 shows the contour plots of the normalized loss under various parameter conditions. Each contour plot is normalized by the loss caused by the conventional modulation method shown in Fig. 3. The loss ratio is minimized at $k = 0.55$ and $d_{\text{zero_peak}} = 0.7$ under the light-load condition as shown in Fig. 6(a). In other words, the loss is reduced by 15.4% compared with the conventional modulation method. This indicates that

the trapezoidal current mode is effective in reducing iron loss because the impact of the compensation current is small under light-load conditions. On the other hand, the loss ratio is minimized at $k = 0.95$ and $d_{\text{zero_peak}} = 0.45$ under the rated-load condition shown in Fig. 6(b). In contrast to the light-load condition, the loss exceeds that of the conventional modulation method under all analysis conditions at the rated load. This indicates that the increase in conduction and copper losses caused by the compensation current exceeds the loss reduction achieved by applying the trapezoidal current mode. Therefore, the loss ratio is minimized when the trapezoidal current mode is applied over a limited operating range. From this analysis, parameter k and $d_{\text{zero_peak}}$ are determined offline and utilized in the trapezoidal current mode.

Fig. 7 shows the control block diagram for the single-phase operation with the trapezoidal current mode. The control block on the single-phase T-type converter side has the same configuration as shown in Fig. 3. The APD circuit side calculates the zero-voltage duty ratio d_9 based on the load condition and the grid phase angle θ . The duty commands d_5 and d_6 for the half-bridge circuit are calculated based on the zero-voltage duty ratio. The duty commands for switching devices S_5 and S_6 are expressed as

$$\begin{cases} d_5 = \frac{v_{\text{APD}}^* - d_9 v_{c2}}{V_{\text{dc}}} \\ d_6 = 1 - d_5 - d_9 \end{cases} \quad (5)$$

where v_{APD}^* is the voltage command of the half-bridge circuit. Note that a compensation gain is applied to the neutral point current command for APD in order to compensate for the current that does not flow into the DC-side capacitor during the zero-voltage period.

IV. EXPERIMENTAL RESULTS

Table II shows the experimental conditions. Each DC-side capacitor is set to 300 μF .

A. Fundamental Operations

Fig. 8 shows the experimental results of the single-phase and three-phase compatible T-type converter during single-phase operation. Fig. 8(a) shows the results without APD, Fig. 8(b) shows the results obtained using the conventional APD modulation method, and Fig. 8(c) shows the results obtained using the proposed trapezoidal current mode. When APD is not applied, the output voltage V_{dc} and the DC-side capacitor voltages pulsate at twice the grid frequency as shown in Fig. 8(a). In contrast, the output voltage pulsation is suppressed when APD is applied as shown in Fig. 8(b) and Fig. 8(c). These results validate the energy-buffer function of the DC-side capacitors achieved by the neutral point current control. In addition, the trapezoidal current mode reduces the current ripple around the zero-crossing point of the APD inductor current as shown in Fig. 8(c). This is because the zero-voltage period is applied around the peak of the switching ripple.

B. Harmonic Analysis of the Output Voltage

Fig. 9 shows the harmonic analysis results of the output voltage under each control method. The fundamental frequency is 50 Hz, and each harmonic component is normalized by the DC component. The conventional APD modulation method reduces the second-order harmonic component by 99.4% compared with operation without APD.

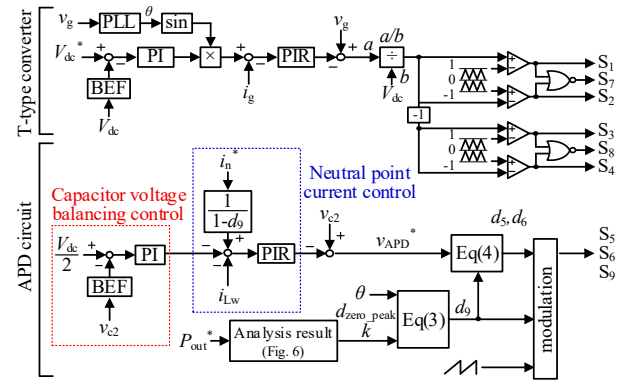


Fig. 7. Control block diagram for the single-phase operation with the trapezoidal current mode.

TABLE II. EXPERIMENTAL CONDITIONS

Parameter	Symbol	Value
Rated output power	P_{out}	3 kW
Grid voltage	v_{in}	200 V _{rms}
Output voltage	V_{dc}	450 V
Grid frequency	f_g	50 Hz
Switching frequency	f_{sw}	20 kHz
DC-side capacitor	C_1, C_2	300 μF
Capacitor voltage utilization factor	a	0.793
Grid-tied inductor	$L_{\text{gi}}, L_{\text{gv}}, L_{\text{gw}}$	170 μH (%Z:0.4%)
Filter inductor	$L_{\text{fi}}, L_{\text{fv}}, L_{\text{fw}}$	170 μH (%Z:0.4%)
Filter capacitor	$C_{\text{fi}}, C_{\text{fv}}, C_{\text{fw}}$	2.0 μF
Switching device	$S_1 \sim S_9$	F3L8MXTR12C2M2_H11

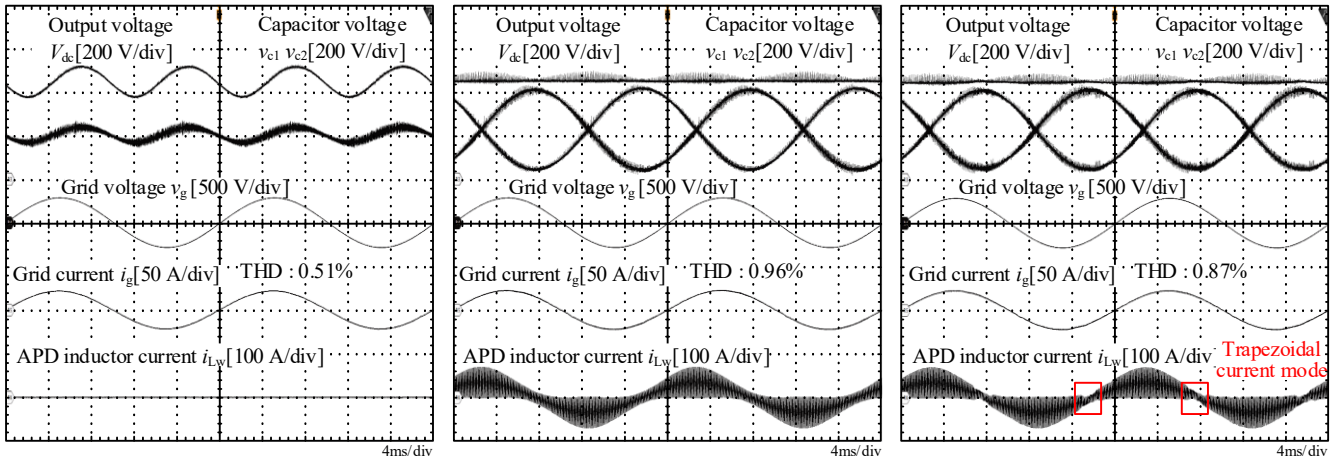
In addition, the proposed trapezoidal current mode reduces the second-order harmonic component by 97.7% compared with operation without APD. These results indicate that the trapezoidal current mode achieves an APD performance comparable to that of the conventional modulation method.

C. Efficiency and Grid Current THD

Fig. 10 shows the efficiency and grid current THD characteristics for each control method. The trapezoidal current mode improves the efficiency at 500 W from 87.5% to 89.2% compared with the conventional modulation method. In other words, the trapezoidal current mode reduces the loss by 15.2% under light-load conditions. However, the efficiency improvement of the trapezoidal current mode decreases near the rated-load condition. This is because the compensation current for the neutral point current increases as the load approaches the rated condition. The THD of the grid current under the rated-load condition is 0.96% with the conventional modulation method and 0.87% with the trapezoidal current mode.

V. CONCLUSION

This paper proposed a trapezoidal current mode-based loss reduction method for a single-phase and three-phase compatible T-type converter with active power decoupling. The proposed trapezoidal current mode clamps the inductor voltage to zero using the bidirectional switch built into the APD circuit. Consequently, the APD inductor-current ripple and the converter loss are reduced by increasing the number of voltage levels applied to the inductor. Experimental results demonstrated that the proposed loss reduction method improves efficiency under light-load conditions from 87.5% to 89.2% and reduces the total loss by 15.2%. In addition, the



(a) without APD (b) conventional APD (c) proposed APD
Fig. 8. Operating waveforms for each control method.

proposed loss reduction method reduces the second-order harmonic component by 97.7%. This indicates that it maintains an APD performance comparable to that of the conventional method.

ACKNOWLEDGMENT

This work was supported by JST SPRING, Japan Grant Number JPMJSP2189.

REFERENCES

- [1] T. -T. Le, G. Abraham, H. -N. Nguyen, H. -T. Tran, T. -T. Nguyen and Q. Bach Nguyen, "A New Control Method for an On-Board Charger for Electric Vehicles Operating in a Split-Phase System," in *IEEE Transactions on Transportation Electrification*, vol. 11, no. 4, pp. 9416-9427, Aug. 2025.
- [2] Zhou K, Chen S-M, Jin N-Z and Sun D-Y, "Research on Single-Phase and Three-Phase Compatible Isolated On-Board Charger and Control Technology," *Energies*, vol. 15, no. 17, p. 6445, Sep. 2022.
- [3] B. P. Do, M. G. Geda, H. -P. Kieu, D. B. H. Nguyen, S. Kim and S. Choi, "Three/Single-Phase Compatibility Single-Stage EV Charger With Six-Switch Full-Bridge Configuration," in *IEEE Transactions on Power Electronics*, vol. 41, no. 1, pp. 561-573, Jan. 2026.
- [4] K. Ohata, H. Watanabe and J. Itoh, "Simplified Droop-Based Distributed Control for Single- and Three-Phase Compatible AC-DC Converters with Series Connectivity," in *IEEE J. Industry Applications*, vol. 15, no. 3, pp. 515-523, Feb. 2026.
- [5] K. Tomida, K. Natori, J. Xu, N. Shimamoto and Y. Sato, "A Novel Control Method to Improve Efficiency in Wide Output Voltage Range for Bidirectional Isolated Three-Phase AC/DC Converter Based on Matrix Converter," in *IEEE J. Industry Applications*, vol. 13, no. 1, pp. 17-23, Oct. 2024.
- [6] S. Malanda, S. Komeda, H. Kifune, S. Takuma, and Y. Ohnuma, "Improvement of Switching Characteristics for an Active Buffer Dual-Active-Bridge AC-DC Converter," in *IEEE J. Industry Applications*, vol. 13, no. 5, pp. 561-569, June 2024.
- [7] J. Kim, D. Lee, C. Suk, G. Yu and S. Choi, "Single/Three-Phase Compatible Sigma-Type OBC With Reduced Electrolytic Capacitor Volume," in *IEEE Transactions on Industrial Electronics*, vol. 72, no. 6, pp. 6027-6037, June 2025.
- [8] K. Irimura, M. Yamaguchi, H. Watanabe and J. Itoh, "Three/Single-Phase Switchable DAB Matrix Converter and Active Power Decoupling Method with Center-Tapped Transformer," in *Proc. of 2025 IEEE Energy Conversion Congress & Exposition Asia (ECCE-Asia)*, Bengaluru, India, 2025.

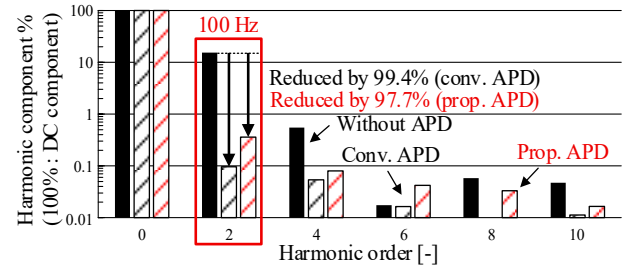


Fig. 9. Harmonic analysis results of the output voltage for each control method.

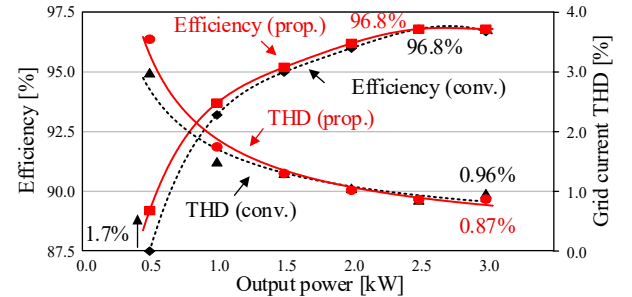


Fig. 10. Load characteristic for each control method.

- [9] Y. Bi, T. Zhao, J. Xu, G. Shu, C. Wu, Y. Wang and T. B. Soeiro, "An Improved Combined Current Control for Single-Phase Operation Mode of Single-/Three-Phase EV Charging System With Voltage Ripple Suppression," in *IEEE Transactions on Power Electronics*, vol. 38, no. 11, pp. 13635-13649, Nov. 2023.
- [10] H. Zhao, Y. Shen, W. Ying, S. S. Ghosh, M. R. Ahmed and T. Long, "A Single- and Three-Phase Grid Compatible Converter for Electric Vehicle On-Board Chargers," in *IEEE Transactions on Power Electronics*, vol. 35, no. 7, pp. 7545-7562, July 2020.
- [11] R. Higashide, H. Watanabe and J. -I. Itoh, "Active Power Decoupling in Single- and Three-Phase Compatible T-Type AC-DC Converter Using a Built-in Leg," in *Proc. of 2025 International Future Energy Electronics Conference (IFEEEC)*, pp. 295-300, Bali, Indonesia, 2025.
- [12] K. Venkatachalam, C. R. Sullivan, T. Abdallah and H. Tacca, "Accurate prediction of ferrite core loss with nonsinusoidal waveforms using only Steinmetz parameters," in *Proc. of 2002 IEEE Workshop on Computers in Power Electronics*, pp. 36-41, Mayaguez, PR, USA, 2002.