

High-Speed Current-Sensorless Triangular Current Mode Control for Single-Phase Inverters Achieving MHz-Class Operation

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Abstract—This paper proposes a triangular current mode (TCM) control method for high-switching-frequency inverters. The proposed method does not require high-speed bottom current detection. The switching frequency is calculated based on the operating conditions. The filter inductor current is controlled by low-bandwidth average current feedback control. The experimental results with 1-kW prototype confirmed that the proposed method achieved zero-voltage switching (ZVS) even when the equivalent switching frequency exceeded 1 MHz. Furthermore, the total harmonic distortion (THD) of the output current was 1.96%, and the conversion efficiency reached 93.9% at the rated output power.

Keywords—triangular current mode, single-phase inverter, current distortion

I. INTRODUCTION

In recent years, the demand for energy conservation and high efficiency has increased. Accordingly, the importance of power electronics has also grown. Compact and highly efficient power converters are required to utilize energy effectively. Therefore, improving the power density of power converters has become an important research topic. One approach to improving power density is to increase the switching frequency. A higher switching frequency enables the use of smaller passive components such as inductors and capacitors. On the other hand, increasing the switching frequency increases the switching loss. As the amount of heat generation increases, larger heat sinks and cooling systems become necessary. To address this problem, soft-switching techniques have attracted considerable attention. Representative soft-switching techniques include zero-voltage switching (ZVS) and zero-current switching (ZCS).

Triangular current mode (TCM) control, which is one of the soft-switching techniques, turns on the switches under zero-voltage conditions. As a result, zero-voltage switching (ZVS) is achieved and the switching loss is significantly reduced. Therefore, TCM control has attracted considerable attention as a control method that achieves both high-switching-frequency operation and high efficiency [1]–[3].

Furthermore, high-switching-frequency operation enables the use of smaller passive components such as inductors and capacitors. Consequently, TCM control also contributes to

improving the power density of the entire power converter [4], [5]. Conventional TCM control secures a negative bottom current margin to achieve zero-voltage switching (ZVS). Therefore, the bottom current must be controlled. High-speed current sensing using a shunt resistor is required to control the bottom current [6], [7]. However, as the switching frequency increases, the effects of the parasitic inductance and parasitic capacitance of the shunt resistor become more significant. In addition, the bandwidth limitation and propagation delay of the current sensing amplifier and its peripheral circuits can no longer be ignored. As a result, accurately detecting the bottom current becomes difficult. Therefore, the applicable switching frequency range of conventional TCM control is limited [8], [9].

To address this problem, this paper proposes a TCM control method that does not require high-speed current sensing. The proposed method does not directly detect the bottom current. Instead, the switching frequency required to maintain the negative bottom current margin for zero-voltage switching (ZVS) is calculated from the current command, the input voltage, the output voltage, and the grid-tied inductor. Furthermore, the calculated switching frequency is applied in real time to achieve TCM operation.

The authors have previously proposed the basic concept of a TCM control method that does not require high-speed bottom current sensing. In addition, its feasibility has been verified through simulations and experiments using a resistive load. However, the previous study was limited to verifying the control principle under resistive load conditions. Therefore, the current quality during grid-tied operation and the effectiveness under MHz-class operation have not been sufficiently evaluated.

This paper applies the proposed control method to a single-phase grid-tied inverter. The effectiveness of the proposed TCM control method without high-speed bottom current sensing is experimentally verified. Experiments using a 1 kW prototype confirmed operation with an equivalent switching frequency exceeding 1 MHz. At the rated output power, the total harmonic distortion (THD) of the output current was 1.96%, and the conversion efficiency reached 93.9%. The experimental results also confirmed that zero-voltage switching (ZVS) was achieved.

II. HIGH-SPEED CURRENT-SENSORLESS TRIANGULAR CURRENT MODE CONTROL

A. Circuit Configuration

Fig. 1 shows the circuit configuration of the single-phase grid-tied inverter with an LCL filter. During TCM operation, the grid-tied inductor current exhibits a triangular waveform with a large switching ripple to achieve zero-voltage switching (ZVS). On the other hand, the LCL filter sufficiently attenuates the high-frequency components. Therefore, the filter inductor current contains little switching ripple. Consequently, the filter inductor current has a smooth waveform composed mainly of the grid frequency component. This characteristic allows the filter inductor current to be used as the feedback signal for average current control.

The proposed method employs variable switching frequency control. Therefore, current sampling is performed asynchronously with the switching operation. If the grid-tied inductor current is sampled directly, the measured current varies significantly depending on the sampling instant because of the switching ripple. As a result, the current control performance may degrade. In contrast, the proposed method uses the filter inductor current as the feedback signal. Because the filter inductor current contains little switching ripple, the current can be measured without being affected by the switching ripple. Therefore, highly accurate average current feedback control is achieved without using a high-speed current sensing circuit.

B. Circuit Operation of TCM

Fig. 2 shows the operating waveforms of TCM. In TCM, the switching period varies according to the operating conditions. As shown in Fig. 2, one switching period consists of four operating modes.

Mode 1 [t_0 – t_1]: As shown in Fig. 3(a), switches S_1 and S_4 are turned on with zero-voltage switching (ZVS) at t_0 . When the capacitor voltage has positive polarity, a voltage of $V_{in} - v_c$ is applied across the TCM inductor. As a result, the inductor current i_L increases linearly.

Mode 2 [t_1 – t_2]: As shown in Fig. 3(b), the output capacitance of S_4 is charged. At the same time, the output capacitance of S_3 is discharged. When the drain-to-source voltage of S_3 decreases to 0 V, the inductor current i_L flows through the body diode of S_3 . As a result, the condition for the ZVS turn-on of S_3 is satisfied.

Mode 3 [t_2 – t_3]: As shown in Fig. 3(c), S_3 is turned on with zero-voltage switching (ZVS) at t_2 . When the capacitor voltage has positive polarity, a voltage of $-v_c$ is applied across the TCM inductor. As a result, the inductor current i_L decreases linearly.

Mode 4 [t_3 – t_4]: As shown in Fig. 3(d), S_3 is turned off when the inductor current i_L reaches the bottom current I_{bot} at t_3 . Subsequently, the output capacitances of S_1 and S_4 are discharged. When the drain-to-source voltages of S_1 and S_4 decrease to 0 V during the dead time, the inductor current i_L flows through the body diodes of both switches. As a result, the conditions for the ZVS turn-on of S_1 and S_4 in the next switching period are satisfied.

In TCM control, the switching frequency is varied to obtain the desired average current while maintaining the

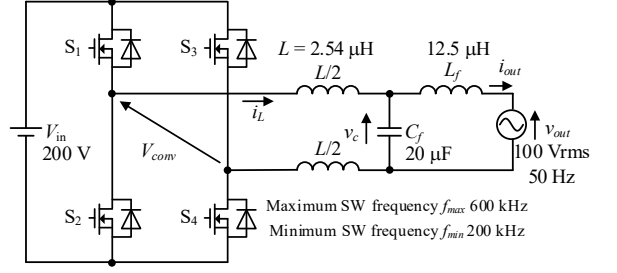


Fig. 1. Circuit diagram of the full-bridge inverter.

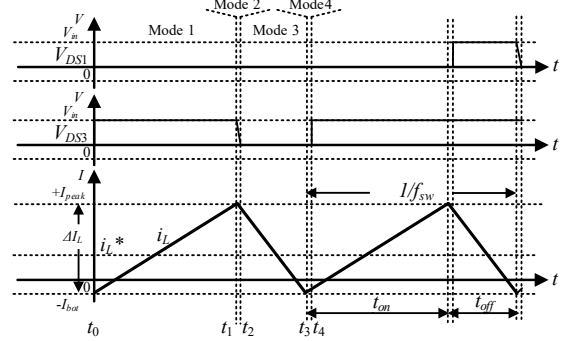


Fig. 2. Grid-tied inductor current waveform diagram of TCM when output voltage polarity is positive.

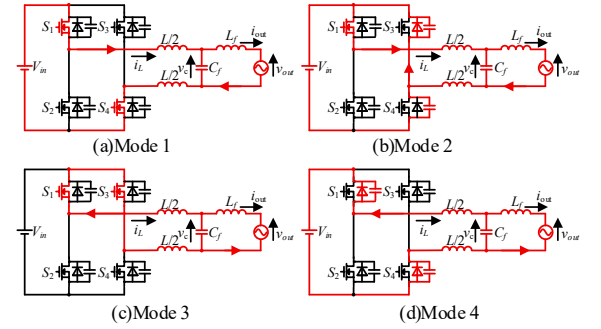


Fig. 3. Operating modes in the proposed TCM method.

negative bottom current required for zero-voltage switching (ZVS). Mode 1 shown in Fig. 2 is considered. In Mode 1, the increase in the inductor current is determined by the on-time. Therefore, the current ripple is expressed as (1). On the other hand, the current ripple can also be expressed using the bottom current magnitude I_{bot} and the average current i_{avg} . This relationship is given by (2).

$$\Delta I_L = \frac{V_{in} - |v_c|}{L} t_{on} = \frac{V_{in} - |v_c|}{L} \frac{|v_c|}{V_{in}} \frac{1}{2f_{sw}} \quad (1)$$

$$\Delta I_L = 2(|i_{ave}| + I_{bot}) = 2(|i_L^*| + I_{bot}) \quad (2)$$

Here, $i_{avg} = (I_{peak} - I_{bot})/2$, where V_{in} is the input voltage, v_c is the filter capacitor voltage, and i_L^* is the current command. By eliminating the current ripple from (1) and (2) and rearranging the resulting equation with respect to the switching frequency f_{sw} , (3) is obtained.

$$f_{sw} = \frac{|v_c| (V_{in} - |v_c|)}{4L V_{in} (|i_L^*| + I_{bot})} \quad (3)$$

From (3), the calculated switching frequency f_{sw} approaches 0 Hz as the filter capacitor voltage v_c approaches 0 V. As a result, the switching period becomes excessively long near the zero crossing of the grid voltage. Therefore, a lower limit is imposed on the calculated switching frequency. Furthermore, the TCM inductance is designed so that the calculated switching frequency does not fall below the lower limit under the peak values of the rated voltage and rated current.

C. Block Diagram of the Proposed Control Method

Fig. 4 shows the control block diagram of the proposed method. The proposed method is intended to achieve TCM operation without directly detecting the bottom current. At MHz-class switching frequencies, current sensing circuits using shunt resistors are affected by bandwidth limitations and noise. Therefore, accurately detecting the bottom current in every switching period is difficult.

Instead, the proposed method does not directly detect the bottom current. The switching frequency is calculated from the current command, the filter capacitor voltage, and the bottom current command required for zero-voltage switching (ZVS) based on the theoretical equation. Furthermore, the calculated switching frequency is applied in real time to achieve variable switching frequency TCM operation according to the operating conditions.

On the other hand, the switching frequency calculated from the theoretical equation does not reflect circuit parameter errors or output current variations. Therefore, the proposed method incorporates conventional average current feedback control. The filter inductor current, in which the switching ripple is sufficiently suppressed, is used for feedback. The difference between the measured filter inductor current and the current command is applied to a PI controller. The PI controller generates the voltage command for the grid-tied inductor.

Next, the voltage command generated by the PI controller is added to the filter capacitor voltage v_c to generate the inverter voltage command. The duty command is then obtained by normalizing the inverter voltage command with the input voltage V_{in} . The duty command is updated in real time by the average current feedback control. Therefore, the output current tracks the current command even in the presence of circuit parameter variations and load variations.

Finally, a triangular carrier is generated based on the calculated switching frequency. The PWM signal is generated by comparing the triangular carrier with the duty command. The generated PWM signal drives each switch. As a result, TCM operation is achieved without requiring high-speed bottom current sensing. In addition, the average current feedback control provides high current tracking performance and excellent steady-state performance.

D. Inductor design for TCM

To achieve TCM operation within the desired switching frequency range, the grid-tied inductance must be designed appropriately. In TCM control, the inductor current ripple strongly depends on the grid-tied inductance. Therefore, the grid-tied inductance is a key design parameter that determines the switching frequency. If the grid-tied inductance is too large, the switching frequency decreases.

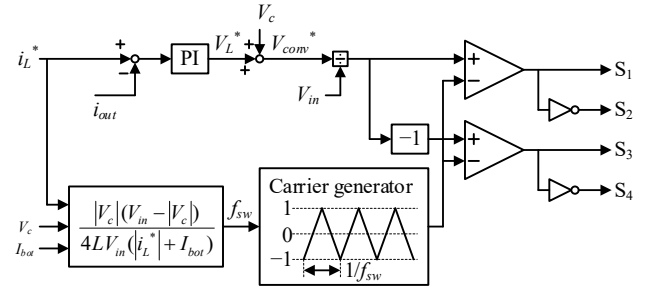


Fig. 4. Block diagram of the proposed TCM control.

On the other hand, if the grid-tied inductance is too small, the current ripple and peak current increase. Therefore, the grid-tied inductance must be designed to satisfy the target switching frequency range.

In this study, the grid-tied inductance is designed based on the minimum switching frequency $f_{sw,min}$, which is the lower limit of the switching frequency. In TCM control, the switching frequency is determined by the filter capacitor voltage v_c , the grid-tied inductor current, the bottom current command I_{bot} , and the grid-tied inductance L . When the fundamental components of the filter capacitor voltage and the grid-tied inductor current both reach their peak values, the current variation during one switching period becomes maximum. As a result, the switching frequency reaches its minimum value. Therefore, the grid-tied inductance is designed to satisfy the target minimum switching frequency under this worst-case condition. Consequently, TCM operation is achieved within the desired switching frequency range over the entire operating range.

To achieve zero-voltage switching (ZVS) in TCM control, sufficient current is required to charge and discharge the output capacitances of the switching devices during each switching transition. This current is referred to as the bottom current. The bottom current required for ZVS is determined by the output capacitance of the switching devices and the DC-link voltage. In this study, the bottom current command required for ZVS is set to $I_{bot}=2$ A.

Based on the above conditions, the grid-tied inductance is designed. Equation (3) represents the switching frequency in TCM control. In this study, the maximum filter capacitor voltage $V_{c,max}$ and the peak value of the rated current $i_{L,max}^*$ are substituted into (3). Equation (3) is then rearranged with respect to the grid-tied inductance (L). As a result, the grid-tied inductance required to satisfy the minimum switching frequency $f_{sw,min}$ is obtained. This relationship is given by (4).

$$L = \frac{|V_{c,max}|(V_{in} - |V_{c,max}|)}{4f_{sw,min}V_{in}(|i_{L,max}^*| + I_{bot})} \quad (4)$$

In this study, $V_{in}=200$ V, $V_{c,max}=141$ V, $f_{sw,min}=200$ kHz, $i_{L,max}^*=14$ A, and $I_{bot}=2$ A are substituted into (4), yielding the required grid-tied inductance of $L=3.25$ μ H. With this inductance, the switching frequency is maintained above 200 kHz even under the worst-case condition where both the voltage and current reach their maximum values. Consequently, TCM operation is achieved within the desired switching frequency range over the entire operating range.

III. SIMULATION RESULTS

A. Operation of the Proposed Method

Table I shows the simulation conditions. In this section, the total harmonic distortion (THD), the switching frequency, and the bottom current are evaluated. In addition, it is verified that the proposed method maintains the negative bottom current margin required for TCM/ZVS operation even under variable switching frequency operation.

The grid-tied inductance L , the DC input voltage V_{in} , and the current command i_L^* were set to 2.54 μH , 200 V, and 10 A, respectively. The grid-tied inductance was designed to be 3.25 μH . However, the PCB parasitic impedance changed due to the transition to a GaN-based prototype. As a result, the measured grid-tied inductance was 2.54 μH . Since the fabricated grid-tied inductor was not modified, both the simulations and experiments in this study were conducted using the measured inductance of 2.54 μH . In general, when the grid-tied inductance is larger than the designed value, the bottom current decreases. As a result, zero-voltage switching (ZVS) becomes more difficult to achieve. On the other hand, the grid-tied inductance used in this study is approximately 22% smaller than the designed value. Therefore, the bottom current increases, and ZVS operation is not hindered. However, the peak current also increases, which may increase the conduction loss and reduce the conversion efficiency.

The switching frequency used for PWM generation was set to 200–600 kHz. The minimum switching frequency $f_{sw \min}$ corresponds to the operating point where both the grid voltage and the output current reach their maximum values. The proportional gain was normalized using the rated impedance Z_n . The normalized proportional gain K_{p-pu} was set to 0.03. The integral time T_i was set to 50 μs .

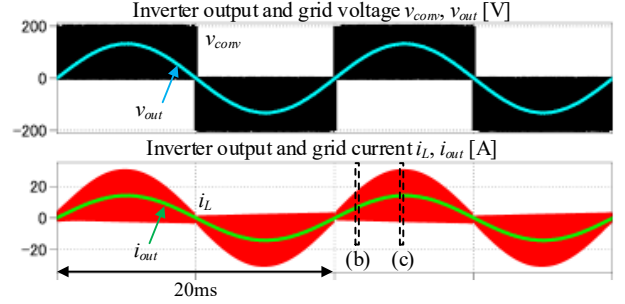
Fig. 5 shows the simulation results of the proposed method. Fig. 5(a) shows the output waveforms at the rated output power of 1 kW and a grid frequency of 50 Hz. The output current is nearly sinusoidal. In addition, the output current is well synchronized with the grid voltage. The total harmonic distortion (THD) of the output current is less than 0.5%. These results confirm that the proposed method maintains high current quality even under variable switching frequency operation.

Figs. 5(b) and 5(c) show enlarged views of the output waveforms. In this study, the equivalent switching frequency is evaluated from the period of the triangular grid-tied inductor current waveform. Fig. 5(b) shows the operating point where the equivalent switching frequency reaches its maximum value. At this operating point, the equivalent switching frequency is approximately 1.01 MHz. Fig. 5(c) shows the operating point where the equivalent switching frequency reaches its minimum value. At this operating point, the equivalent switching frequency is approximately 546 kHz. In the proposed method, the switching frequency varies continuously according to the grid current. As a result, variable switching frequency operation is achieved according to the operating conditions.

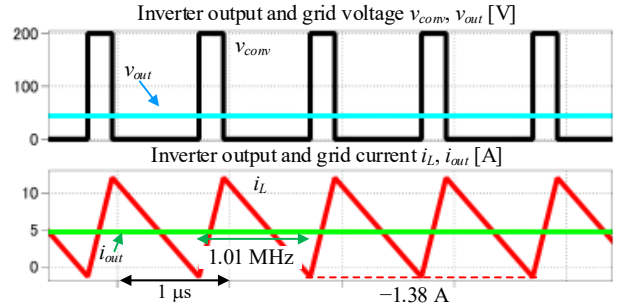
Figs. 5(b) and 5(c) show that the value of the bottom current was 1.38 A at the maximum equivalent switching frequency and 2.07 A near the peak current. The bottom current at the maximum equivalent switching frequency was approximately 0.62 A lower than the designed value of 2 A.

Table 1. Simulation and experimental parameters with TCM operation

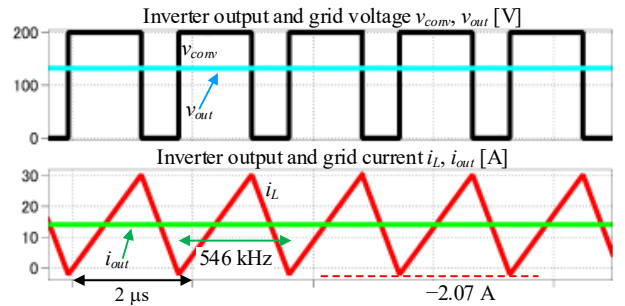
Parameters	Symbol	Value
Input Voltage	V_{in}	200 V
Output voltage	v_{out}	100 V _{rms}
Rated output power	P_{rated}	1 kW
Grid frequency	f_g	50 Hz
Maximum switching frequency	$f_{sw \max}$	600 kHz
Minimum switching frequency	$f_{sw \min}$	200 kHz
Bottom current	I_{bot}	2 A
Grid-tied inductance	L	2.54 μH (%Z=0.0080%)
Filter inductance	L_f	12.5 μH (%Z=0.0393%)
Filter capacitance	C_f	20 μF (%Y=6.28%)
Rated impedance	Z_n	10 Ω
Normalized proportional gain	K_{p-pu}	0.03 (K_p/Z_n)
Integration time	T_i	50 μs



(a) Output current waveform at 50 Hz, with a THD of less than 0.5%.



(b) Enlarged waveform at an equivalent switching frequency of approximately 1.01 MHz, confirming variable-frequency operation (switching frequency: 200–600 kHz range).



(c) Enlarged waveform at an equivalent switching frequency of approximately 546 kHz, confirming variable-frequency operation (switching frequency: 200–600 kHz range).

Fig. 5. Waveforms during rated-operation simulations of the TCM inverter.

On the other hand, the bottom current near the peak current agreed well with the designed value.

IV. EXPERIMENTAL RESULTS

A. Operation of the Proposed Method

Fig. 6 shows the experimental results of the proposed method. The experimental conditions are shown in Table 1. Fig. 6(a) shows the experimental waveforms under the rated operating condition at a grid frequency of 50 Hz. At the rated output power of 1 kW, the proposed method achieved a total harmonic distortion (THD) of 1.96% for the output current and a conversion efficiency of 93.9%. The output current is nearly sinusoidal. These results confirm that the proposed method achieves high current quality.

Fig. 6(b) shows an enlarged view of the waveforms at the operating point where the equivalent switching frequency reaches its maximum value. At this operating point, the equivalent switching frequency is approximately 1.06 MHz. The grid-tied inductor current exhibits a triangular waveform. In addition, the bottom current reaches approximately -1.61 A. These results confirm that TCM operation is achieved. The switching period was 947 ns, which corresponds to an equivalent switching frequency exceeding 1 MHz.

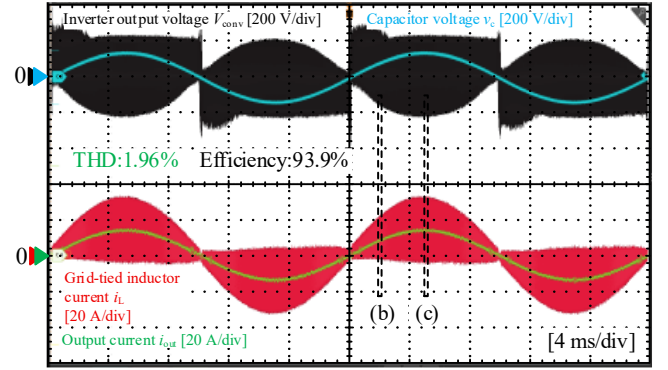
On the other hand, Fig. 6(c) shows an enlarged view of the waveforms at the operating point where the equivalent switching frequency reaches its minimum value. At this operating point, the equivalent switching frequency is approximately 506 kHz. Even under low-switching-frequency operation, the grid-tied inductor current maintains a triangular waveform. In addition, the bottom current is approximately -3.82 A. These results confirm that the proposed method maintains TCM operation over the entire operating range while continuously varying the switching frequency according to the operating conditions.

However, under variable switching frequency operation, the bottom current was not maintained at the designed value of 2 A and varied depending on the operating point. One possible reason is the mismatch between the output current command used to calculate the switching frequency and the average value of the grid-tied inductor current. The grid-tied inductor current is expressed as the sum of the output current and the filter capacitor current. Therefore, the average value of the grid-tied inductor current does not generally coincide with the output current command. As a result, a mismatch arises between the average current assumed in the switching frequency calculation and the actual average value of the grid-tied inductor current. Consequently, the actual bottom current deviates from the designed value even when the output current accurately tracks the current command.

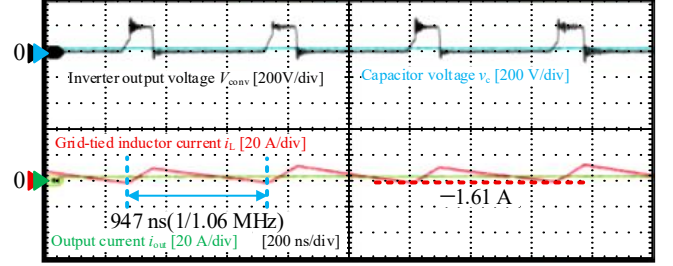
Furthermore, as shown by the rising edge of the inverter output voltage in Fig. 6(c), the switching voltage transitions smoothly without changing abruptly. This waveform indicates that the output capacitance of the switching device is discharged by the inductor current before turn-on. As a result, the switching device is turned on under zero-voltage conditions. These results confirm that the proposed method achieves zero-voltage switching (ZVS).

B. Current Step Response

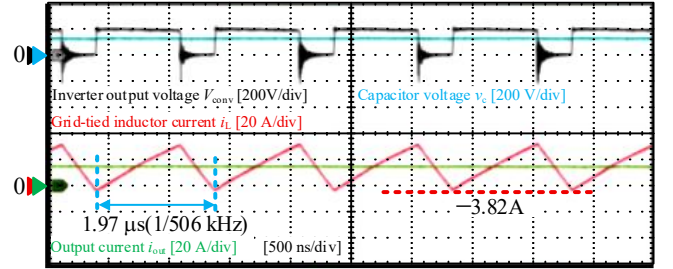
Fig. 7 shows the experimental waveforms when the current command was stepped from 7 A to 10 A. Fig. 7(a) shows the overall waveforms when the current command was stepped at a grid voltage phase of $\pi/4$. After the step change, the filter inductor current and the output current



(a) Output current waveform at 50 Hz, with an efficiency of 93.9% and a THD of 1.96%.



(b) Enlarged waveform at an equivalent frequency of approximately 1.06 MHz



(c) Enlarged waveform at an equivalent frequency of approximately 506 kHz.

Fig. 6. Experimental results of the TCM inverter. smoothly converge to the new command without significant oscillation or overshoot. In addition, the inverter output voltage and the capacitor voltage remain stable during the transient period. These results confirm that the proposed method maintains stable operation even in response to a step change in the current command.

Fig. 7(b) shows an enlarged view of the waveforms around the step change. As the current command increases, the peak value of the grid-tied inductor current increases. In contrast, the bottom current of the grid-tied inductor current is maintained at approximately 2.72 A. Therefore, it is hardly affected by the change in the current command. These results confirm that the proposed method achieves stable TCM operation with good current tracking performance without requiring high-speed bottom current sensing.

C. Efficiency and Output current THD Evaluation

Fig. 8 shows the conversion efficiency and the output current THD over the output power range from 0.1 to 1 kW. At the rated output power of 1 kW, the proposed method achieved a maximum conversion efficiency of 93.9% and an output current THD of 1.96%. In the proposed method, TCM control achieves zero-voltage switching (ZVS) during the turn-on of each switching device. In ZVS, the output capacitance of the switching device is discharged by the

inductor current before turn-on. Therefore, there is little overlap between the device voltage and the device current during turn-on. As a result, the turn-on switching loss is significantly reduced. On the other hand, the turn-off switching loss, conduction loss, and losses caused by parasitic elements still remain. Therefore, the switching loss cannot be eliminated completely. Nevertheless, the proposed method achieved a conversion efficiency of 93.9% at the rated output power.

Furthermore, the conversion efficiency decreases as the output power decreases. When the output power decreases, the output current also decreases. Therefore, the conduction loss, which is proportional to the square of the current, decreases. On the other hand, losses such as the device loss and the inductor loss do not decrease to the same extent as the output power. As a result, under light-load conditions, these losses account for a larger proportion of the total loss, which reduces the conversion efficiency.

V. CONCLUSION AND FUTURE WORK

This paper proposed a TCM control method for single-phase grid-tied inverters that does not require high-speed bottom current sensing. The proposed method calculates the switching frequency based on the operating conditions. Furthermore, by applying the calculated switching frequency in real time, the proposed method achieves TCM operation without requiring high-speed bottom current sensing.

Experimental results obtained using a 1 kW prototype demonstrated that the proposed method achieved an output current THD of 1.96% and a conversion efficiency of 93.9%. The results also confirmed that the proposed method maintains the negative bottom current margin required for TCM/ZVS operation. Furthermore, zero-voltage switching (ZVS) was successfully achieved.

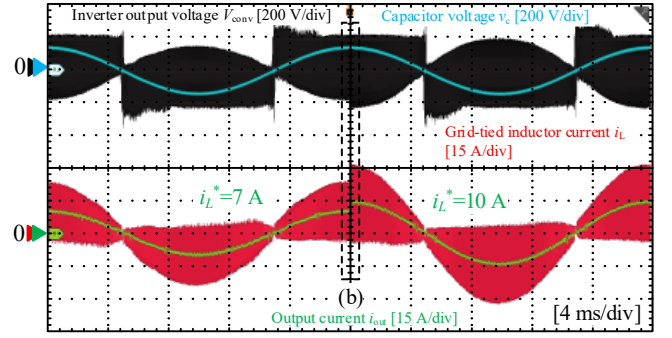
Future work will focus on further increasing the switching frequency into the MHz range, improving the conversion efficiency, and conducting a detailed loss analysis.

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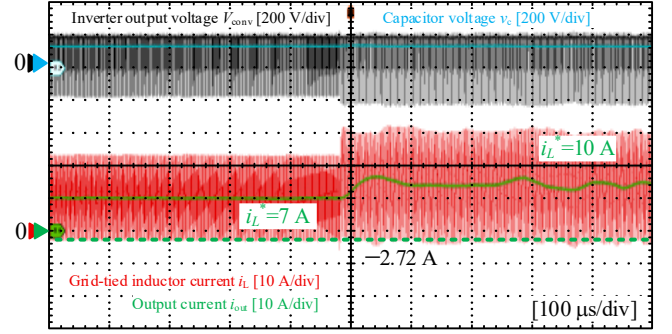
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(a) Overall waveforms over two grid cycles, showing the current command step from 7 A to 10 A.



(b) Enlarged waveforms around the current command step, confirming a fast transient response from 7 A to 10 A.

Fig. 7. Experimental waveforms for a step change in current command from 7 A to 10 A.

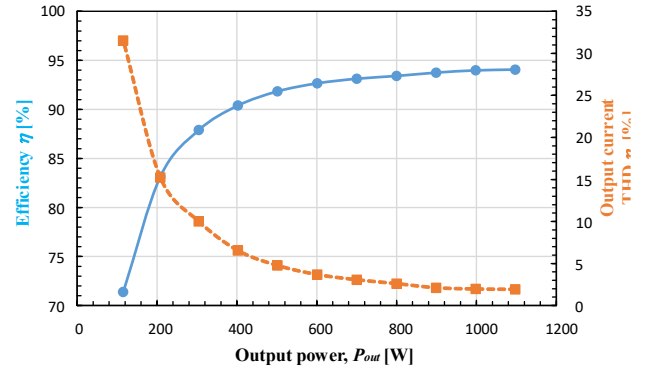


Fig. 8. Measured efficiency and output current THD curves of TCM operation.

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