Square Wave Operation for a Single-phase PFC Three-phase Motor Drive System without a Reactor

Jun-ichi Itoh*, Nobuhiro Ohtani*
* Electrical and Electronic Engineering, Nagaoka University of technology
1603-1 Kamitomioka-cho Nagaoka city Niigata, Japan

Abstract**-- This paper proposes a square wave control strategy for a new boost-up converter which uses the leakage inductance of a motor instead of a boost up reactor. Since the power supply is connected to the neutral point of the motor, the current distortion in the power supply occurs when the inverter outputs square waveforms.**

First, this paper describes the characteristic of the proposed circuit and the problems in the square wave operation. Next, a current control method for the square waveform is proposed to suppress the current distortion. Finally, the validity of the proposed converter and its control strategy are demonstrated by experimental results.

Index Terms**-- Boost-up converter Leakage inductance, Square wave operation, Neutral point**

I. INTRODUCTION

Recently, single-phase motors are often to use in consumer electronics. However, in order to reduce the size and the weight, it is required to use a three-phase motor instead of a single-phase motor [1]. For single-phase input consumer electronics, it needs a single-phase to three-phase converter to drive a three-phase motor. This system requires a high efficiency and small size converter. Furthermore, the input current is required to meet the harmonic standard [2].

Figure 1 shows a conventional circuit which is composed by a diode-bridge rectifier, a boost chopper circuit and a three-phase inverter. Although a diode rectifier is low cost, it can not meet the input current harmonic standard since the input current involves large distortion [3-5]. A DC reactor with a diode rectifier is used so the input current can meet the harmonics standard; however the DC reactor can not suppress the harmonics current under a large output power. The boost chopper works as a power factor correction (PFC) converter [6-7]. In the view of the efficiency, a full-bridge or half bridge pulse width modulation (PWM) rectifier is one of good solution for PFC. However, all PFC converters require a large boost up reactor and consequently, it needs higher cost and larger size.

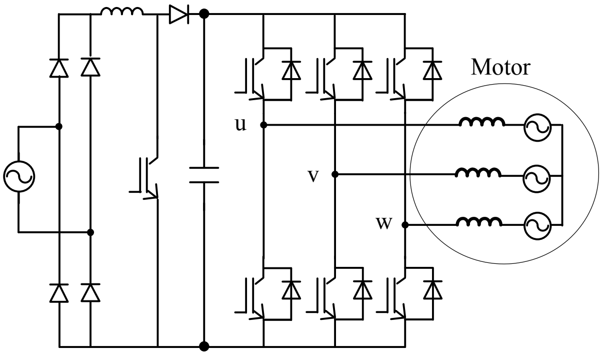


Fig. 1. Conventional circuit with the diode-bridge rectifier and boost chopper circuit.

The authors have been proposed that a leakage inductance of the motor is used instead of boost-up reactor [7-8]. Since it consists of a simple circuit structure than the conventional circuit, the proposed circuit can achieve a smaller size and lower cost application. The motor is controlled by the proposed converter using PWM.

On the other hands, a square wave operation is used for many applications such as high speed motor drive, electric vehicle, rail way system. The square wave operation of the inverter can increase the voltage utilization and can achieve higher efficiency than a PWM operation since the switching frequency of a square wave operation is lower than that of PWM drive [9]. In the proposed circuit, when the square wave operation is applied to the inverter control, the voltage of the neutral point of the motor has fluctuation of three times of the output frequency. Since the power supply is connected to the neutral point of the motor, the input current distortion occurs from the fluctuation of the neutral point of the motor.

This paper proposes a square wave operation strategy for the proposed circuit, which uses the neutral point of a motor. The objective of this paper is to suppress the input current distortion under a square wave operation. The input current distortion is suppressed by auto current regulation (ACR) and feed forward compensation. First, this paper describes the characteristic of the proposed circuit and the principle operation. So, when the output frequency is high, it is presented that the DC link voltage is two times higher than the peak input voltage. Next, this paper discusses the problem of the input current distortion which is caused by the fluctuation of the neutral point of the motor under outputs square wave operation. In addition, a high power factor control for suppressing the input current distortion with a square wave operation is proposed. Finally, the proposed circuit control strategy is demonstrated by experimental results.

II. REACTOR FREE PFC CONVERTER

A. Circuit configuration

Figure 2 shows the proposed circuit using the neutral point of the motor. The proposed circuit consists of a three phase inverter, a electrolytic capacitor and a switching leg using series IGBT. The input power supply is connected between the center of the leg and the neutral point of the motor. The input reactor of the proposed circuit is substituted with the zero phase inductance which is also known as the leakage inductance of the motor [7-8]. Therefore the input reactor is unnecessary in the proposed circuit. In addition, the number of the switching elements can be decreased in comparison to a conventional single phase full-bridge PWM rectifier and inverter system because the inverter parts in the proposed circuit is substituted for another leg in the rectifier. As a result, the parts in gate drive circuits or peripheral control units are reduced.

The input current control of the proposed circuit is achieved by a zero phase component of the output voltage and the motor current control is achieved by a positive phase at the same time.

B. Positive phase equivalent circuit

Figure 3 shows the equivalent circuit of the positive phase sequence in the proposed circuit. In this case, the power supply and the rectifier leg do not appear in the equivalent circuit since it is in zero phase components. So, the equivalent circuit of motor current control is similar to a conventional three-phase inverter. It is noted that the zero phase current in the motor does not generate torque because the zero phase flux denies with each other.

A square wave operation for the three-phase inverter is applied to reduce the switching loss of the inverter in comparison to a PWM inverter. During the square wave operation, the switching frequency agrees with the output frequency. The output line voltage becomes a 120 degree square waveform, then, the fundamental voltage of the output is given by (1).

$$V_{out} = \frac{\sqrt{6}}{\pi} E_{dc} \qquad (1)$$

where V_{out} is the output line voltage, E_{dc} is the DC link voltage.

C. Zero phase equivalent circuit

Figure 4 shows the equivalent circuit of the zero phase sequence in the proposed circuit. The back electromotive force (EMF) does not appear in the zero phase equivalent circuit but only the leakage inductance occurs. It is noted that the EMF includes of multiple third order harmonics, those harmonics components appear in the zero phase equivalent circuit. On the other hands, the inverter legs become single leg which will switch at zero-vector output ratio.

Figure 5 shows the relations of the phase voltage and the neutral point voltage during the square wave operation. When the inverter is operated at the square wave, the neutral point of the motor has a fluctuation that is plus or minus one of sixth of the DC link voltage. As a result, each of the phase voltage becomes the square wave of ±1/6 of the DC-link voltage.

In the proposed circuit, the neutral point of the motor is connected to the power supply. That is, the voltage fluctuation of the neutral point disturbs the current control of the power supply. Subsequently, the input current has the distortion three times of the output frequency. When the output voltage of the inverter leg fluctuates with ±1/6 of the DC-link voltage, the rectifier leg has to output the sum of ±1/6 of the DC-link voltage and peak voltage of the input power supply. Therefore, in order to compensate the disturbance by the square wave

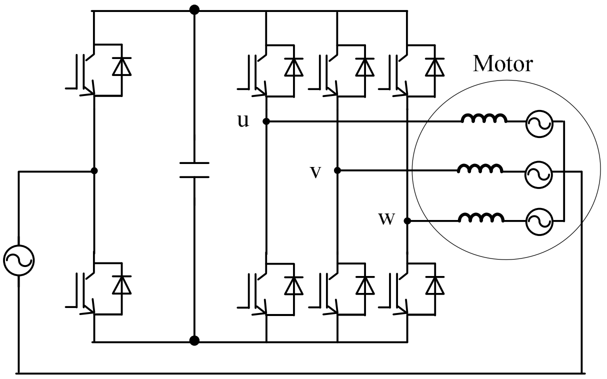


Fig. 2. Proposed circuit using the neutral point of the motor.

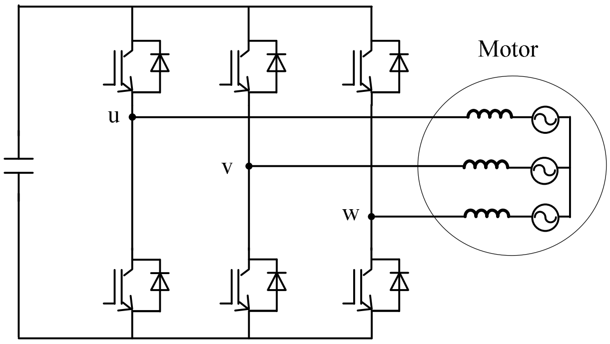


Fig. 3. Equivalent circuit of the positive phase in the proposed circuit using the neutral point of the motor.

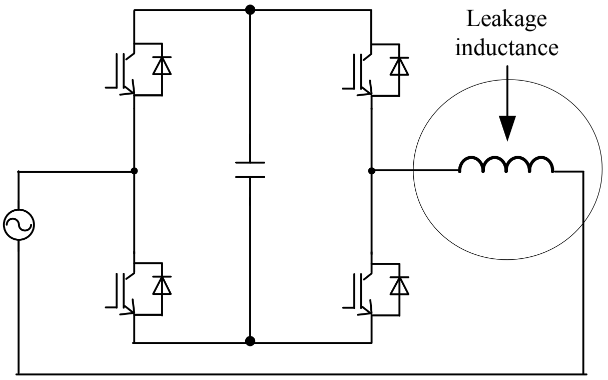


Fig. 4. Equivalent circuit of the zero phase in the proposed circuit using the neutral point of the motor.

operation, the DC link voltage is constrained by (2).

$$\frac{E_{dc}}{2} \geq \frac{1}{6}E_{dc} + \sqrt{2}V_{in}$$

$$E_{dc} \geq 3\sqrt{2}V_{in} \tag{2}$$

where E_{dc} is the DC link voltage, V_{in} is the power supply voltage.

On the other hands, if the frequency of the fluctuation in the neutral point of the motor is much higher than the input current control response, the voltage fluctuation can be neglected. Then, the DC link voltage requires only two times of the power supply voltage because the control of the rectifier is the same as the half-bridge PWM rectifier.

Figure 6 shows a control block diagram of the current control in order to discuss the condition of the required DC link voltage. A proportion-integration (PI) controller is used as a current regulator and the neutral point of the motor is considered as a voltage disturbance. When the influence of the disturbance voltage can be disregard for the input current, the DC link voltage may be twice of the peak voltage of the input voltage. The transfer function from a disturbance voltage to the input current is obtained by (3).

$$\frac{I_{in}}{V_{dis}} = s\frac{T_i}{K_p} \times \frac{1}{s^2\frac{LT_i}{K_p} + sT_i + 1} \times \sqrt{\frac{3}{2}} \tag{3}$$

where K_p is the proportional gain, T_i is the integration time constant of the PI regulator, L is the leakage inductance, and s is Laplace operator.

Figure 7 shows the relations between the input current total harmonic distortion (THD) and the inverter output frequency. Where the natural angular frequency ω_n is 4000rad/s and the damping factor ζ is $1/\sqrt{2}$. It is noted that the disturbance frequency is three times of the inverter output frequency and the DC link voltage is set to twice of the peak voltage of the input voltage. Symbol '▲' shows the theoretical curve calculated by (3), symbol '■' shows the current THD calculated by a circuit simulator. When the inverter frequency is low, THD increases in the simulation results because the disturbance voltage can not be neglect in the current controller. That is, the DC link voltage is not enough to control the current. In order to overcome the problem, the DC link voltage is required to have at least two times or more than the input peak voltage. In this condition, the limit of the inverter output frequency is set to 330Hz. That is, before 330Hz, the required DC link voltage is twice of the input peak voltage and after that, the DC link voltage has to increases according to the inverter output frequency.

III. PROPOSED CONTROL STRATEGY

Figure 8 shows a block diagram of the proposed circuit. The current control of the power supply is the same as a conventional PWM rectifier. It is noted that the leakage inductance is used instead of the boost reactor; however, the leakage inductance decreases to 1/3 of the leakage inductance of the motor since the leakage inductance is connected in parallel in the zero-phase equivalent circuit.

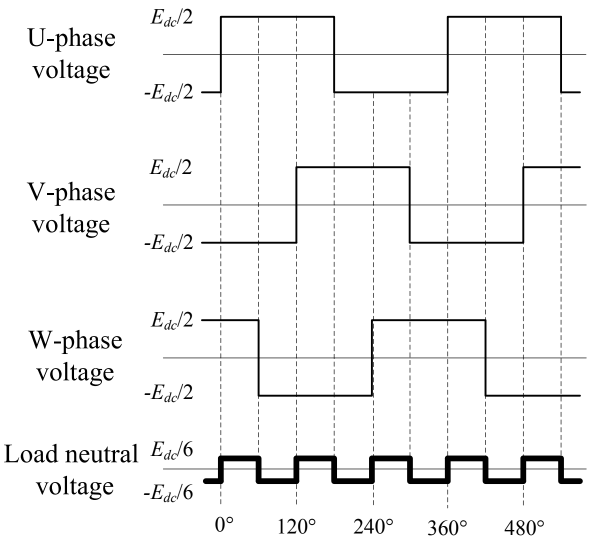


Fig. 5. Relations between each of the phase voltage and the load neutral point voltage.

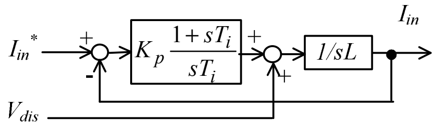


Fig. 6. Control block diagrams of the current control.

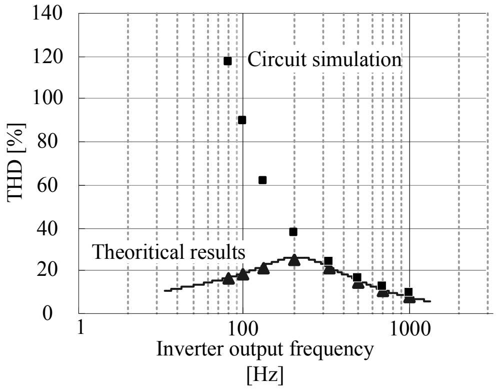


Fig. 7. Relations between input current THD and inverter output frequency.

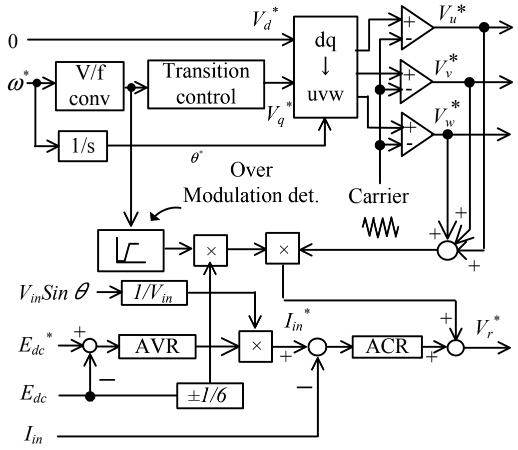
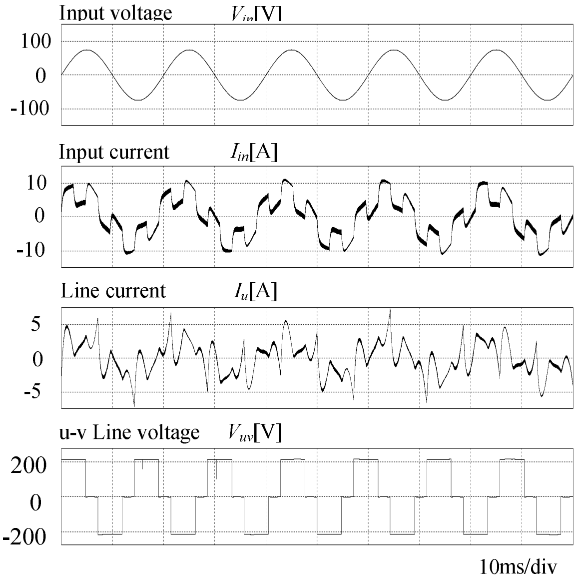
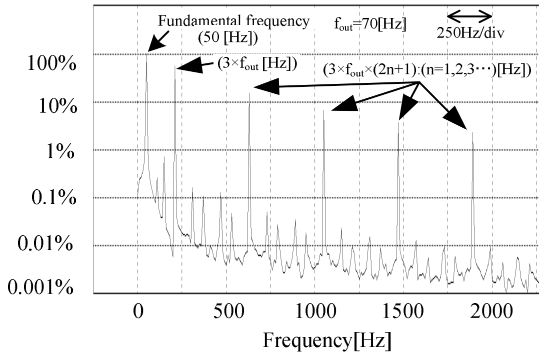


Fig. 8. Block diagram of the proposed circuit.

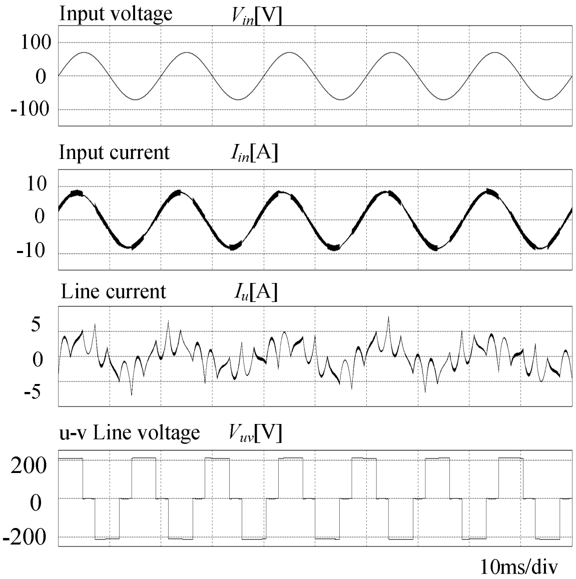


(a)Simulation waveforms

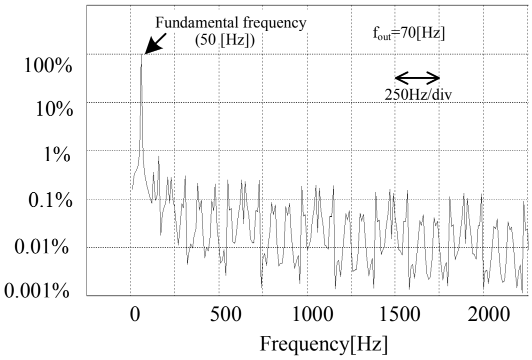


(b)Harmonics analysis results of the input current

Fig. 9. Simulation result without proposed control



(a)Simulation waveforms



(b)Harmonics analysis results of the input current

Fig. 10. Simulation result with proposed control

As discussed in previous chapter, the neutral point voltage of the motor has fluctuation of $\pm 1/6E_{\mathrm{dc}}$ with three times of the inverter output frequency in the square wave operation. In order to compensate the voltage fluctuation, a feed forward control is applied to the ACR. The voltage fluctuation is estimated by the DC link voltage and pulse pattern of the inverter. 'Over modulation det' finds the square wave operation mode by using modulation index.

For the inverter side, the PWM control is slowly changed into a square wave control via the trapezoidal pulse modulation. When the inverter is in PWM operation, the output voltage is linearly increasing. However, the output voltage is nonlinearly increasing at the over-modulation area. The transition control in Figure.8 is a proportional compensation to the amplitude of the output voltage command.

IV. SIMULATION RESULTS

Figure 9 shows the simulation results during a square wave operation. The motor model is expressed in the EMF, the leakage inductance and the armature resistance. The input voltage is 50V, the input frequency is 50Hz and the the output frequency is 70Hz. From Fig. 9, it is confirmed that the input current contains the 3rd harmonic components of the output frequency. The total harmonic distortion (THD) of the input current is 56.5% in Fig. 9.

Fig. 10 shows that the distortion of the input current is suppressed by proposed control. The THD of the input current THD is 1.3%. In contrast to the Fig. 10, the distortion of the input current is suppressed drastically by the feed forward compensation.

V. EXPERIMENTAL RESULTS

Figure 11 shows experimental results using the inverter in PWM operation mode. The input voltage, input current, line current, and u-v line-to-line voltage were examined. The parameter of the induction motor that used in experiment is 750W, 200V and 50Hz. The input voltage is 50V and 50Hz. In Fig.11, the output frequency of the positive phase is 44Hz. A sinusoidal input current waveform is obtained because the neutral point of the motor voltage is constant during PWM operation. The THD of the input current is 3.9%. The amplitude of the line current is changed because the line current consists of the input current of 50Hz and the positive current of the motor of 44Hz.

Figure 12 shows the acceleration characteristics from PWM operation to square wave operation. The PWM waveform is gradually changed into a square wave control that can be confirmed by the u-v line voltage. The pulse mode moves from PWM to the square mode without rush current. It is noted that fluctuation of the line current is generated due to the difference between the input frequency and the output frequency.

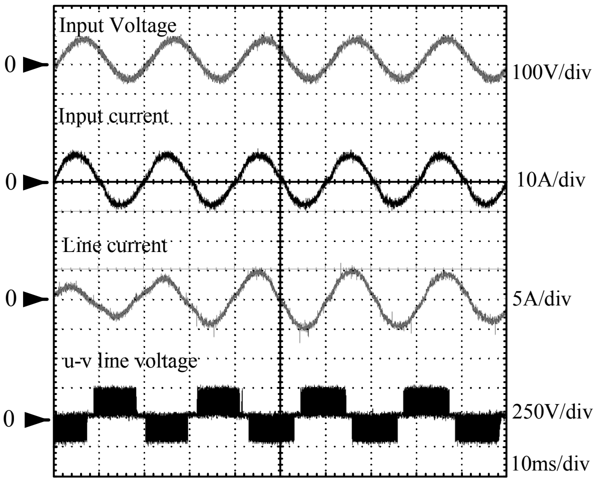
Figure 13 shows the experimental results during a square wave operation. In Fig. 13, the harmonic distortion of the input current is suppressed and the DC link voltage is kept constant that can be confirmed by the u-v line voltage. In addition, the input current is confirmed to contain the 3rd harmonic components of the output frequency. The THD of the input current is 29.1%. It is noted that the output current includes ripple due to the square wave operation.

Figure 14 shows that the distortion of the input current is suppressed by proposed control. The THD of the input current THD is 6.1%. In comparison with Fig. 13, the distortion of the input current is suppressed to less than 1/20 times. In addition, the THD of the input current is 23% reduced. The input current harmonics of the proposed control method meets the standard of IEC61000-3-2.

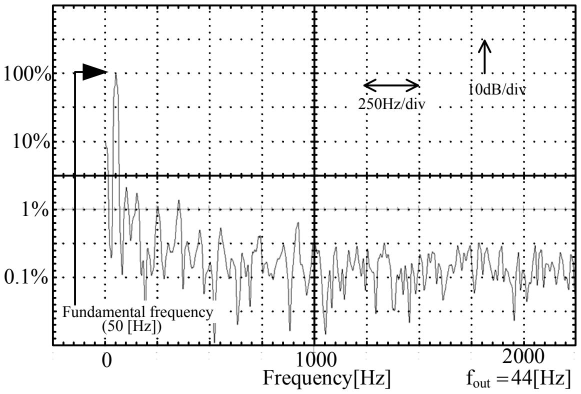
Overall, the experimental results confirmed the validity of the proposed feed forward compensation control method.

VI. CONCLUSIONS

The control strategy for the reactor free converter has proposed to achieve a square wave operation in an

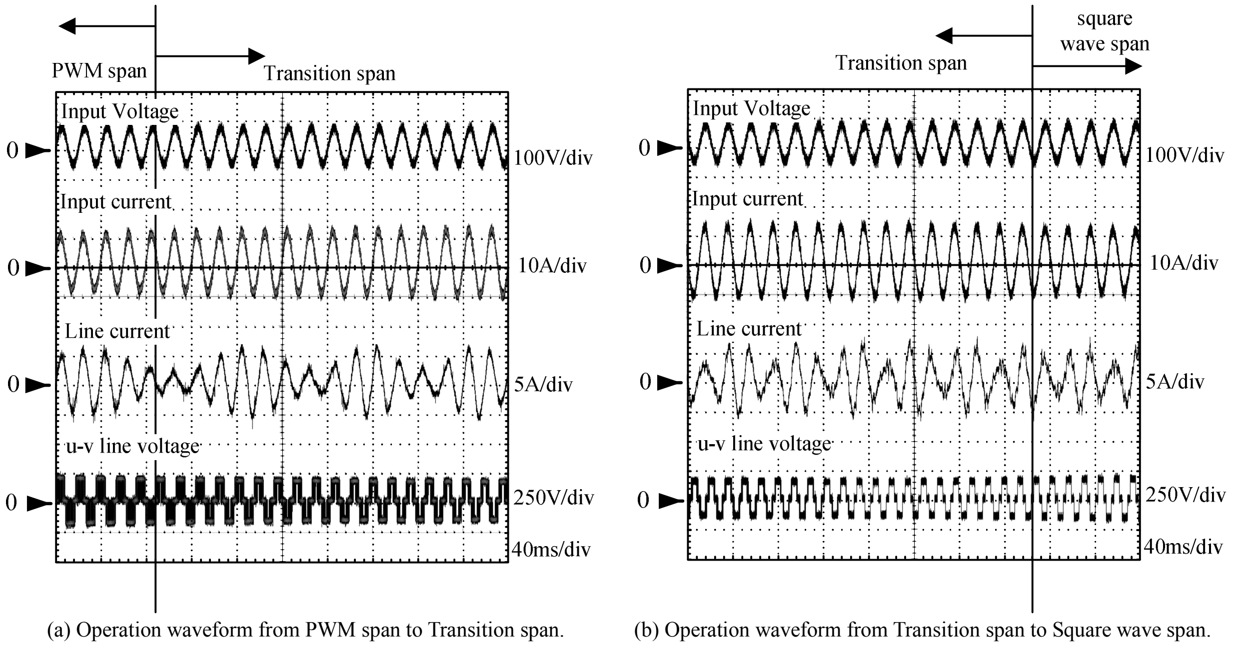


(a) Operation waveform



(b) Harmonics analysis results of the input current

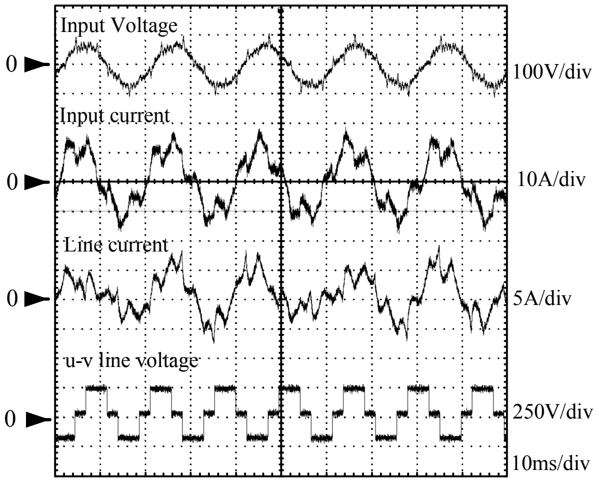
Fig. 11 Experimental results using the inverter in PWM operation mode.



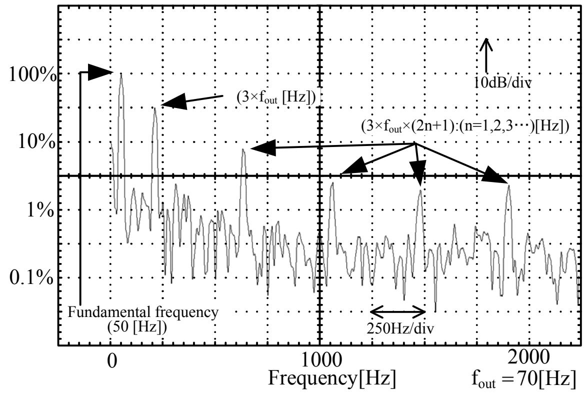
(a) Operation waveform from PWM span to Transition span.

(b) Operation waveform from Transition span to Square wave span.

Fig. 12 Acceleration characteristics.

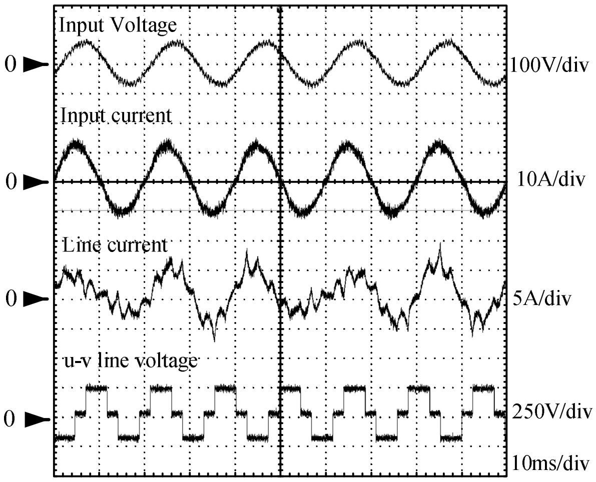


(a)Operation waveform.

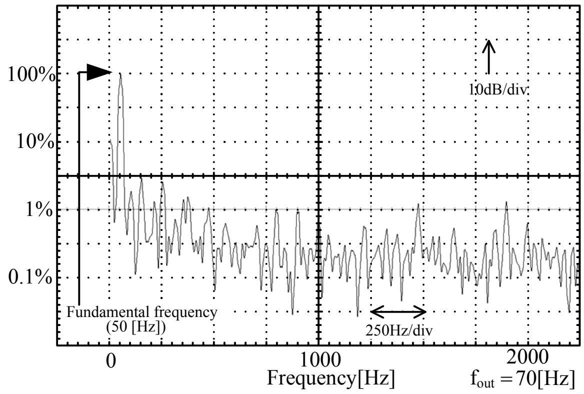


(b)Harmonics analysis results of the input current.

Fig. 13 Experiment results without proposed control.



(a)Operation waveform.



(b)Harmonics analysis results of the input current.

Fig. 14. Experiment results with proposed control.

adjustable speed drive motor application. The known problem is where the current distortion in the power supply occurs when the inverter outputs square waveforms. In order to overcome the problem, a feed forward control is proposed to suppress the input current distortion with a square wave operation. The proposed control method successfully suppresses the input current distortion to 1/20 times smaller than the no feed forward control. In addition, the THD of the input current is 23% reduced.

In future works, the proposed converter and controller will be applied and examined in a high speed permanent magnetic motor.

REFERENCES

[1] Dong-Choon Lee,Young-Sin Kim:“Control of Single-Phase-to-Three-Phase AC/DC/AC PWM Converters for Induction Motor Drives” *IEEE Transactions on Industrial Electronics*, ,Vol,54No.2 p797-804 April 2007

[2] Jaehong Hahn,N.Enjeti,Ira J.Pitel: “A New Three-Phase Power-Factor Correction(PFC)Scheme Using Two Single-Phasw PFC Modules” *IEEE Tranceactions On Industry Applications* ,Vol,38,No.1 p123 ～ 130 JANUARY/FEBRUARY 2002

[3] Alfio Consoli, Mario Cacciato, Antonio.Testa, Francesco Gennaro, “Single Chihp Integration for Motor Drive Converters With Power Factor Capability”*IEEE Tranceactions On Power electronics,* Vol,19,No.6, p1372 ～1379 NOVEMBER 2004

[4] Olorunfemi Ojo , Zhiqiao Wu, Gan Dong, Sheetal K Asuri, “High-Performance Speed-sensorless Control of an Induction Motor Drive Using a Minimalist Single-Phase PWM Converter”*IEEE Tranceactions On Industry Applications,* Vol,41,No.4, p996～1004 JULY/AUGUST 2005

[5] Ricardo Quadros Machado, Simone Buso, Jose Antenor Pomilio, “A Line-Interactive Single-Phase to Three-Phase Converter System”*IEEE Tranceactions On Power electronics,* Vol,21,No.6, p1628 ～ 1636 NOVEMBER 2006

[6] S.M.Bashi,N,Mariun,S.B.Noor and H.S.Athab: “Three-Phase Single Switch Power Factor Correction Circuit with Harmonic Reduction” *Journal of Applied Sciences*5(1):80 ～84, 2005

[7] J. Itoh, K. Fujita, “Novel Unity Power Factor Circuits Using Zero-Vector Control for Single-Phase Input Systems,” *IEEE Transactions on power electronics*, Vol.15, No.1, p.36-43, January 2000.

[8] J. Itoh, S. Ishii, “Novel Single-phase High Power Factor Converter with Load Neutral Point Applied to PM Motor Drive” *T.IEE Japan*, Vol.121-D, No.2, p.219-224, 2001.

[9] K.Moriya, H.Nakai, Y.Inaguma, S.Sasaki, “A DC/DC Converter Using Motor Neutral Point and its Control Method”*IEEJ* 4-179 March 2004(at Sagamihara)