Analysis of the Phase-Shift Angle in Trapezoidal Current Mode for a Single-Phase and Three-Phase Compatible T-Type Converter

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Abstract - This paper analyzes the phase-shift angle in the trapezoidal current mode for a single-phase and three-phase compatible T-type converter. A phase-shift angle is introduced into the zero-voltage duty calculation. The loss analysis indicates that the conversion loss is minimized at a phase-shift angle of 90°. Experimental results obtained using the analytically selected parameters demonstrate an efficiency improvement at light load.

Keywords single-phase and three-phase compatible converter, T-type converter, active power decoupling, trapezoidal current mode

I. Introduction

A single-phase and three-phase compatible T-type converter with active power decoupling (APD) has been proposed for EV on-board chargers [1]. In order to improve the efficiency of this converter, a trapezoidal current mode is considered. The conventional trapezoidal current mode reduces losses by setting a zero-voltage period around the zero-crossing point of the neutral-point current. However, the influence of the position of the zero-voltage period on the converter loss has not been investigated. In this paper, a phase-shift angle is introduced into the zero-voltage duty calculation. The converter efficiency with the analytically selected parameters is then evaluated experimentally.

II. Circuit Configuration and Control Strategy

Fig. 1 shows the circuit configuration of the single-phase and three-phase compatible T-type converter. The converter changes the mechanical relay connections according to the grid configuration. Consequently, the circuit operates as a three-phase T-type converter with a three-phase grid and as a single-phase T-type converter with an APD circuit with a single-phase grid. The input power contains a pulsating component at twice the grid frequency during single-phase operation. APD is achieved by regulating the neutral-point current flowing through the DC-link capacitors C_1 and C_2. The neutral-point current required for APD is expressed as

$$i_{\mathrm{n}} = 2\omega_{\mathrm{g}} C V_{\mathrm{c}} \sin\left(\omega_{\mathrm{g}} t + \frac{\pi}{4}\right) \tag{1}$$

where ω_{g} is the grid angular frequency, C is the capacitance of the DC-side capacitors, and V_{c} is the amplitude of the capacitor voltages. The capacitances of C_1 and C_2 are assumed to be equal.

III. Analysis of the Phase-Shift Angle

Fig. 2 shows the operating waveforms of the trapezoidal current mode. The bidirectional switch S_9 clamps the inductor voltage to zero. Consequently, the trapezoidal current mode reduces the inductor core loss and the switching ripple in the neutral-point current. However, the neutral-point current does not flow through the DC-link capacitors during the zero-voltage period, so a compensation current is required to maintain APD operation. In the conventional method, the trapezoidal current mode is applied around the zero-crossing point of the neutral-point current in order to minimize the compensation current. In this paper, the phase-shift angle ϕ, the offset parameter k, and the maximum zero-voltage duty ratio $d_{\mathrm{zero_peak}}$ are varied to identify the parameter combination that minimizes the conversion loss.

Table I shows the parameter ranges. The three parameters are varied for each load condition. The conversion loss is calculated from the conduction and switching losses of the switching devices and the inductor copper and core losses using the operating waveforms.

Fig. 3 shows the loss analysis results under light-load conditions. The conversion loss is minimized at a phase-shift angle of 90° for both $d_{\mathrm{zero_peak}}$ = 0.3 and 0.7. This indicates

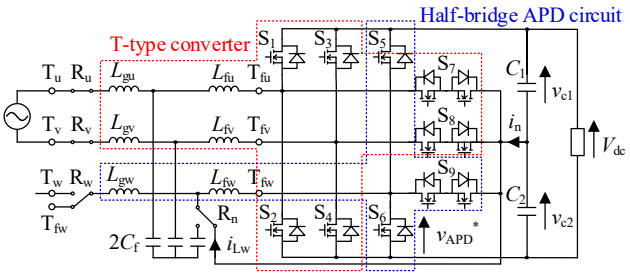


Fig. 1. Circuit configuration of the single-phase and three-phase compatible T-type converter in single-phase operation.

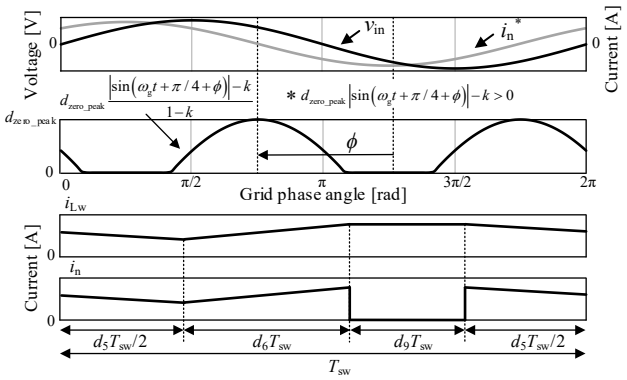


Fig. 2. Operating waveforms of the trapezoidal current mode.

that the trapezoidal current mode is most effective when applied around the zero-crossing point of the neutral-point current. In addition, a larger $d_{\text{zero_peak}}$ provides a greater loss reduction under the light-load condition.

Fig. 4 shows the loss analysis results under rated load. As in Fig. 3, the conversion loss is minimized at a phase-shift angle of 90°. At rated load, the minimum loss is obtained when the zero-voltage period is limited. These results indicate that the conversion loss of the trapezoidal current mode is minimized at a phase-shift angle of 90°.

Fig. 5 shows the control block diagram. The duty commands in the APD circuit are expressed as

$$\begin{cases} d_5 = \dfrac{v_{\text{APD}}^{*} - d_9 v_{\text{c2}}}{V_{\text{dc}}} \\ d_6 = 1 - d_5 - d_9 \\ d_9 = d_{\text{zero_peak}} \dfrac{\left|\sin\left(\omega_{\text{g}} t + \dfrac{\pi}{4} + \phi\right)\right| - k}{1-k} \quad \text{when} \quad \left|\sin\left(\omega_{\text{g}} t + \dfrac{\pi}{4} + \phi\right)\right| - k \geq 0 \end{cases} \tag{2}$$

where v_{APD}^{*} is the voltage command of the half-bridge circuit. The parameters ϕ, k, and $d_{\text{zero_peak}}$ are set to the values selected from the loss analysis. The neutral-point current command compensates for the current bypassed during the zero-voltage period to maintain APD operation.

IV. Experimental Results

Fig. 6 shows the experimental waveforms of the trapezoidal current mode. The output-voltage ripple is suppressed by the APD control. In addition, the trapezoidal current mode reduces the switching ripple around the zero crossing point of the neutral-point current as shown in Fig. 6. This is because the zero-voltage period is applied around the peak of the switching ripple as shown in Fig. 2.

Fig. 7 shows the efficiency characteristics of the conventional and trapezoidal current modes. At 500 W, the trapezoidal current mode improves the efficiency from 87.5% to 89.2% compared with the conventional modulation method. This efficiency improvement corresponds to a loss reduction of 15.2%. However, the efficiency improvement of the trapezoidal current mode decreases near rated load. This is attributed to the increase in the compensation current as the output power approaches the rated value.

V. Conclusion

This paper analyzed the phase-shift angle of the trapezoidal current mode for a single-phase and three-phase compatible T-type converter. Experimental results obtained with the analytically selected parameters show that the trapezoidal currentmode improves the efficiency from 87.5% to 89.2% at 500 W.

References

[1] R. Higashide, H. Watanabe, and J. Itoh, "Active Power Decoupling with Capacitor Voltage Utilization Factor Design for Single-phase and Three-phase Compatible T-type Converter in EV On-board Chargers," *in Proc. of International Power Electronics Conference (IPEC2026)*, Nagasaki, Japan, 2026.

TABLE I. PARAMETER RANGES FOR LOSS ANALYSIS

Symbol	Range	Step
ϕ	0° ~ 180°	10°
k	0.5 ~ 0.9	0.1
$d_{\text{zero_peak}}$	0.1 ~ 0.8	0.05
P_{out}	500 W ~ 3000 W	500 W

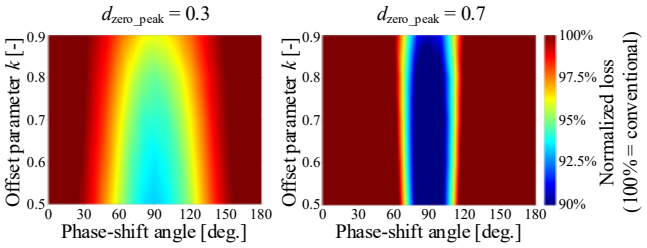


Fig. 3. Loss analysis results at 500 W.

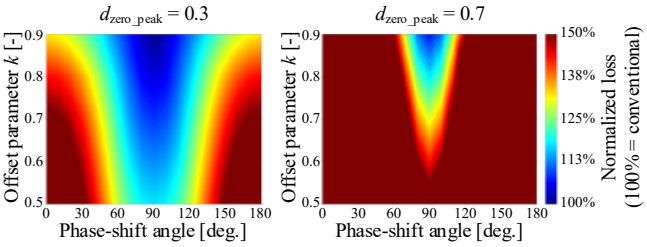


Fig. 4. Loss analysis results at 3.0 kW.

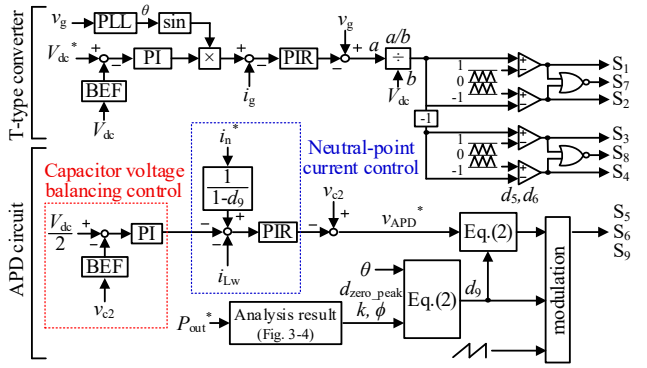


Fig. 5. Control block diagram of the trapezoidal current mode.

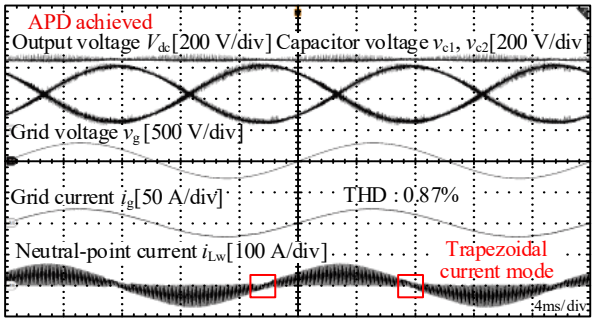


Fig. 6. Experimental waveforms of the trapezoidal current mode.

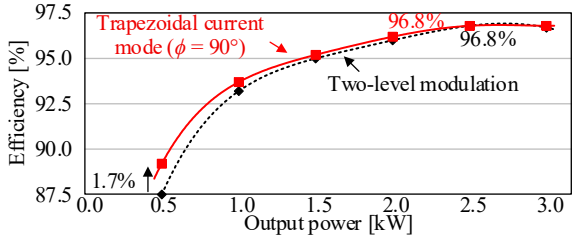


Fig. 7. Efficiency characteristics.