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Paper

Optimal Frequency Tracking Method for Phase-Shift PWM Inverter

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This paper proposes a new resonant frequency tracking control method for full-bridge-type high-frequency inverters. Whereas the ordinary phase-locked loop (PLL) based frequency control method uses a current sensor and a voltage sensor, the proposed technique can achieve the same purpose with a single current sensor. In high-frequency power supply systems using a PLL, it is impossible to perform power control with an inverter. Therefore, an active converter must be used for power control, and the system grows larger. On the other hand, high-frequency inverters using the proposed control system simultaneously enable power control and achieve the same resonant frequency tracking as a PLL, and thus high-frequency power supply systems become extremely simple. This paper explains in detail the principle underlying the control method, and presents an example of a circuit to realize it. The theory is backed up by using a prototype high-frequency power supply system which actually employs the proposed control system, thereby demonstrating its practical utility in industry. © 2012 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

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1. Introduction

Induction heating is widely used in the heat-treatment of metals, such as quenching and annealing, and as a heat source to replace gas in large cooking equipment [1–3]. Full-bridge-type high-frequency inverters are widely used as high-frequency power supply system needed for induction heating.

Figure 1 shows a full-bridge-type high-frequency inverter to which a series resonance circuit is connected as a load. If the operating frequency is set to match the resonant frequency of the load, in the state where the gate signal phase of the inverter has been shifted, then a soft switching state can be obtained, and thus the inverter can operate at high power conversion efficiency [4]. However, in devices that use induction heating, it is widely known that the equivalent impedance of the load varies depending on the temperature state of the heated object, and thus the resonant frequency also fluctuates. Therefore, it is necessary to provide control so that the high-frequency inverter is constantly operated at the resonant frequency.

Phase-locked loop (PLL) is the most widely used control technique for adjusting the operating frequency of a high-frequency inverter to the resonant frequency or an optimal frequency close to that (referred to below as the 'optimal operating frequency') [5–8]. A PLL controller has zero-cross detectors and multiple Current transformer (CT) or PT in order to monitor the phase of the output voltage and the output current of the inverter. The oscillation frequency—i.e. the operating frequency of the inverter—is controlled so that the phase difference of the detected voltage and current is zero or constant. A number of suppliers offer a variety of integrated circuits (ICs) especially for PLL control, and thus these ICs are easy to acquire and stable in price. Introducing PLL control to a high-frequency inverter is comparatively easy.

On the other hand, power control is also an important function of high-frequency power supplies for induction heating. Pulse frequency modulation (PFM) control or phase-shift PWM control is used in many actual systems as the power control technique for full bridge-type inverters with a small or medium output of a few tens of kilowatts or less [4,9].

The PFM-controlled inverter operates at a slightly higher frequency than the resonant frequency. The output power can be decreased by making the operation frequency high. The operation frequency has to be made higher by a certain method when the equivalent load inductance decreases during heating. At the same time, the equivalent load resistance also becomes low and the quality factor of the resonant circuit becomes high. So the output current tends to be overlimited. In order to this overcome this current problem, the operation frequency should be high. Additionally, it is necessary to make the the operation frequency higher when temperature control is required. Thus PFM inverter needs to operate at wide frequency range. It may be limited for the actual use in high-temperature induction heating applications.

In phase-shift PWM control, power control is performed, as the name indicates, by shifting the phase. Power control is achieved by changing the phase difference between the output voltage and the output current through frequency control. However, PLL is a control scheme that fixes the phase difference between the output voltage and the output current of the inverter. Since the principle of PLL and the principle of power control are contradictory, it is impossible to achieve both types of control with a single high-frequency inverter.

Therefore, in large high-frequency power supply systems for high-temperature induction heating applications, the inverter is provided with a PLL function, and the power control function is realized by adding an active converter. The power control function is achieved by raising and lowering the DC bus voltage, and is called *pulse amplitude modulation* (PAM) (Fig. 2(a)) [6, 7]. In this way, high-frequency power supply systems require multiple power conversion circuits. As a result, they tend to be bulky, and there are also concerns about power conversion losses. When providing a PFC converter, it is difficult to obtain an adequate power control function from the PFC converter. Therefore, high-frequency power supply systems become large, as in Fig. 2(b), and there are concerns about a further drop in efficiency.

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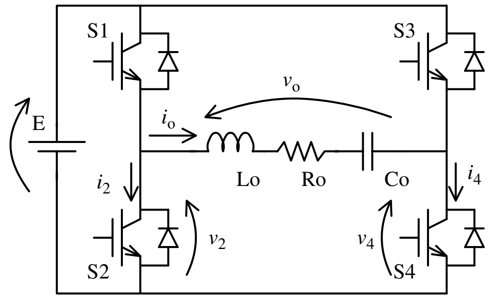

Fig. 1. Full bridge inverter with series load resonant circuit

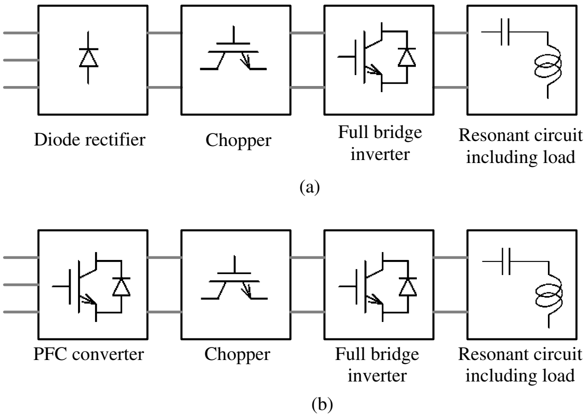

Fig. 2. Conventional power supply for large induction heating applications. (a) High-frequency inverter with chopper. (b) High-frequency inverter with chopper and PFC converter

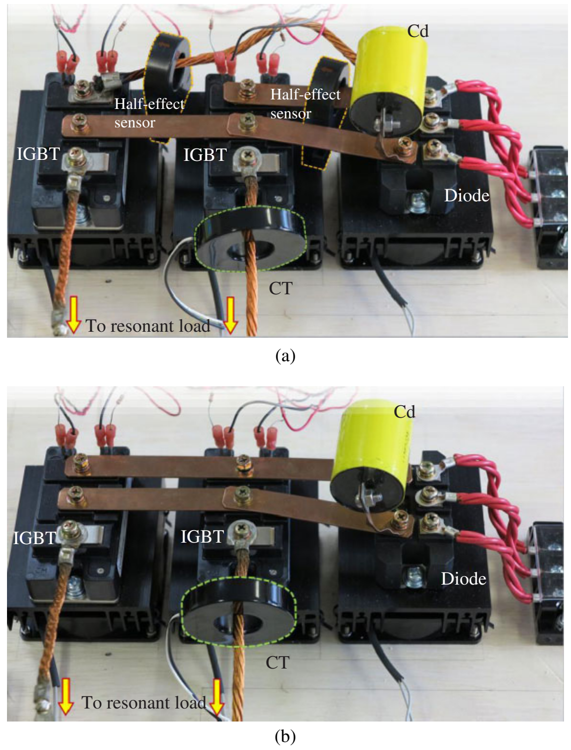

Fig. 3. Inverter main circuit. (a) Inverter main circuit controlled by CTBL that had been proposed before. (b) Inverter main circuit controlled by the proposed method

Conduction Time Balanced Loop (CTBL) has been proposed as one type of optimal operating frequency control to address this issue [10]. It is a controller for phase-shift PWM high-frequency inverters. A CTBL controller is comprised of two current sensors, one comparator, and an oscillator for detecting the current of switching devices used in the high-frequency inverter. In this control, the basic principle is that the conduction time of the switching devices is detected at two points, and frequency of the oscillator is controlled so that those lengths of time are equal. Unlike a PLL, the zero-cross points and phase of the output voltage and output current are not used as control information. Therefore, even if the zero-cross points vary due to phase-shift PWM, it does not interfere in any way with CTBL control. Therefore, it is possible to simultaneously achieve power control using phase-shift PWM and optimal operating frequency tracking control using CTBL with a single high-frequency inverter.

However, with CTBL it is necessary to detect the current of switching devices, and thus it is necessary to install Hall-effect sensors capable of detecting the large current between the DC bus and each switching device (Fig. 3(a)). For this reason, wiring between the DC bus and switching devices grows longer and stray inductance increases. There are concerns that this inductance may promote surge voltages during switching, or increase switching loss [11]. In addition, a Hall-effect sensor with a high frequency measurement range is extremely expensive compared to a CT. In order to improve the above disadvantages of CTBL, this paper proposes a new technique for optimal operating frequency control which can be realized with only a single current transformer as the sensor (Fig. 3(b)). By using the newly proposed control system, it is possible to achieve optimal operating frequency control with a single high-frequency inverter, just as with CTBL. Therefore, high-frequency power supply systems are simplified, as in Fig. 4(a), and an active converter for power control becomes unnecessary. Even if a PFC converter is provided, overall it is a two-converter system, and thus suppression of power conversion loss can be expected (Fig. 4(b)).

2. Principle of the Proposed Method

The proposed operating frequency control detects the output current by CT just like a traditional PLL. However, its distinguishing feature is that it acquires control information not from the current phase but from its waveform. Figure 5 shows a schematic diagram of the operating waveforms of each part when a high-frequency inverter controlled by phase-shift PWM is operating at the resonant frequency. V_{G1}–V_{G4} are the gate pulse signals applied to the switching devices S1–S4. The output voltage waveform is a square wave which takes three values: $+E$, 0, and $-E$. Here, E indicates the DC bus voltage. In general, the quality factor of the resonant circuit, which includes the induction heating load, is high, and thus the output current waveform approaches a sine wave.

Focusing attention on the current waveform during the period when the output voltage is zero, the area of the positive current waveform is equal to the area of the negative current waveform. In other words, on the condition that the operation frequency is tuned to the resonant frequency, the integrated value of the instantaneous values of the output current becomes zero in the period when the output voltage is zero. Furthermore, it is evident from the schematic diagram that the relationship mentioned above always holds, regardless of the state of power control by phase-shift PWM.

On the other hand, Fig. 6(a) shows the waveform in the state where the operating frequency is lower than the resonant frequency. Under this condition, the integral of the output current is negative. Conversely, it is clear that this integral is positive when the operating frequency is higher than the resonant frequency (Fig. 6(b)).

From these considerations, it is clear that the value of the output current integrated over the period where output voltage is zero can

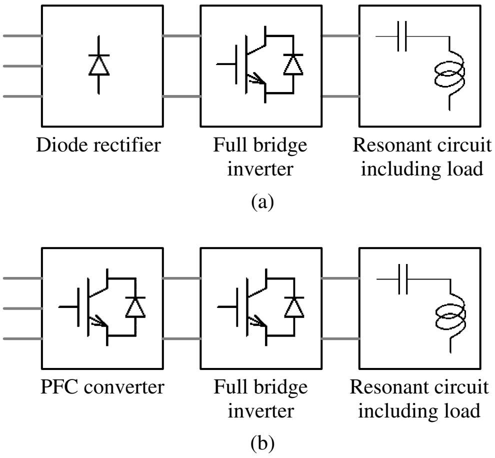

Fig. 4. Proposed power supply for large induction heating applications. (a) Simplified high-frequency power supply. (b) High-frequency power supply with PFC converter

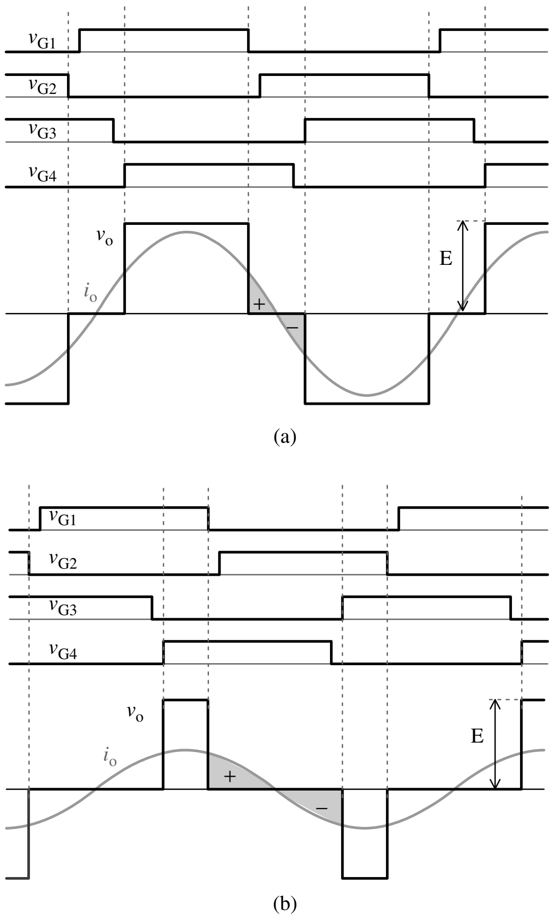

Fig. 5. State in which the operation frequency is matched. (a) High-power state. (b) Low-power state

be used as information for optimal operating frequency control. That is, by controlling the frequency so that the integral is always zero, it is possible, as a result, for the inverter to track the resonant frequency. The period over which the output voltage is zero can be discerned from the timing of the gate signals. Thus, the proposed control can be realized with only a single AC current sensor. For reasons of simplicity, this control system is tentatively called the *integration zero loop* (IZL) in this paper.

As is evident from the previous explanation, the state of power control using phase-shift PWM does not affect the principle of control of the IZL. In other words, the two control rules do not mutually interfere. Therefore, it is possible to simultaneously achieve both output power control and optimal operating frequency control with a single high-frequency inverter. As a result, there is no longer a need for an active converter, such as a chopper circuit, for power control, and thus it is easy to simplify high-frequency power supply systems.

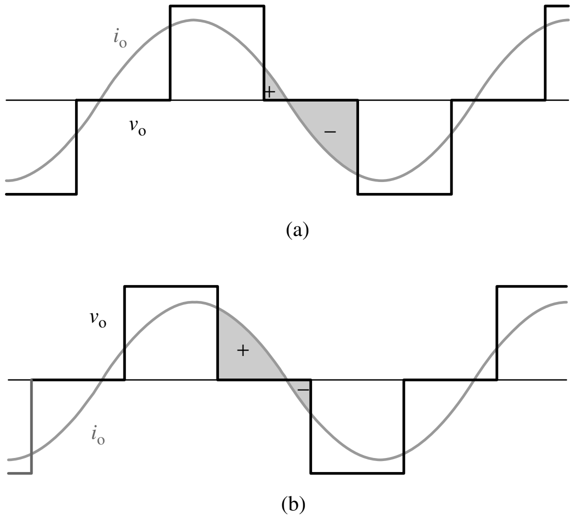

Fig. 6. State in which operation frequency is not matched to resonant frequency. (a) Operation frequency less than the resonant frequency. (b) Operation frequency greater than the resonant frequency

3. Controller

Figure 7 shows an example of a block diagram that realizes control rules for both phase-shift PWM and IZL. The functions of each are described in detail below.

3.1. Power control The inverter output power is controlled by a phase-shift PWM. In this control, the phase of the gate signal input to S3 and S4 is varied with respect to the phase of the gate signal applied to S2 and S1. For example, if the phase difference of S4 (S3) with S1 (S2) is large, the output power decreases.

3.2. Optimal operating frequency control When starting the inverter, the initial voltage is input for a short time to the frequency control circuit (see A in Fig. 7). The voltage-controlled oscillator (VCO) oscillates because of that initial voltage, and its frequency becomes the operating frequency of the inverter at startup. The output current is detected by the AC current sensor, and converted to a low-voltage signal waveform (B in Fig. 7). V_{G1} and V_{G3} are input to a NOR gate (C in Fig. 7). The output signal indicates the period over which the output voltage becomes zero. The analog switch goes ON when the NOR gate is at the high level (D in Fig. 7). The output current waveform signal is trimmed during the period when the output voltage is zero. The trimmed signal waveform is integrated (E in Fig. 7). The sample-and-hold circuit maintains the voltage value of the integration result (F in Fig. 7). If that voltage is positive, the inverter operating frequency is increased by raising the input voltage of the VCO. Conversely, if the voltage is negative, the operating frequency of the inverter is lowered by lowering the input voltage of the VCO. The held voltage is added to the VCO input voltage as control information (G in Fig. 7).

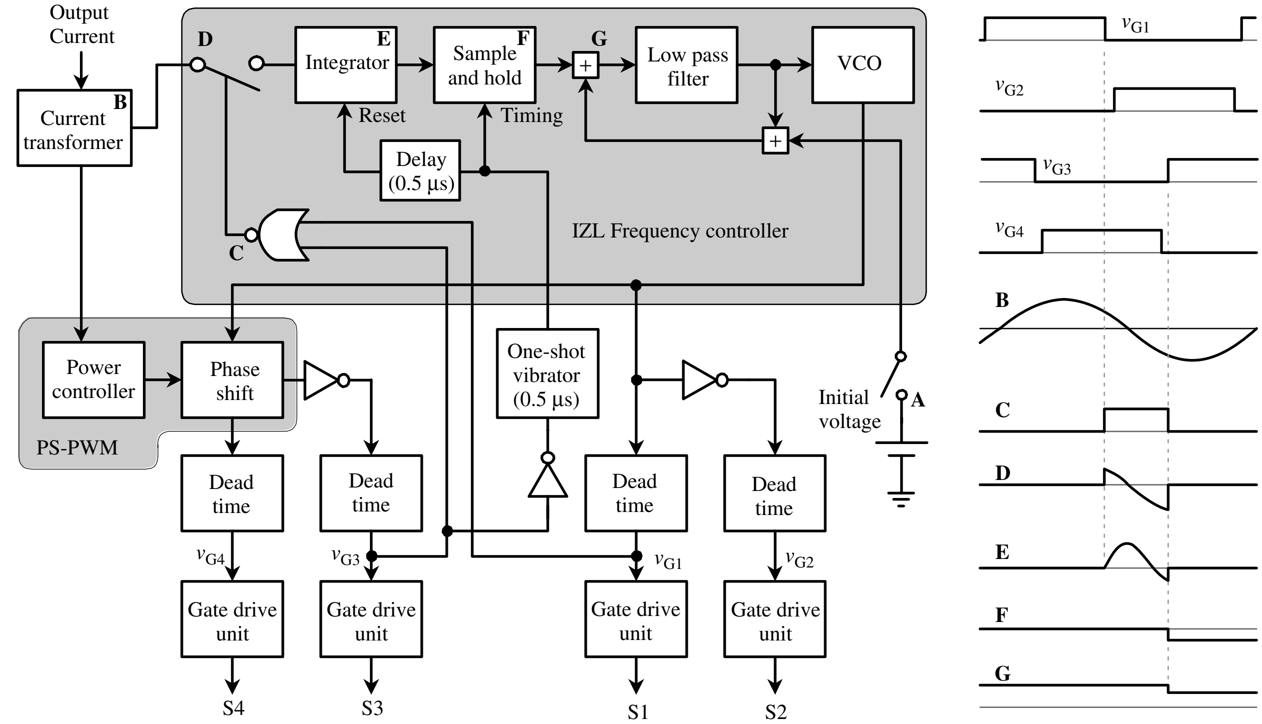

Fig. 7. Sample block diagram for the proposed frequency control

4. Experiments and Evaluation

A prototype was constructed of a phase-shift PWM high-frequency inverter incorporating the proposed optimal operating frequency control. Specifications of the prototype high-frequency inverter and dummy load are provided in Table I. The purpose was to evaluate the control method, and therefore an experiment was conducted using a dummy load rather than an actual induction heating load. Consequently, the quality factor of the dummy load circuit is low compared to that of an actual induction heating load, but there is no substantial difference in the implementation of this experiment. A solenoid coil was fabricated with litz wire in order to imitate the equivalent inductance of the induction heating load. A bulk of ferrite core was removed from this solenoid coil as an impeder. While the inverter is in operation, it inserts the ferrite core into the solenoid coil, and thus the inductance value changes. The variation in resonant frequency can be simulated by using this variation in the inductance value. The equivalent resistance of the induction heating load was simulated by connecting eight water-cooled resistors in parallel. The DC bus voltage E is obtained by rectifying the three-phase voltage which is regulated by an auto-transformer.

First, Fig. 8 shows the power control performance of the prototype high-frequency inverter. If the load meets fixed conditions, wide-ranging and continuous power control performance from 100% to less than 1% can be obtained. It was confirmed that, at this time, the high-frequency inverter itself attained a power conversion efficiency from three-phase input power to high-frequency output power of 96% for over half load, and more than 90% with a light load.

Next, an experimental evaluation was conducted of the variation in resonant frequency due to variation in inductance, and the associated tracking performance. Figure 9 shows the experiment results. The dotted line shows the theoretical resonant frequency before and after the change in the inductance value. Inductance varies by close to 50% in a short time, but the prototype proposed control circuit controls the operating frequency almost exactly according to theoretical values. The reason why the operating frequency and theoretical frequency do not match exactly may be that the inverter output current is not a sine wave. In this experiment, the quality factor of the resonant circuit is low, and

Table I. Specifications of devices in main circuit

Item	Rated value	Product
Six-pulse diode	600 V, 50 A	6RI50E
Two-in-one IGBT modules	600 V, 100 A	CM100DU-12F × 2
Resonant capacitors; Co	1.344 µF	RC24P631224 × 6
Water cooled resistors; Ro	5.6 Ω	W-1000D × 8
Imitation coil; Lo	61.9 µH (with core) 32.1 µH (without core)	Litz wire ϕ0.35 mm ×100
Current transformer	200 A_{max}	CTL-24-S28-2.5Z

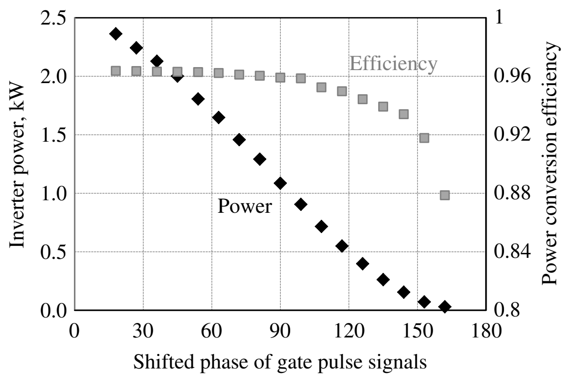

Fig. 8. Power control performance (three-phase voltage = 100 V, $Lo = 61.9$ µH, $Ro = 5.6$ Ω, $Co = 1.344$ µF)

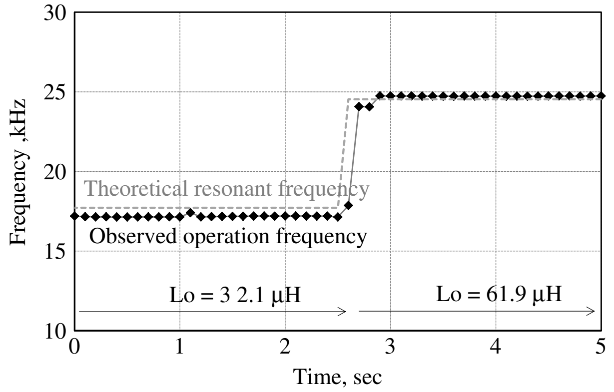

Fig. 9. Controlled operation frequency

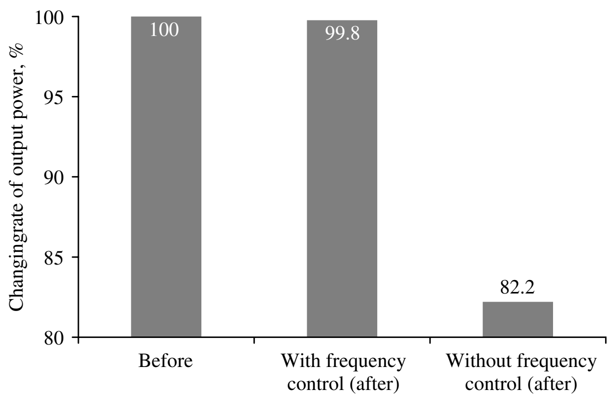

Fig. 10. Power with and without tracking the resonant frequency

thus the output current waveform is somewhat distorted. With the proposed control system, the inverter output current is assumed to be a sine wave, and that waveform itself is used as control information. Therefore, if the current waveform is distorted as in this experiment, the operating frequency will not perfectly track the resonant frequency.

Figure 10 shows the variation in inverter output power before and after changing the resonant frequency. These are results when the experiment was conducted by turning only the proposed frequency control function ON, and turning the automatic output power control function OFF. The value of the dummy load resistance does not change, and only the resonant frequency changes. Therefore, there is no difference in output power as long as the operating frequency tracks the resonant frequency. For this reason, in the experimental results, major differences are not apparent in the output power before and after the change in resonant frequency. On the other hand, if the resonant frequency tracking function is also turned OFF, then it can be confirmed that the power factor on the inverter output side drops, and the output power drops, in accordance with the change in resonant frequency.

Figure 11 shows the observed waveforms at each part of the inverter before and after the change in inductance value. The phase of the inverter output voltage and output current match well even after the resonant frequency has changed. Soft switching due to current resonance is maintained at each switching device, and ZVZCS turn-on is achieved for S4, and ZVZCS turn-off for S2.

Figure 12 shows the operating waveforms after changing the resonant frequency when the proposed control system is not used. It is obvious that phases of the output voltage and the output current are not matched. It was measured that the power conversion efficiency of the inverter also drops by about 1.5% at full load condition.

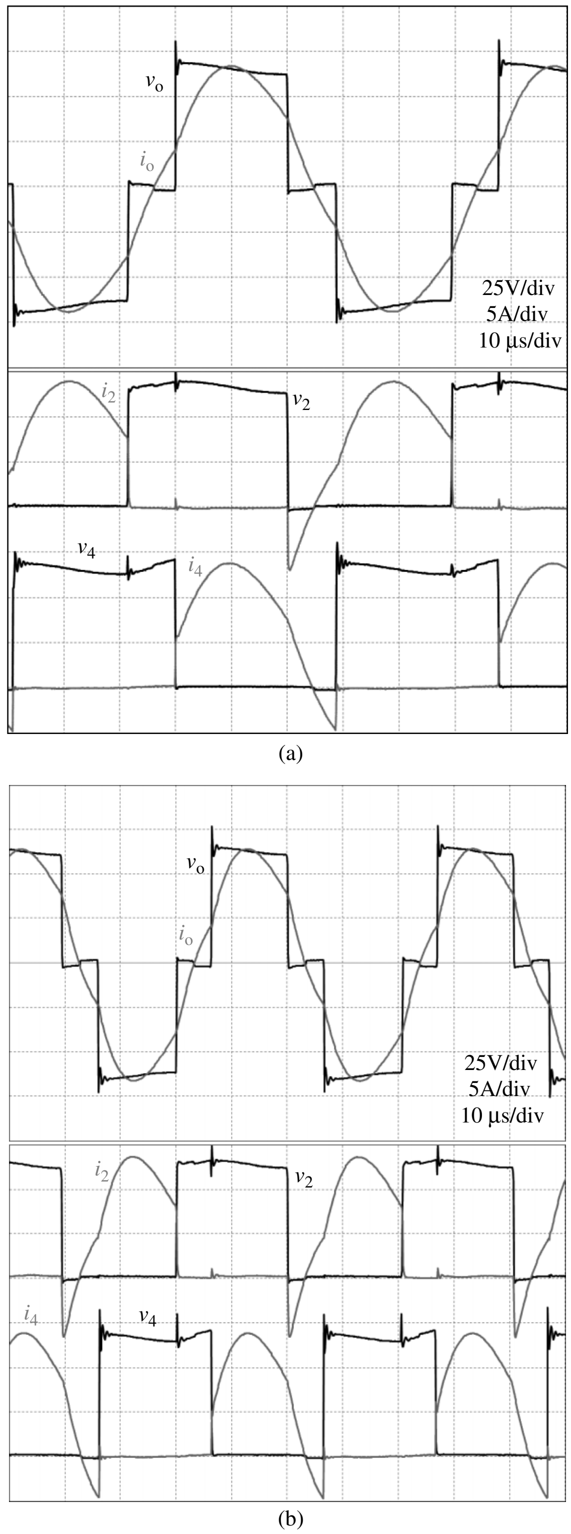

Fig. 11. Observed waveforms of prototype inverter with proposed frequency control (Power = 528 W, Power factor = 0.952). (a) Before changing inductance. (b) After changing inductance

5. Conclusion

In this paper, a simple new control system was proposed that simultaneously achieves a resonant frequency tracking control function and a wide-range power control function with a single high-frequency inverter. The proposed control system enables detection of the control information necessary for operating frequency control with a single current transformer, and thus is a practically effective control technique.

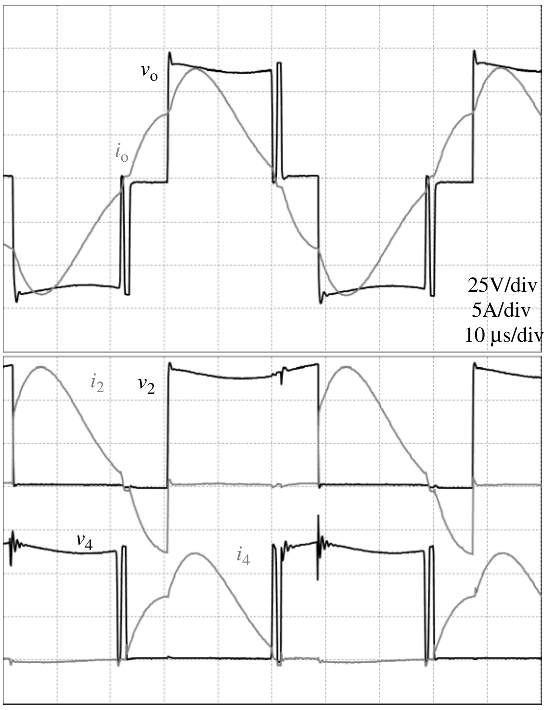

Fig. 12. Observed waveforms of prototype inverter without the proposed frequency control (Power = 451 W, Power factor = 0.838)

This paper has focused on optimal operating frequency control, but a detailed description was not provided of the soft switching of the switching devices, in particular the soft switching method for turning off S1 and S4 and turning on S2 and S3. The soft switching of the phase-shift PWM control inverter, to which the proposed control applies, is explained in Ref. [10], and turning-on and turning-off of all switching devices can be easily achieved by simply adding a small inductance and a capacitor to the main circuit.

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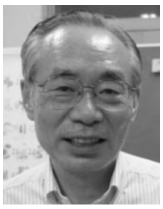

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