An Experimental Verification and Analysis of a Single-phase to Three-phase Matrix Converter using PDM Control Method for High-frequency Applications

Yuki Nakata
Nagaoka University of Technology
nakata@stn.nagaokaut.ac.jp

Jun-ichi Itoh
Nagaoka University of Technology
itoh@vos.nagaokaut.ac.jp

***Abstract*-This paper discusses the PDM (Pulse Density Modulation) control method for a single-phase to three-phase matrix converter (MC) in the high-frequency application. The proposed circuit is used as an interface converter for a wireless power transfer system. This converter can input a several hundred kHz frequency and outputting a low frequency, ie 50 Hz, for commercial power grid. The proposed circuit achieves zero voltage switching (ZVS) operation by using the PDM control method and obtains high efficiency. In this paper, the PDM control strategy is using delta-sigma conversion and improving the PDM pattern generation method based on Space Vector Modulation (SVM). Also, the simulation, experimental and loss analysis results of the proposed system will be demonstrated and discussed. As a result, the total harmonic distortion (THD) of the input current and the output voltage are 84.6 % and 5.4 % respectively. The efficiency of 91.5% is obtained from the prototype circuit. Additionally, the effect of power source side impedance for a high-frequency single-phase-to-three-phase MC is discussed. It is clear that the line-to-line capacitance at the power source side must be kept as small as possible in order to suppress the resonance.**

I. INTRODUCTION

In recent year, wireless power transfer systems have been actively researched [1-3]. There are two types of wireless power systems known as electromagnetic induction and 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 coupling is reduced and the transmitting efficiency decreases with increasing of the transmission distance. As a result, a large coupling 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 electromagnetic resonant coupling type is over 90% in case of the intermediate distance which is about 1m.

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 has a high input frequency from several hundred kHz and able to deliver a low output frequency (50Hz or 60Hz) suitable for commercial power grid. The structure of the interface converter is an AC to AC converter. The matrix converter (MC) has been attracted attentions as the AC interface converter for the wireless system, because it delivers advantages in terms of sizing and energy saving [4]. However, the implementation of MC in the high-frequency power source has not been reported.

In this paper, the MC is structured into a single-phase to three-phase converter. The authors propose to use the PDM [5-8] control method for the high-frequency power source [9-11]. The proposed circuit has an advantage that switching loss can be decreased nearly close to zero by Zero Voltage Switching (ZVS) operation. This paper shows the possible applicable of the MC for the high-frequency power source circuit. Firstly, the configurations of the proposed circuit introduced. Secondly, the PDM control strategy using delta-sigma conversion and improved PDM pattern generation method based on the Space Vector Modulation (SVM) are explained and simulated. Next, the converter loss is analyzed by simulation. After that, the validity of the proposed circuit is confirmed by the experimental results. Finally, the effect of the impedance on the power source is analyzed.

II. CIRCUIT CONFIGURATIONS

A. Single-phase to Three-phase Matrix Converter

Figure 1 shows the circuit configuration of a single-phase to three-phase MC. This circuit is an AC to AC direct converter which is constructed by six bidirectional switches and it does not composed of an electrolytic capacitor in the DC link. Furthermore, the efficiency of a MC is higher than a conventional system that is constructed by a rectifier, electrolytic capacitors and a three-phase inverter because of less switching devices in the current path.

B. Indirect Single-phase to Three-phase Matrix Converter

Figure 2 shows another circuit configuration of an indirect type of single-phase to three-phase MC. This circuit is constructed by a diode rectifier as an input interface and a three-phase inverter. In this circuit, the conduction loss is higher than the single-phase to three-phase MC, because the numbers of conduction device are larger than the single-phase to three-phase MC as shown in Fig.2. Although the circuit structures of these two converters are different, the control methods are identical. In this paper, the indirect type structure is verified and confirmed the operation in simulation and experiment.

III. Control Strategy

A. PDM Control using Delta-sigma Conversion

PDM controls the density and the plus/minus of the constant-width pulse, and then these pulse signals are used as the output unit.

Figure 3 shows the control block diagram of the proposed circuit. The PDM signals used for the switching can be obtained by converting the delta-sigma command (v_u*, v_v*, v_w*) value from each phase. Delta-sigma conversion is a kind of analog-digital conversion. These PDM signals are used to turn on/off each of the inverter arm at the indirect single-phase to three-phase MC circuit. However, the polar characteristic of the input signal is changing occasionally because the input of this circuit is a single-phase AC voltage. Then the functions of the upper and lower arms are inverted. As a result, it is necessary to detect the input voltage polarity and convert the switching signals, when the input voltage is in minus pole.

Additionally, the zero cross points exist with respect to the frequency since the input voltage is a sinusoidal waveform. ZVS operation is performed at every zero cross points of the input voltage. The loss at the switching devices is reduced drastically because the switching loss can be decreased nearly to zero by the ZVS operation.

However, there are some parts, which refer to constant voltage in this method. In these parts, switching loss increases because ZVS is not achieved. The phenomenon occurs because PDM patterns using delta-sigma conversion contains the switching patterns, where the phase between the output voltage and current become too large instantaneously. When the phase between the current and voltage vector becomes larger than 30 degrees, DC link current flows backward to power source side in the inverter. As a result, DC link voltage is equaled to snubber capacitor voltage. In order to resolve this problem, the method based on Space Vector Modulation (SVM) is applied to the generation of PDM patterns. This method is explained detail in the next chapter.

B. PDM Control based on Space Vector Modulation

The waveform is improved applying PDM pattern generation method based on SVM. In SVM, the instantaneous voltage vector that the phase between the output current and voltage does not become too large rapidly is selected and output. Therefore, DC link current does not flow backward, and the phase error between voltage and current does not occur.

Figure 4 shows the PDM signal generation block based on Space Vector Modulation. The switching signals generated from SVM is an input to the d flip flop (D-FF), and +/- detection signal from the input voltage is used to detect the zero cross points of input voltage, this signal is an input to the CLK. The output of the D-FF, "Q" is synchronized at the edge of +/- signal, which is the zero cross point of input voltage. As a result, the switching signals generated by SVM are quantized by a pulse where the width is half cycle of the input voltage.

In addition, the switching frequency is proportional to the carrier frequency of SVM. A ratio between the input voltage and carrier frequency is very important factor related to resolution of the control. Hence, decision of the carrier frequency of SVM is significant in this method.

This method is called "Space Vector Base Pulse Density Modulation" or "SVB-PDM" for short.

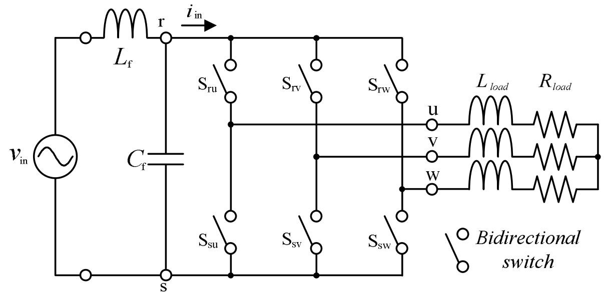


Fig. 1. Single-phase to three-phase MC.

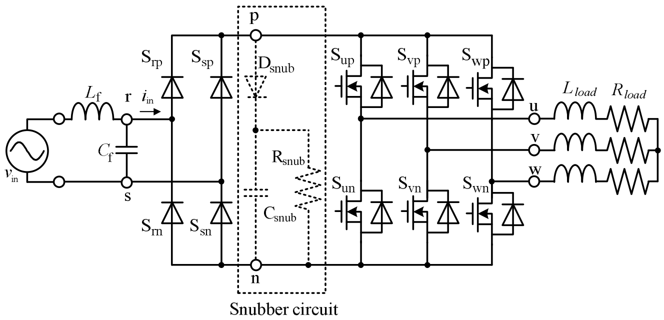


Fig. 2. Indirect single-phase to three-phase MC.

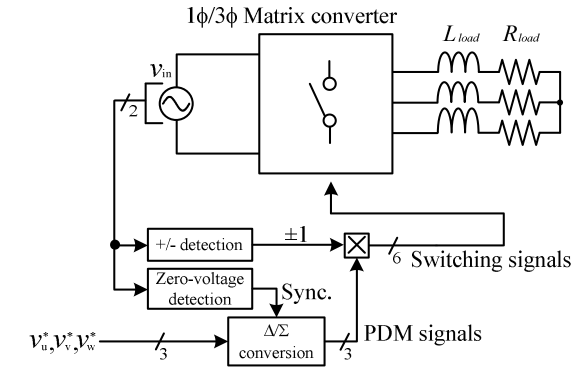


Fig. 3. PDM control block diagram using Delta-sigma Conversion.

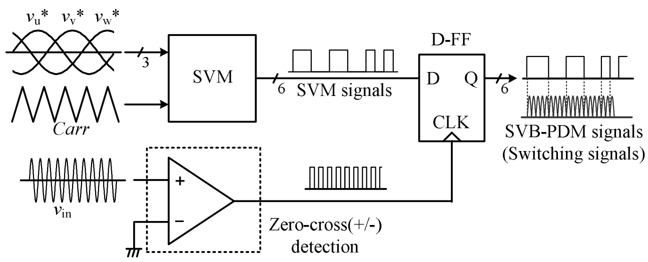


Fig. 4. PDM signal generation block based on Space Vector Modulation.

IV. SIMULATION RESULTS

The following is the simulation results using indirect type circuit in Fig.2. As a simulation condition, a 100kHz, 400V sinusoidal voltage is used as the input, output voltage is 50Hz, 200V, and a 300W inductive load is used as a load.

A. Simulation results of PDM using Delta-sigma Conversion

Figure 5(a) shows the operation waveforms of the proposed circuit in the simulation with PDM using delta-sigma conversion. From the result, 50 Hz sinusoidal waveforms are obtained at the output voltage and current. The PDM control operation which uses the half cycle of the input sinusoidal waveform as the output minimum unit can be verified and confirmed at the simulation results Fig. 5. However, there are some inverse voltage pulses in this case. These pulses affect the distortion of waveforms.

Figure 5(b) shows extended view of waveform of the interval "A" in Fig. 5(a). As a result, the output line-line voltage v_{uv} confirms that the switching of the inverter is approximately at each zero cross point of the 100 kHz sinusoidal input waveform. However, there are some areas, the constant voltage is occurring. In these areas, switching loss increases because ZVS is not achieved.

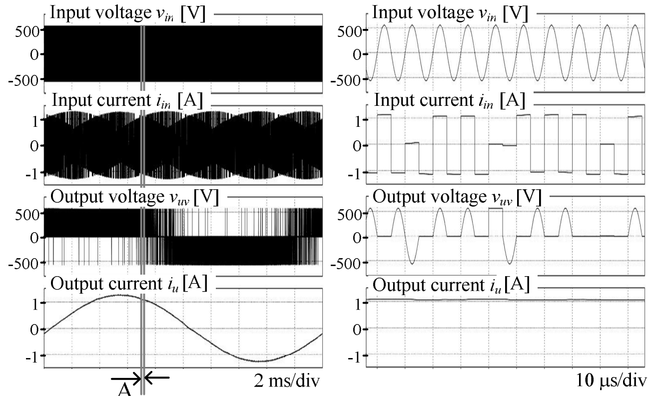
Figure 6(a) shows the harmonics analysis of the output voltage from simulation result with PDM using delta-sigma conversion. From (a), the output voltage does not consist of low-order harmonic components closely to 50 Hz and the output voltage THD is 11.8 %. Figure 6(b) shows the harmonics analysis of the input current from simulation result with PDM using delta-sigma conversion. From (b), the input current includes of the integral-multiple harmonic nearly closed to 100 kHz and therefore the input current THD is 78.8 %.

B. Simulation Results of SVB-PDM

Figure 7(a) shows the operation waveforms of the proposed circuit in the simulation with SVB-PDM. From the result, 50 Hz sinusoidal waveforms are obtained at the output voltage and current. The PDM control operation which uses the half cycle of the input sinusoidal waveform as the output minimum unit can be verified and confirmed at the simulation results. Notice there are no inverse voltage pulses in this case.

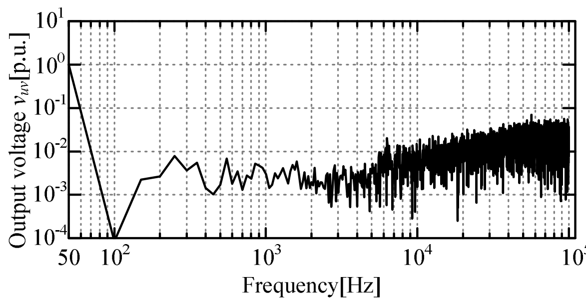
Figure 7(b) shows extended view of waveform of the interval "B" in Fig. 7(a). As a result, the output line-line voltage v_{uv} confirms that the switching of the inverter is approximately at each zero cross point of the 100 kHz sinusoidal input waveform. In this case, areas that contain the constant voltage have been resolved. Therefore, switching loss is negligible small because ZVS is achieved in this case.

Figure 8(a) shows the harmonics analysis of the output voltage from simulation result with SVB-PDM. From (a), the output voltage does not consist of low-order harmonic components closely to 50 Hz and the output voltage THD is 6.96 %. In this case, output voltage includes of the integral-multiple harmonic nearly to 5 kHz, which is the carrier frequency of SVM used in this simulation. Figure 8(b) shows

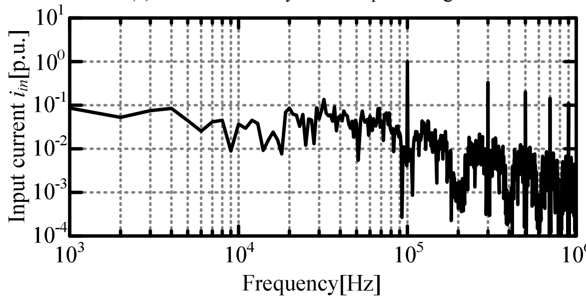


(a) Input and output operation waveforms. (b) Extended each operation waveform.

Fig. 5. Operation waveforms of the proposed circuit in the simulation with PDM using delta-sigma conversion.

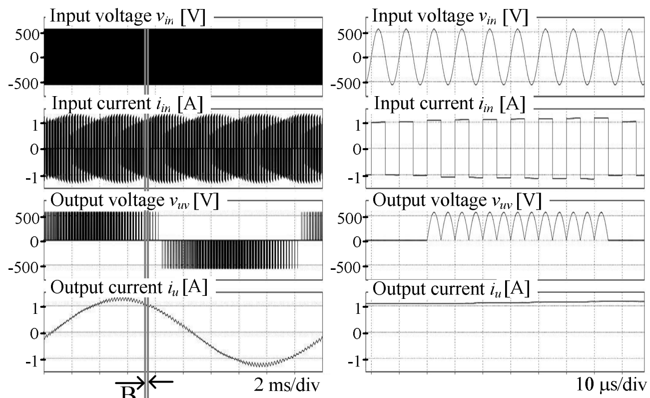


(a) Harmonics analysis of output voltage.



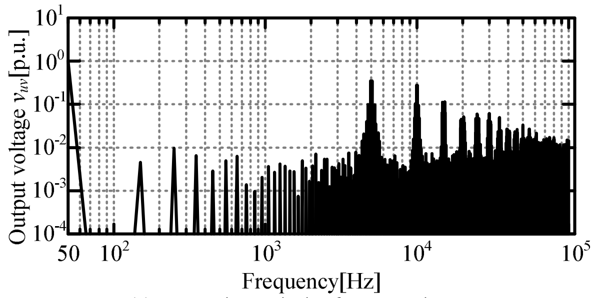
(b) Harmonics analysis of input current.

Fig. 6. Harmonics analysis of output voltage and input current in the simulation with PDM using delta-sigma conversion.

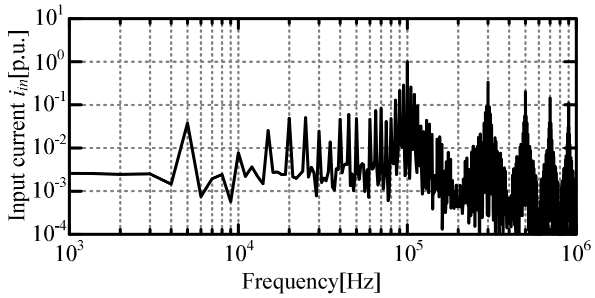


(a) Input and output operation waveforms. (b) Extended each operation waveform.

Fig. 7. Operation waveforms of the proposed circuit in the simulation with SVB-PDM.



(a) Harmonics analysis of output voltage.



(b) Harmonics analysis of input current.

Fig. 8. Harmonics analysis of output voltage and input current in the simulation with SVB-PDM.

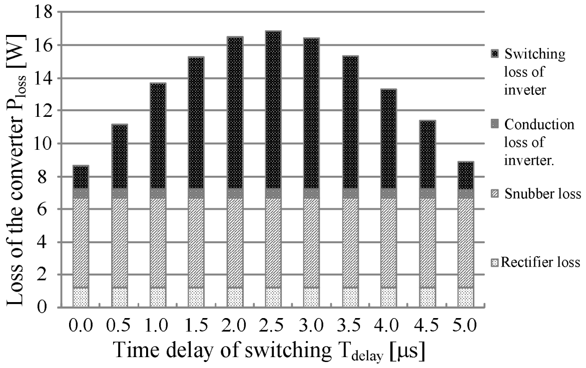


Fig. 9. Converter losses vs delay time of switching with PDM using delta-sigma conversion.

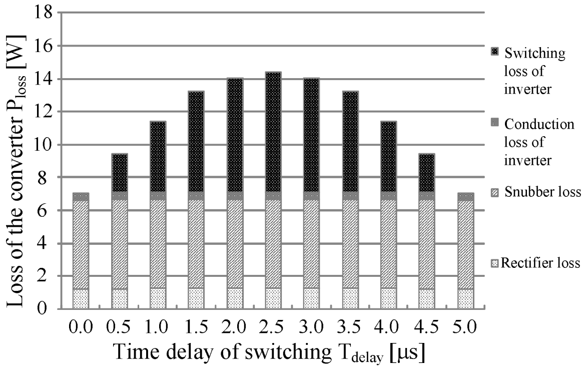


Fig. 10. Converter losses vs delay time of switching with SVB-PDM.

the harmonics analysis of the input current from simulation result with SVB-PDM. From (b), the input current includes of the integral-multiple harmonic nearly to 100 kHz and therefore the input current THD is 78.9 %.

V. Loss Analysis

The following is the loss analysis results using indirect type circuit as shown in Fig. 2. The simulation condition is as same as the parameters discussed in chapter IV. The device parameters are from datasheets MOSFET : IRFP460 (500V, 20A) and diode: S20L60 (600V, 20A), which are similar in the prototype circuit[12-13].

A. Loss Analysis of PDM using Delta-sigma Conversion

Figure 9 shows result of loss analysis with PDM using delta-sigma conversion. The figure compares the converter loss and the time delay in switching. Rectifier loss, snubber loss and conduction loss of the inverter are maintained virtually constant about 7W. Switching loss of the inverter changes accordingly to the time delay.

The frequency of the voltage which is applied to the switch is twice input frequency of 100 kHz. On the other hand, the frequency of the current which flows through the switch is the output frequency of 50 Hz. Hence, the current can be assumed constant during switching period. Additionally, the voltage becomes the peak value when the time delay of switching equals to one-fourth of input cycle. Therefore, the switching loss becomes maximum value then.

Even, the time delay t of switching is 0μs, there is switching loss of 1.4 W occurs due to the phase error waveforms.

B. Loss Analysis of SVB-PDM

Figure 10 shows result of loss analysis with SVB-PDM. The characteristics of this result are same to the delta-sigma conversion. The difference in this case is when the time delay of switching is 0μs, there is no switching loss because phase error waveform does not exist. Comparing to the result from Fig. 9, the loss is reduced by approximately 18 %.

VI. Experimental Verification at Low-order Voltage

In order to demonstrate the validity of the proposed circuit, a prototype circuit has been built and tested. The indirect type single-phase to three- phase MC was tested in the experiment with PDM using delta-sigma conversion. A 20 kHz sinusoidal voltage is used as the input of the circuit initially to confirm the basic principle of the proposed circuit. Table 1 shows the experimental conditions.

Figure 11(a) shows the operation waveforms of the proposed circuit. From the result, 50 Hz sinusoidal waveforms are obtained at the output voltage and current. The PDM control operation which uses the half cycle of the input sinusoidal waveform as the output minimum unit can be verified and confirmed at the experiment results Fig. 11.

Figure 11(b) shows the extended view of waveform of the interval "C" in Fig. 11(a). As a result, the output line-line voltage v_{uv} confirms that the switching of the inverter is approximately at each zero cross point of the 20 kHz sinusoidal input waveform. However the switching has a 3 μs delay due to the reasons, slow detections on the zero cross points and the dead time of the inverter. The delay of the zero cross point detection is approximately 2μs, and dead time of the inverter is set to 1μs. The delay can be improved by the modifying the zero cross point detection circuit, and re-design the dead time based on the device parameters. Additionally, although the switching has a short delay, the switching loss and surge voltage are lower than the hard switching method at the zero cross point.

In addition, the efficiency 91.5% is obtained from the prototype circuit. This efficiency can be improved by optimizing the dead time and criteria selection of the switching devices.

Figure 12 shows the harmonics analysis of the output voltage. From the result, the output voltage consists of low-order harmonic components closely to 50Hz and the output voltage THD is 5.4 %. Figure 13 shows the harmonics analysis of the input current. From the result, the input current includes of the integral-multiple harmonic nearly to 20 kHz and therefore the input current THD is 84.6 %.

Based on these results, the validity of proposed circuit is confirmed by the experiment.

VII. Experimental Results using High-impedance Power Source

In order to consider about the effect of the impendence in a power source, a prototype circuit has been tested using high-impedance power source. Delta-sigma conversion is used as the modulator.

Figure 14 shows the equivalent circuit of the power source circuit. It is constructed by a full-bridge inverter, a low pass filter (LPF) and a transformer.

Figure 15(a) shows the operation waveforms of the proposed circuit without an input filter. From (a), there are resonance phenomena (approximately 330 kHz) occurring on the input and output waveforms.

Figure 15(b) shows the operation waveforms of the proposed circuit with an input filter (22 nF filter capacitor and 136 Ω dumping resistance). These filter parameters are designed from the leakage inductance (139 μH), cut-off frequency (approximately 90 kHz) and a damping factor (0.85). From (b), the resonance is being suppressed by adding filter capacitance and damping resistance input side. However, the non-ZVS periods caused distortions on the operation waveforms because of the in slow detection error.

VIII. Consideration about Effect of a Power Source Side Impedance

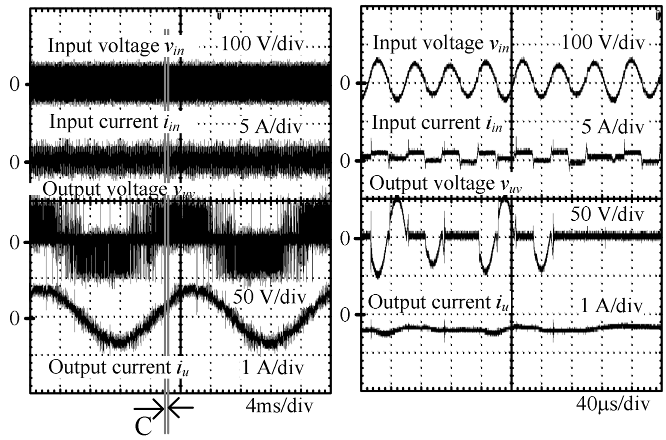
Since the resonance phenomena (approximately 330 kHz) are found in the operation waveform as shown in Fig. 15(a), the impedance on the power source is considered as the element to cause the resonance. In order to consider the cause of resonance, the proposed circuit is analyzed by using simulator with the same practical parameters.

Figure 16(a) shows the simulation results of the proposed circuit without the leakage inductance and line-to-line capacitance of a transformer. At (a), there are no resonance phenomenon found in the operation waveforms.

Figure 16(b) shows the simulation results of the proposed circuit with the leakage inductance and line-to-line

Table 1. Experimental parameters.

Input voltage	35V
Input frequency	20kHz
Output voltage	19.5V
Output frequency	50Hz
Load	R_{load}=19Ω L_{load}=3mH (50W)



(a) Input and output operation waveforms.
(b) Extended each operation waveform.

Fig. 11. Operation waveforms of the proposed circuit in the experiment.

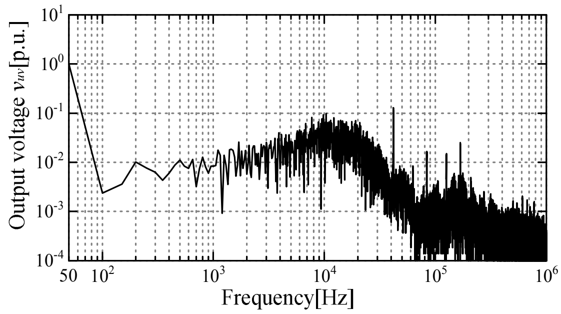


Fig. 12. Harmonics analysis of output voltage.

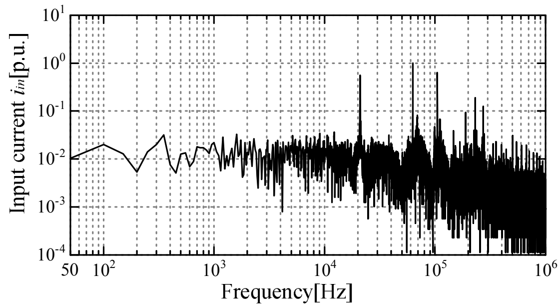


Fig. 13. Harmonics analysis of input current.

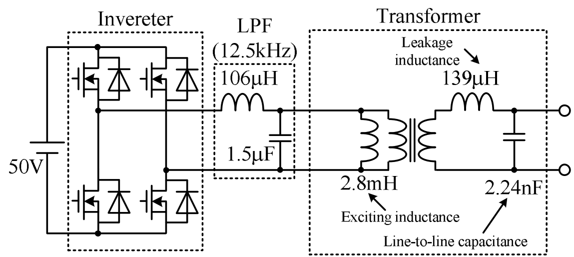


Fig. 14. Equivalent circuit of source circuit.

capacitance of a transformer. In this condition, resonance phenomena are confirmed in the operation waveforms. The resonance frequency is about 300 kHz, and it is identical to the experimental result. It can be considered that the resonance is caused by the leakage inductance, line-to-line capacitance and load inductance. Additionally, when leakage inductance of transformer changes. Thus resonance frequency more change than when load inductance changes, and when line-to-line capacitance transformer changes, resonance frequency most change. The energy of the leakage inductance can be absorbed by the filter capacitance and damping resistance input side. However, the effect of the damping resistance is small when the line-to-line capacitance is large because the damping resistance is connected parallel with the capacitance.

IX. Conclusion

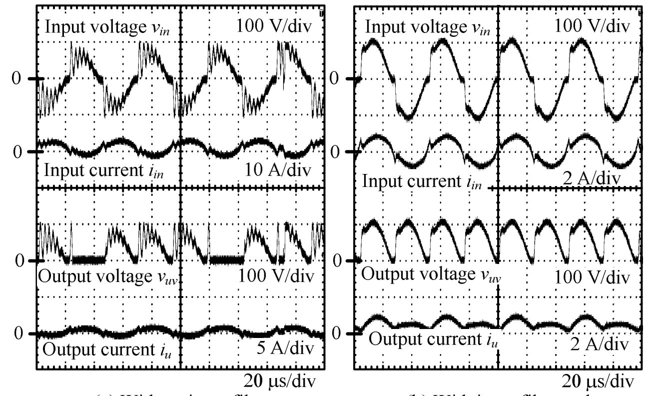
A single-phase to three-phase MC using the PDM control method for the high-frequency power source has been proposed. The proposed circuit is able to achieve the ZVS operation by using the PDM control method that is according to half cycle of the input sinusoidal voltage. Then the validity of the proposed circuit is confirmed in this paper.

The loss analysis results show that the switching loss of the case of SVB-PDM is lower than the case of PDM using delta-sigma conversion.

The experimental results from prototype circuit confirmed the following aspects; the output voltage and current are sinusoidal waveforms. Further, the switching of the inverter arm at the proximity of zero cross point is obtained. Moreover, THD of the output voltage and the input current of proposed circuit are 5.4% and 84.6 %. In addition, the efficiency of 91.5% is obtained.

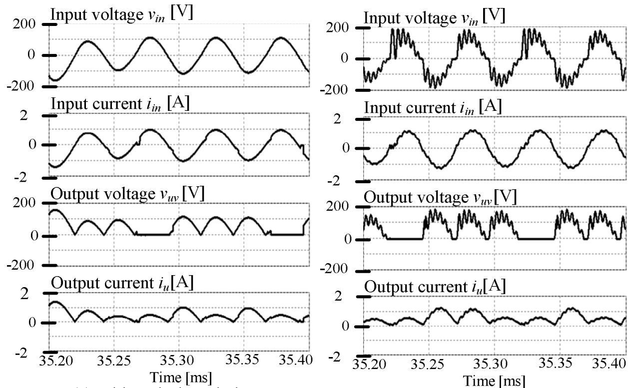
Additionally, the effect the impedance on the input power source is considered. It is clear that the line-to-line capacitance at the power source side must be kept as small as possible in order to suppress the resonance. Therefore, design of the system requires attentions in the capacitance of the magnetic coupling circuit and magnetic resonance antenna.

In future work, an experiment using SVB-PDM will be investigated, the zero cross point detection circuit will be improved, and tested with a higher input frequency that is equivalent to the wireless power transfer system. Also, the bidirectional switches MC will be tested.



(a) Without input filter and damping resistance (b) With input filter and damping resistance

Fig. 15. Operation waveforms of the proposed circuit in the experiment using high-impedance power source.



(a) Without leakage inductance and line-to-line capacitance (b) With leakage inductance and line-to-line capacitance

Fig. 16. Simulation results considering the impedance of power source.

References

[1] A.Kurs, A.Karalis, R.Moffatt, J.D.Joannopoulos, P.Fisher, M.Soljačić : "Wireless Power Transfer via Strongly Coupled Magnetic Resonances", *Science*, vol.317, pp.83-86, 2007

[2] Takehiro IMURA, Yoichi HORI : "Wireless Power Transfer Using Electromagnetic Resonant Coupling", *IEEJ Journal*, vol.129, No.7 pp.414-417, 2009

[3] Keisuke Kusaka, Satoshi Miyawaki and Jun-ichi Itoh : "A Experimental Evaluation of a SiC Schottky Barrier Rectifier with a Magnetic Resonant Coupling for Contactless Power Transfer as a Power Supply", 2010 Annual Conference of IEEJ, Industry Applications Society, No.1-41, 2010 (in Japanese)

[4] J. Itoh, I. Sato, H. Ohguchi, K. Sato, A. Odaka and N. Eguchi: "A Control Method for the Matrix Converter Based on Virtual AC/DC/AC Conversion Using Carrier Comparison Method", *IEEJ Trans. IA*, vol.124-D, No.5, pp.457-463, 2004 (in Japanese)

[5] Y. L. Feng, Y. Konishi, and M. Nakaoka : "Current-Fed Soft-Switching Inverter with PDM-PWM Control Scheme for Ozone Generation Tube Drive", *IEEJ Trans. IA*, Vol.120, No.10 pp.1239-1240, 2000

[6] Yuelu Feng and Mutsuo Nakaoka : "Voltage-Source Series Resonant Zero Current Soft Switching High-Frequency Inverter with PDM Scheme for Induction Heating Roller in Copy Machine", *IEEJ Trans. IA*, Vol.123, No.2 pp.112-120, 2003

[7] T. Lee, M.E. Elbuluk, D.S. Zinger : "Performance of MCTs in a Current Regulated Ac/Ac PDM Converter", Power Electronics Specialists Conference 1993, pp.935 - 941, 1993

[8] Abdelhalim Sandali, Ahmed Cheriti, Pierre Sicard : "Design Considerations for PDM Ac/ac Converter Implementation", P Applied Power Electronics Conference 2007, pp. 1678 - 1683, 2007

[9] Y. Nakata, J. Itoh: "A Basic analysis of a High-frequency Single-phase-to-three-phase Matrix Converter using PDM Control", Tokyo Branch Niigata Annual Conference, IEEJ, IV-07, p.114, 2010 (in Japanese)

[10] Y. Nakata, S. Miyawaki, J. Itoh: "An Experimental Verification of a Single-phase-to-three-phase Matrix Converter Using PDM Control for High-frequency Applications", Technical Meeting on Semiconductor Power Converter, IEEJ, SPC-11-20 (in Japanese)

[11] Y. Nakata, S. Miyawaki, J. Itoh: "A Consideration about Effect of a Power Source Side Impedance for a High-frequency Single-phase-to-three-phase Matrix Converter using PDM Control", IEEJ Annual Conference 2011, p.4-027 (in Japanese)

[12] IXYS: "N-Channel Enhancement Mode, HDMOS^{TM} Family IRFP460", Datasheet (2000)

[13] Sindengen Electric Mfg.Co.Ltd: "Super Fast Recovery Rectifiers S20L60", Datasheet (2000)