Several-Hundred-kHz Single-phase to Commercial Frequency Three-phase Matrix Converter using Delta-Sigma Modulation with Space Vector

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***Abstract*—This paper discusses the pulse density modulation (PDM) control methods for a single-phase to three-phase matrix converter (MC) in the high-frequency application. This converter outputs a commercial power grid frequency, i.e. 50 Hz or 60 Hz from the input of several-hundred-kHz frequency. The proposed circuit achieves zero voltage switching operation by using the PDM control method. In this paper, two PDM control strategies are compared between a conventional PDM control method based on space vector modulation (SVM) and the proposed PDM control method, which is combined with SVM and a delta-sigma conversion. Also, the experimental results of the proposed control method will be demonstrated and discussed. As a result, the total harmonic distortion (THD) of the output voltage with the proposed PDM control method is improved to 1.87% from 9.05% of the conventional PDM control method.**

I. INTRODUCTION

In recent years, wireless power transfer systems have been actively researched [1-3]. There are two types of wireless power transfer systems known as the electromagnetic induction and a magnetic resonant coupling. In the electromagnetic induction type, the frequency of the coil for the transmission is low, and it can transmit high-capacity power with relative ease. However, the transmitting efficiency decreases when the coupling is reduced by increasing in the transmission distance. As a result, a large coupling of the transmission coils is necessary in order to improve the transmitting efficiency. Likewise, the transmitting distance needs to become shorter. On the other hand, the efficiency of the magnetic resonant coupling type is over 90% at the intermediate distance which is approximately 1 meter though the high frequency is used [1].

In the wireless power transfer system, the frequency of the generated voltage at the receiving coil is from tens of kHz to several MHz, which is identical to the power source frequency. Accordingly, in order to connect this system to a load, an interface converter which converts the received power into a controlled output power is required. The characteristic of this interface converter must have a high input frequency (several hundred kHz) and a low output frequency (50 Hz or 60 Hz) which is suitable for commercial power grid. That is, an AC-to-AC converter is generally clarified as the interface converter for this system. In general, back-to-back (BTB) system, which is constructed by a PWM rectifier, a smoothing capacitor and a PWM inverter, is used as this AC-to-AC converter. However, it is difficult to use the PWM rectifier in the input side due to high-frequency input. Additionally, the DC link voltage is smoothed by using smoothing capacitor in BTB system. Unless the soft switching technique is applied, the switching loss becomes large because of the hard switching.

On the other hand, matrix converters (MC) have been attracted attentions as the AC interface converter for the wireless system, because it delivers advantages in terms of a size reduction and an energy saving owning to high efficiency [4-6]. The MC which has the several-hundred-kHz of high-frequency output has been researched. However, the implementation of the control method utilizing the characteristics of high-frequency power source as shown below for the MC with the high-frequency input has not been reported.

The authors have proposed to use the single-phase to three-phase MC in high-frequency as the interface converter. A pulse density modulation (PDM) [7-10] control method is applied to the converter by using the half cycle of the input voltage as a pulse for PDM control. This converter achieves an advantage that the switching loss can be decreased nearly close to zero by the switching at zero input voltage. The PDM control based on space vector modulation (SVM) with D-flip flop (conventional PDM control method) has been proposed as one of the PDM for the converter [11-13]. However, the output voltage waveforms have distortion

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when the modulation ratio is low and carrier frequency is high in the conventional PDM method.

This paper proposes a novel PDM method which is combined with SVM and delta-sigma conversion in order to improve the quality of the output voltage waveforms. The proposed PDM method improves the performance compared to the conventional PDM method. The reason is as follows; the output voltage waveforms at the low modulation ratio and high carrier frequency have distortion in the conventional PDM method, because the control resolution of the output voltage becomes low, on the other hands, the proposed PDM method achieves high resolution by using delta-sigma conversion synchronized with zero cross points of the input voltage. In order to confirm the effect of the proposed PDM method, the conventional PDM method and the proposed PDM method is compared based on the experimental results.

This paper is organized as follows; first, the configurations of the proposed circuit are introduced; second, the PDM control strategy using the conventional method and proposed method are discussed; finally, the validity of the proposed method is confirmed in the experimental results.

II. Circuit Configuration

A. System Configuration

Fig. 1 shows a configuration of the wireless power transfer system. The receiving coil voltage is a high-frequency AC, which has same as the frequency of the source. In order to connect to the commercial grid, a single phase AC to three phase AC converter is required as an interface converter.

The interface converter inputs several-hundred-kHz sinusoidal waveform, and outputs the low-frequency waveform such as 50 Hz and 60 Hz. Hence, the PDM control which uses a half cycle of the input voltage as a pulse can be applied to the interface converter.

Therefore, the use of the matrix converter as an interface converter for wireless power transfer system is proposed. The matrix converter achieves high frequency by applying a PDM control. The detail of PDM control is explained in next chapter.

B. Single-phase to Three-phase Matrix Converter

Fig. 2 shows the circuit configuration of the proposed single-phase to three-phase MC. This circuit is constructed by six bidirectional switches. Since this converter does not require smoothing capacitors in the DC link, the lifetime of the circuit is longer and the size is more compact than that of the conventional system, which is constructed by a PWM rectifier, smoothing capacitors and a three-phase PWM inverter. Further, the efficiency of a MC is higher than the conventional system because the conversion number is reduced in comparison with the conventional system. In addition, the proposed system can improve the efficiency in terms of not only conduction loss but also the switching loss in comparison with the conventional system. The proposed

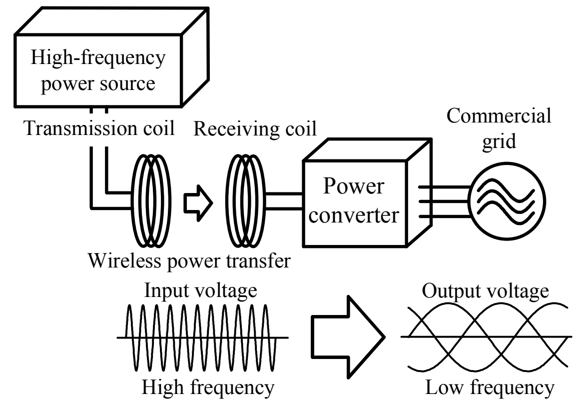


Figure 1. Wireless power transfer system.

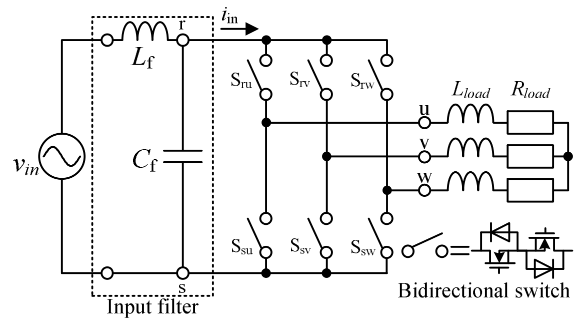


Figure 2. Single-phase to three-phase matrix converter.

system reduces switching loss drastically because the switching devices switch when the switch voltage is 0 V in this system. As a result, this system achieves PDM control, which uses a half cycle of the input voltage as a control unit.

Note that a snubber circuit is connected to the output side of the converter as a protection circuit in the experimental circuit. It is constructed by diodes, a small capacitor and a resistor.

In addition, the voltage transfer ratio of the conventional system, which has smoothing capacitor in DC link is 1. In contrast, the voltage transfer ratio of the proposed single-phase to three-phase matrix converter is 0.637 as explained in (1).

$$V_{out} = \frac{2}{\pi} \cdot V_{in} = 0.637 \cdot V_{in} \qquad (1)$$

Where, V_{out} and V_{in} are the RMS value of the output voltage v_{uv} and input voltage respectively. Therefore, the voltage transfer ratio of the proposed converter is lower than that of the conventional system.

However, this drawback is not important in the wireless power transmission system. This system is supposed to match certain impedance because if it assumes that the input of this system is secondary side of the wireless transfer system. In this case, the input voltage of this system increases proportion to the impedance when the output power becomes large. For example, assuming that this system outputs several-kW power, the input voltage becomes approximately from 400 V to 500 V. Therefore, by assuming that this system is used in wireless transfer system, the proposed single-phase to three-phase matrix converter can be used for the utility system operates as a step-down converter.

C. *Design of the Input Filter*

The impedance matching is important on the circuit for the high-frequency application in order to prevent the reflection of the power and achieve the high efficiency transmission [3]. In this system, the input filter is connected to the input side as an impedance matching circuit, which can match the impedance of the voltage source and the circuit. The design method which matches the impedance Z_{in} to 50 Ω is explained in this section because the general high-frequency power sources have 50 Ω of matching impedance.

Fig. 3 shows the configuration of the input filter. It is constructed from a reactor L_f and a capacitor C_f. The impedance of the load connected to the filter is expressed by resister R_{load} as shown in Fig. 3. The value of L_f and C_f are determined that the real part of the synthetic impedance equals to 50 Ω and the imaginary part equals to 0 Ω in order to achieve 50 Ω of the matching impedance. L_f and C_f are calculated by (2) and (3), where, $\omega=2\pi f$ is the input voltage angular frequency. L_f and C_f are 80 μH and 16 nF respectively, when the frequency of f is 100 kHz, and R_{load} is 100 Ω. These values are used in the experiment.

$$L_f = \frac{C_f R_{load}^{\ 2}}{1+(\omega C_f R_{load})^2} \tag{2}$$

$$C_f = \frac{1}{\omega R_{load}}\sqrt{\frac{R_{load}}{50}-1} \tag{3}$$

III. Control Strategies

A PDM control method is applied to the proposed system in order to reduce the switching loss of the converter. PDM controls the density and the polarity of the constant-width pulse, and these pulse signals are used as the output unit.

Fig. 4 shows a view showing a frame format of the PDM control waveform for the single-phase to three-phase MC. Assuming that the single-phase to three-phase MC is connecting to a wireless power transfer system as input power source, it is receiving high-frequency sinusoidal voltage as an input. Therefore the PDM control can be applied to the proposed circuit by using the half cycle of the input voltage as a pulse for PDM control as shown in Fig. 4.

A. *PDM Control based on Space Vector Modulation*

Fig. 5(a) shows the PDM signal generation block of a conventional PDM control method based on the SVM. The selected vector signals generated from the SVM is the input

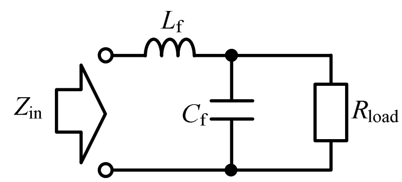


Figure 3. Configuration of the input filter.

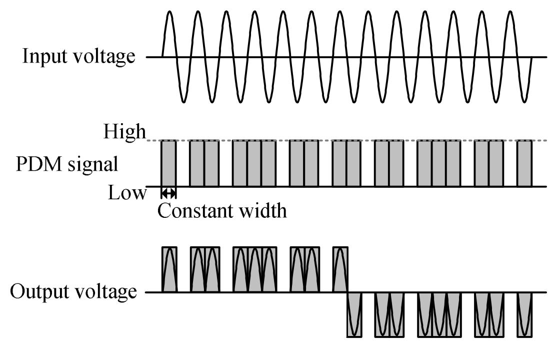
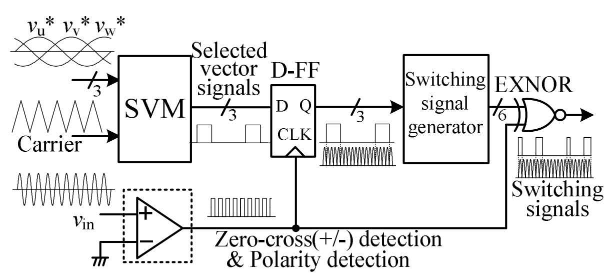
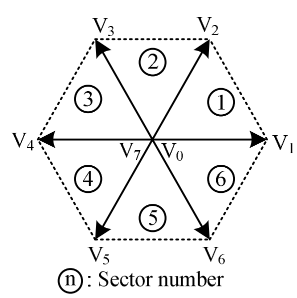


Figure 4. PDM control waveform of the proposed circuit.



(a) PDM signals generation block diagram based on SVM.



(b) Space vector diagram.

Selected vector	Switching pattern		
	u	*v*	*w*
V_0	0	0	0
V_1	1	0	0
V_2	1	1	0
V_3	0	1	0
V_4	0	1	1
V_5	0	0	1
V_6	1	0	1
V_7	1	1	1

"1": ON, "0": OFF

(c) Switching pattern table.

Figure 5. Control block diagram of the conventional PDM method based on SVM.

to the D flip flop (D-FF). The plus/minus detection signal from the input voltage is used to detect the zero cross points of input voltage, and this signal is an input to the CLK of the D-FF. The output of the D-FF, "Q" is synchronized at the edge of plus/minus signal, which is the zero cross point of the input voltage. After that, the switching signals which correspond to the vectors in Fig. 5(b), are generated from output signals of the D-FF using pattern table in Fig. 5(c).

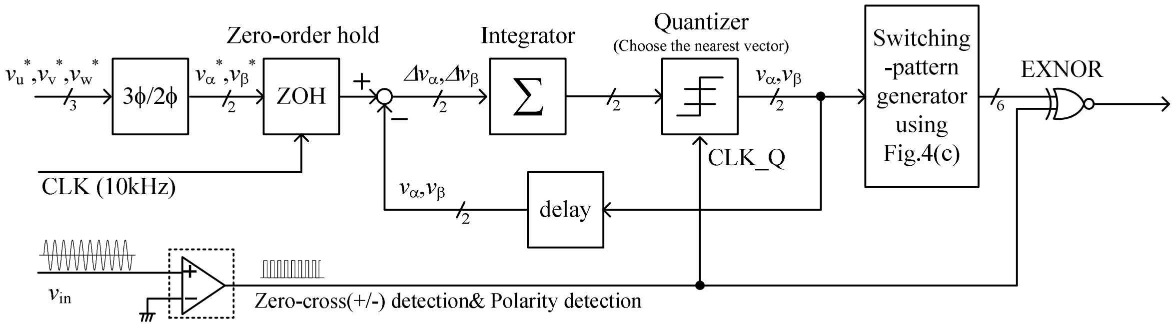


Figure 6. PDM signals generation block diagram of the proposed PDM method combined with the SVM and delta-sigma conversion.

The "1" and "0" in the Fig. 5(c) show the output states of each arm. As a result, a PDM control which uses a half cycle of the input voltage as an output unit are obtained, and the switching at approximately zero point of the input voltage is achieved. Furthermore, the switching signals are exclusive NORed with the polarity of the input voltage, because it is necessary to exchange the switching signals of the upper arm and the lower arm depending on the polarity of the input voltage.

Therefore, the switching patterns generated by SVM are quantized by the pulse whose width is half cycle of the input voltage and the switching timing is synchronized with the zero cross point of the input voltage. The output voltage waveforms become the PWM waveforms synchronized with the zero cross point of the input voltage. As a result, this PDM control method based on SVM can achieve the switching at zero voltage.

In this method, the output voltage is controlled by regulating the on duty per one cycle of the carrier wave. As a result, the output voltage ripple and distortion increase at low modulation ratio. Hence high carrier frequency is needed in this method in order to suppress the output ripple. However, when the carrier frequency is high and become close to the input frequency, the output voltage control resolution becomes low. It is because that the rate of a pulse width versus one control cycle is large and the quantization error of the output voltage becomes large when the carrier frequency is high. Moreover, this method has low resolution at low modulation ratio because of the same reason.

A new PDM method is proposed in order to suppress the output voltage distortion, and detail of the method is explained in next section.

B. PDM Control based on Space Vector Modulation combined with Delta-Sigma Conversion

In this section, a proposed PDM method, which is combined with SVM and delta-sigma conversion, is proposed in order to suppress the output voltage distortion.

Fig. 6 shows block diagram of the proposed PDM method. The each phase command values v_u*, v_v* and v_w* are converted to each component of the command vector v_α* and v_β* by coordinate transformation. The command value (vector) is updated with a period of 100 μs (10 kHz). This frequency corresponds to carrier frequency of the conventional PDM method. The error between each components of the command vector (v_α*, v_β*) and output vector (v_α, v_β) are calculated, and integrated. The integrated errors are compared with candidate vectors, and the closest vector is selected and output. After that, switching patterns are generated from selected vector in Fig. 5(b) using switching table in Fig. 5(c). Furthermore, the switching patterns are exclusive NORed with the polarity of the input voltage for the same reason as conventional PDM method. The calculator and integrator of the errors operate in synchronization with zero cross points of the input voltage. As a result, the control resolution remains nearly unaffected by update cycle of the command values and modulation ratio in this proposed PDM method, unlike conventional method.

In addition, this method achieves the advantages of "oversampling" and "noise shaping" techniques [14], and suppresses the low order harmonics components. The harmonic components because of quantization error occur because this method quantizes the commands of the output voltage. However, the power spectrum density of the harmonics from the quantization error spreads in the wide frequency band, by sampling with substantially-larger frequency than the fundamental frequency of the output voltage commands (i.e. oversampling). The harmonics from the quantization error is distributed on the high frequency side owing to a feedback circuit. As a result, low order harmonics are suppressed, and the output voltage THD becomes small. Therefore, it means that the output filter, which is necessary to connect the utility system is smaller than conventional method.

IV. VERIFICATIONS OF THE PDM METHODS

In order to confirm the basic operation of the conventional method and the proposed method, the prototype circuit is demonstrated in experiment with load condition. Table 1 shows the experimental conditions.

A. Experimental Results with the Conventional PDM Method

Fig. 7(a) shows the operation waveforms of the proposed circuit in the experiment with the conventional PDM method. The result confirms that 50 Hz sinusoidal

TABLE I. EXPERIMENTAL CONDITIONS

Input voltage		70.7 V (100 V_{peak})
Input frequency		100 kHz
Output line-line voltage		35 V
Output frequency		50 Hz
Load	R_{load}	25 Ω
	L_{load}	5 mH
Carrier frequency of the SVM (Updating cycle of command)		10 kHz (100 μs)
Modulation ratio		0.5

waveforms are obtained on the output voltage and current. However, from the output current waveform, the output voltage has distortion because of the reason which is explained in section III-A. Therefore, the output voltage includes the low order harmonics.

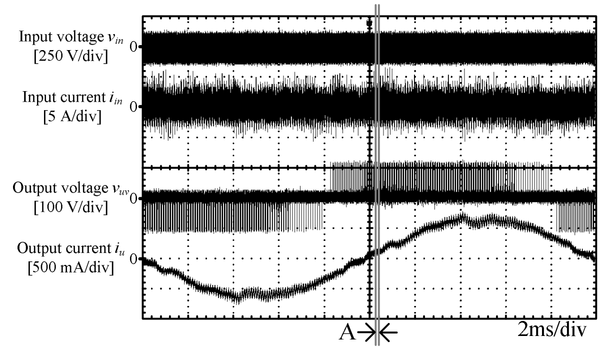
Fig. 7(b) shows the extended view of the interval "A" in Fig. 7(a). As a result, the output line-to-line voltage v_{uv} confirms that the switching of the MC is happened at approximately each zero cross point of the 100 kHz sinusoidal input waveform. Therefore, basic operation of the conventional PDM method is confirmed. However, the output current has the ripple of carrier frequency. In this method, the output voltage waveforms become PWM waveforms because the PWM signals from SVM are synchronized at zero cross points of the input voltage. Therefore, the output current waveforms include the ripple of the carrier frequency.

Fig. 8 shows the harmonics analysis of the output voltage and the input current from the experimental result with the conventional PDM method. From Fig. 8(a), the low-order harmonic components of 50 Hz are included in the output voltage, and the output voltage THD of 9.05% is obtained. In addition, the output voltage includes the integral-multiple harmonic nearly to the carrier frequency of 10 kHz, which is the control cycle because the output voltage is controlled by regulating the on duty per one cycle of carrier wave in this method. Additionally, the integral-multiple harmonic nearly to the 200 kHz is included in the output voltage and other high-order harmonic components because the output voltage has the fluctuation, which is twice of the input frequency. Furthermore, from Fig. 8(b), the input current includes the integral-multiple harmonic nearly closed to the carrier frequency of 10 kHz and the input frequency of 100 kHz, and the input current THD is 55.2%.

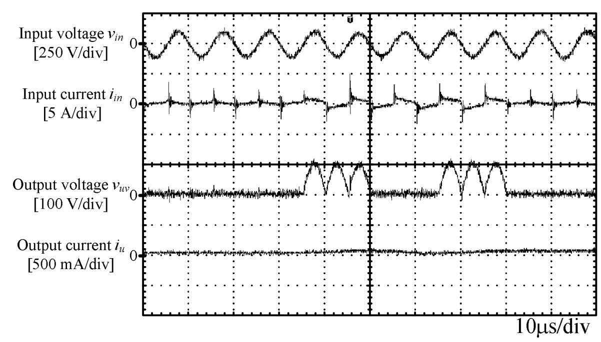
From these results, it is confirmed that the output waveforms have large distortion at the low modulation ratio in this method because the resolution of the control becomes low.

B. Experimental Results with the Proposed PDM Method

Fig. 9(a) shows the operation waveforms of the proposed circuit in the experiment with the proposed PDM method. The result confirms that sinusoidal waveforms of 50 Hz are

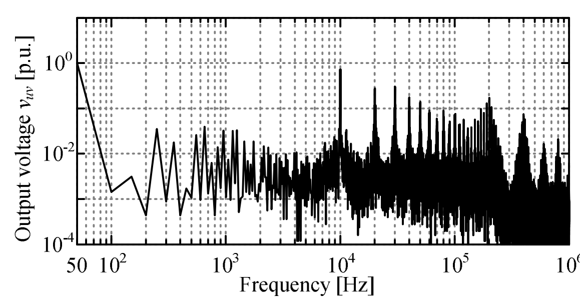


(a) Input and output operation waveforms.

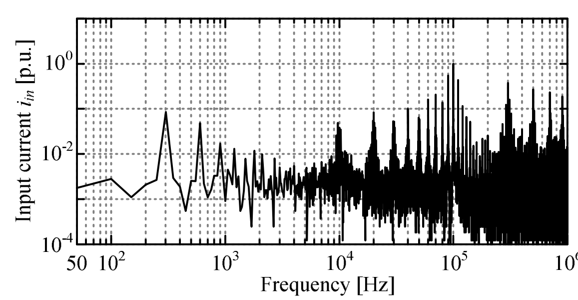


(b) Extended each operation waveform.

Figure 7. Operation waveforms of the proposed circuit in the experiment with the conventional PDM control.



(a) Harmonics analysis of the output voltage.



(b) Harmonics analysis of the input current.

Figure 8. Harmonics analysis of the output voltage and the input current with the conventional PDM control.

obtained on the output voltage and current. From the output current, the output voltage does not have distortion because of the reason explained in section III-B.

Fig. 9(b) shows the extended view of the interval "B" in Fig. 9(a). As a result, it is confirmed that the switching of the MC is synchronized with each zero cross point of the 100 kHz sinusoidal input waveform from the output line-to-line voltage v_{uv}. The output current waveform has the smaller current ripple in comparison with that of the conventional method because the delta-sigma conversion operates per half cycle of the input voltage and the output vectors in this method are changed per shorter period compared with the conventional method. From these results, the operation of the proposed PDM method is confirmed.

Fig. 10 shows the harmonics analysis of the output voltage and the input current from the experimental result with the proposed PDM method. From Fig 10(a), the low-order harmonic components of 50 Hz are not included in the output voltage, and the output voltage THD of 1.87% is obtained. In addition, the output voltage does not include the integral-multiple harmonic nearly to the carrier frequency of 10 kHz, which is the control cycle. Additionally, the integral-multiple harmonic nearly to the 200 kHz is included in the output voltage in the high-order harmonic components because of the same reason as the conventional PDM method. Moreover, the harmonics are distributed for the high frequency side as explained in section III-B.

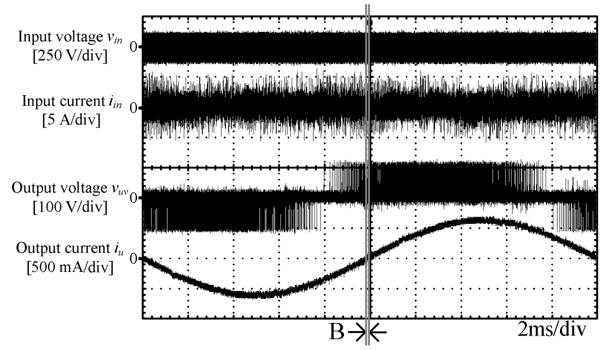
Furthermore, Fig. 10(b) shows that the input current has the integral-multiple harmonic nearly closed to input frequency of 100 kHz, and therefore the input current THD is 49.8%. In this case, the input current does not include the integral-multiple harmonic nearly closed to the updating cycle of 10 kHz in contrast to the conventional PDM control method.

From these experimental results, it is confirmed that the resolution degradation problem at low modulation ratio in the conventional PDM method is solved by applying the proposed method, and the output voltage waveforms are improved.

C. Evaluation for THD and Switching Ripple of the Conventional Method and the Proposed Method

Fig. 11 shows the output voltage total harmonic distortions of the proposed circuit. From the result, the THD of the conventional PDM method increases when the modulation ratio is low because of the reason which is explained in section III-A. In the conventional PDM method, it is necessary to use the proposed circuit over 0.8 of modulation ratio in order to operate under 5% of THD. On the other hand, the THD of the output voltage is under 5% at over 0.2 of modulation ratio in the proposed PDM method because of the reason which is explained in III-B.

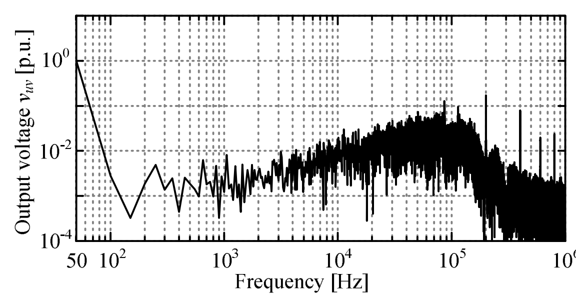
From these experimental results, it is confirmed that the output voltage at low modulation ratio is improved by applying the proposed PDM method.



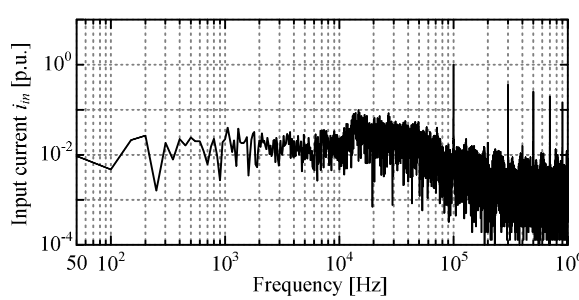
(a) Input and output operation waveforms.

(b) Extended each operation waveform.

Figure 9. Operation waveforms of the proposed circuit in the experiment with the proposed PDM control.



(a) Harmonics analysis of the output voltage.



(b) Harmonics analysis of the input current.

Figure 10. Harmonics analysis of the output voltage and the input current with the proposed PDM control.

In addition, the output voltage waveform does not have the integral-multiple components of 10 kHz as shown in the harmonics analysis. It indicates that the switching ripple of the output current is smaller in comparison with that of the conventional method. In other word, the value of the interconnection reactor can be small if it assumes this system connects to the commercial grid. The effect of the proposed PDM method is confirmed by the simulation and the simulation results are shown in Fig. 12.

Fig. 12 shows the grid voltage and current waveforms when the conventional and the proposed PDM method are applied. It assumes that the output of this converter connects the three-phase 200 V commercial grid and the output power is 1 kW. Fg.12 (a) shows the operation waveforms with the conventional PDM method and the interconnection reactor of 20 mH (= 15.7%) is connected. From Fig. 12(a), the current flowing through the interconnection reactor includes the switching ripple component when the conventional PDM method is applied and the ripple factor is approximately 11%. Furthermore, Fig. 12(b) shows the operation waveforms with the proposed PDM method and the interconnection reactor of 5 mH (= 3.9%) is connected. The ripple factor of the current flowing through the interconnection reactor is on the same level as that of the conventional PDM method and the ripple factor is approximately 11%. From this result, it is confirmed that the value of the interconnection reactor can be a quarter by applying the proposed PDM method. From these results, the effect and validity of the proposed PDM method is confirmed.

D. Efficiemcy Charasteristics

Fig. 13 shows the efficiency characteristics of the prototype circuit with the conventional PDM control method and the proposed PDM control method. The input and output voltage conditions are as shown in table 2, and the output power is controlled by changing the load value.

From the result, the maximum efficiency with conventional PDM control and with proposed PDM control are 94.5% and 94.8% respectively at approximately 50-W load. Furthermore, the efficiency decreases at heavy load condition. It is because that the output current becomes large at heavy load, and the conduction loss becomes large.

In addition, the efficiency for the proposed PDM control method is higher than that of the conventional PDM control method at all measurement regions. Therefore, the proposed PDM control method improves the output voltage waveforms and THDs without the efficiency reduction.

V. Conclusion

This paper discusses the PDM control methods for a single-phase to three-phase MC in the high-frequency application. Several-hundred-kHz frequency is inputted to this converter, and the converter outputs a low frequency, i.e. 50 Hz or 60 Hz, for commercial power grid. The proposed circuit achieves zero voltage switching operation by using the PDM control method and obtains high efficiency. In this paper, two PDM control strategies are compared between

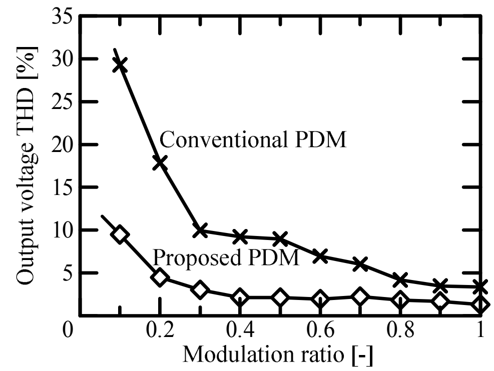
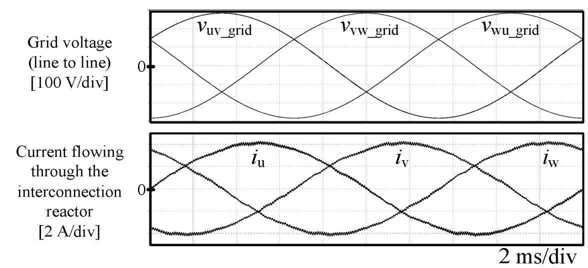
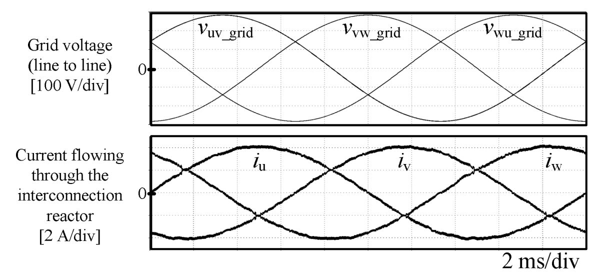


Figure 11. Output voltage total harmonic distortions of the proposed circuit.



(a) Operation waveforms with the conventional PDM method using the interconnection reactor of 20 mH (15.7%).



(b) Operation waveforms with the proposed PDM method using the interconnection reactor of 5 mH (3.9%).

Figure 12. Grid voltage and current waveforms connecting the commercial grid.

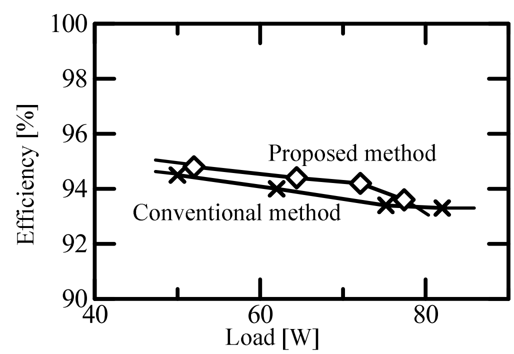


Figure 13. Efficiency of the proposed circuit.

TABLE II. EFFICIENCY MEASUREMENT CONDITIONS

Input voltage	176 V (250 V_{peak})
Input frequency	100 kHz
Output line-line voltage	90 V
Output frequency	50 Hz
Carrier frequency of the SVM (Updating cycle of command)	10 kHz (100 µs)
Modulation ratio	1.0

PDM control based on SVM and the proposed PDM method which is combined with SVM and delta-sigma conversion, and suppress the distortion of the output voltage. Also, the experimental results of the proposed system are demonstrated with load condition and discussed. As a result, the THD of the output voltage with the conventional method and the proposed method are 9.05% and 1.87% respectively, when the modulation ratio is 0.5. Therefore, the validity of the proposed method has been confirmed for improvement of the output waveforms.

In addition, the AC-to-AC converter for the high-frequency application is necessary in other case. For example, the MC for high-frequency application can be applied to trans-linked converter, whose secondary side is connected to commercial grid. For downsizing the converter, the transformer for high-frequency link size is a major bottleneck [15]. Therefore, the size of the transformer can be small by higher frequency converter using high-speed switching devices such as SiC and GaN.

In future work, the experiment will be conducted with a heavier load condition and the investigation about the efficiency of this circuit with both PDM methods.

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