Induction Heating PWM High Frequency Inverter using New Active Auxiliary Resonant Snubber

Sang-Pil Mun* · Chil-Ryong Kim · Jong-Kurl Lee · Hong-Sin Kim · Sang-Hwa Jung · Soon-Kurl Kwon**

Abstract

This research presents a new active auxiliary resonant snubber with for induction heating PWM high frequency inverter solving the problem of induction heating PWM high frequency inverter circuit which is using widely in the practical application of an induction heating apparatus, the soft switching operation and power control are impossible when the lowest power supply in the active auxiliary resonant snubber with for induction heating PWM high frequency inverter. The inverter circuit which is attempted by the on-off operation of a switch has the effect of reducing the power loss due to soft switching and high frequency switching. This confirms that power regulation is possible on a continuous basis from 0.25[kW] to 2.84[kW] where the duty factor (D) changes from 0.08 to 0.3 under zero current switching which operates by an asymmetrical pulse width modulating control. The power conversion efficiency is 95[%]. Due to these results, the active auxiliary resonant snubber for an induction heating PWM high frequency inverter is considered effective as a source of induction heating.

Key Words : ZCS PWM, Induction Heating(IH), Induction heating apparatus, Asymmetrical pulse width modulating control

1. Introduction

Due to the advantages of power semiconductor switches such as IGBTs, power MOSFETs,

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MCTs, SITs, and SITHs, research of high-frequency resonant systems that use power semiconductor switches has drawn a great attention [1-7]. With technological advancement in power systems such as load resonant high-frequency inverters and anti-resonance converters, induction heating power high-frequency resonant inverters have been in wide use in industrial areas such as forging, molding, surface hardening, soldering, welding, and dissolving. Heating methods include resistance heating, arc heating, beam heating, and high-frequency induction heating. Specifically, the high-frequency induction heating method is highly

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efficient, reliable, stable, clean, light, and rapid. Furthermore, it has the advantages of stable temperature tracking and accurate temperature control as well. This method is used in cooking pans, warm water systems, dryers, water heaters, fryers, and rice cookers.

Because the induction heating system used in these applications is highly efficient due to the half-bridge high frequency inverter, it is also economical and output and temperature control are conveniently accessed. This system is safe and sanitary as it uses an electromagnetic indirect induction fluid heating system [7-14]. In this study, a new induction heating ZCS PWM SEPP high-frequency inverter has been designed. This paper introduces this inverter and describes the characteristics of electromagnetic induction heating technology, an equivalent electric circuit model of induction heating load, and the way in which to measure the load parameter. In comparison with conventional ZVS PWM SEPP high-frequency inverters, this study has also aimed to expand the soft switching operation range and allow for efficiency for high power conversion in a low power range. Based on the said conditions, this paper has investigated the validity of the induction heating apparatus in the proposed inverter circuit through simulations and experiments.

2. General Induction Heating-related Theories

2.1 Induction heating principle

IH(Induction Heating) is a way of heating metals using electromagnetic induction based on Faraday's Law of Induction. If a coil is wrapped around a conductor such as metal and high-frequency current is applied to the coil, EMF (Electromotive Force) occurs inside of the conductor by Faraday's Law of Induction. This in turn causes an Eddy Current. In an Eddy Current, which flows inside of a conductor, a loss occurs because of resistance on the surface. The Eddy Current loss is converted to heat energy by Joule's Law. As shown in Fig. 1, if a metal rod is placed in a wrapped coil and alternating current is supplied to the coil, flux occurs in the metal rod.

If the metal object is a magnetic substance like an iron, a Hysteresis loop is drawn by the flux against alternation. As a wider area is wrapped by the loop, the Hysteresis loss becomes greater. The Hysteresis loss can be calculated as follows by Steienmetz:

$$P_b = \eta f B_m^{1.6} V \quad [W] \tag{1}$$

Here,
η f : Hysteresis constant, frequency(Hz)
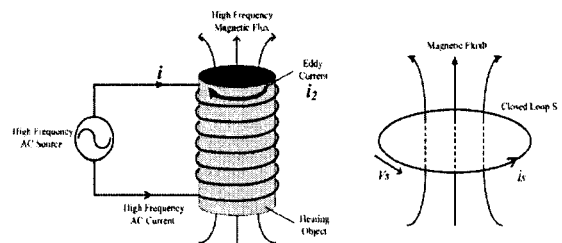B_m: Magnetic flux density [Wb/m^2],
V : Iron core bulk [m^2]

Fig. 1. Principle of High-frequency Induction Heating

Due to electromagnetic induction in a conductor, the induced current is observed in the secondary winding as shown in Fig. 1 above. Therefore, Eddy Current is supplied. However, Eddy Current is not supplied equally to each horizontal part of the metal as shown in Fig. 2 but to the entire surface intensively.

$$I_x = I_0 \, \varepsilon^{-\left(\frac{x}{p}\right)} \varepsilon^{j\left(-\frac{x}{p}\right)} \tag{2}$$

Here,

I_x : Current at x[m] toward the middle from the surface [A]

I_0 : Current on the surface of cylinder metal [A]

$p \, \varepsilon$: Depth of current drop by 1 [m]

$\varepsilon(\because$: natural logarithm)

If the Eddy Current flows in a conductor that has random resistance, Joule heat occurs in the conductor. This is called 'Eddy Current Loss.' This can be stated as follows:

$$P_e = \frac{8\pi^6 \cdot a^4 \cdot f^2 \cdot \mu_r^2 \cdot n^2 \cdot I^2}{\rho} \times 10^{-4} \quad [W/m] \tag{3}$$

Here,

$a \, f$: Radius of iron core [m], frequency [Hz]

$\mu, \rho \, n \, I$: Relative permeability of material [H/m], resistivity [Ω/m], No. of turns on a coil [No. of turns/m], current [A]

In Equation (2), $p \, \mu, \rho \, f$ refer to depth of penetration of high-frequency current set by relative permeability, resistvity [Ω/m], and frequency [Hz] as shown in Equation (4) [7-14].

$$p = \frac{\sqrt{\rho \times 10^7}}{2\pi\sqrt{\mu_r f}} = 503\sqrt{\frac{\rho}{\mu_r f}} \quad p \, f[m] \tag{4}$$

Here,

$\rho \, \mu$: Specific resistance, frequency

μ, μ_r: Relative permeability (General = 1)

In Equation (4), if the specific resistance is converted to [Ω/cm], the equation shall be as follows:

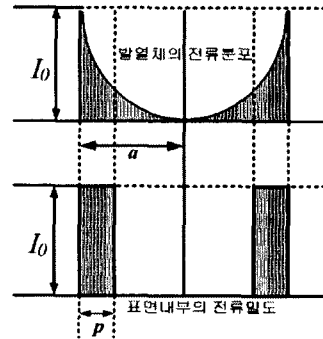$$p = 5.033\sqrt{\frac{\rho}{\mu_r f}}[cm] \tag{5}$$

Fig. 2. Eddy Current Distribution

2.2 Induction heating load and equivalent circuit models

The equivalent models of induction heating load and conventional transformer are similar. Therefore, they can be demonstrated as shown in Fig. 3. In general, to prevent skin effect in a working coil that heats a container, LitzWire is used, which allows coil resistance R_{L1} to be sufficiently reduced. For this reason, it has been ignored in this paper. Because it is difficult to measure secondary circuit constants L_2 and R_2 of a transformer type equivalent circuit model in induction heating load, new parameters k and τ have been defined as shown in Equation (6) below:

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad \tau = \frac{L_2}{R_2}, \tag{6}$$

Here,

τ: Magnetic coupling coefficient

k: Load relaxation time

In Equation (6), therefore, a transformer type equivalent circuit model can be described using a magnetic coupling coefficient (τ), load relaxation time (k), working coil resistance (R_{L1}), and

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magnetic inductance (L_1).

If Equation (3) can be restated for a transformer type equivalent circuit model as follows:

$$v_{L1} = \left\{ \left(R_{L1} + \frac{\omega^2 M^2 R_{\ell}}{R_{\ell}^2 + \omega^2 L_{\ell}^2} \right) + j\omega \left(L_1 - \frac{\omega^2 M^2 L_{\ell}}{R_{\ell}^2 + \omega^2 L_{\ell}^2} \right) \right\} i_{L1} \tag{7}$$

If it is assumed that $R_0 = R_s + R_{L1}$ is a real number and $L_0 = L_s R_0 L_0$ is an imaginary number in Equation (7), the DC equivalent resistance and DC equivalent inductance can be stated as follows:

$$R_0 = R_s + R_{L1} = \frac{\omega^2 M^2 R_{\ell}}{R_{\ell}^2 + \omega^2 L_{\ell}^2} + R_{L1}$$

$$L_0 = L_s = \left(L_1 - \frac{\omega^2 M^2 L_{\ell}}{R_{\ell}^2 + \omega^2 L_{\ell}^2} \right) \tag{8}$$

Using DC equalivaent resistance and DC equalivaent inductance in Equation (8), the transformer type equivalent circuit model in Fig. 3 can be replaced with an RL DC equivalent circuit model in Fig. 4.

3. Proposed ZCS PWM SEPP High-frequency Inverter

3.1 Proposed circuit configuration and operating principle

Fig. 5 demonstrates the ZCS SEPP high-frequency inverter circuit that is widely used in IH apparatus applications. The circuit consists of switches $Q_1(S_1/D_1)$ and $Q_2(S_2/D_2)$, ZCS inductor L_{S1}, the induction heating load, and power factor correction capacitor C_S. Because the time of the power supply mode cannot be set any lower than the auxiliary resonant cycle, the time of the minimum power supply mode becomes greater.
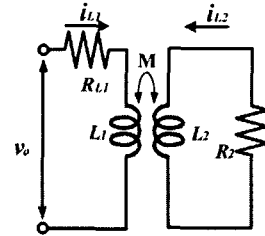

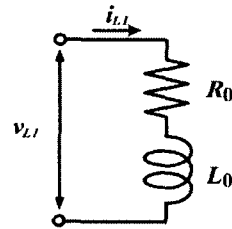Fig. 3. Transformer Type Equivalent Circuit Model

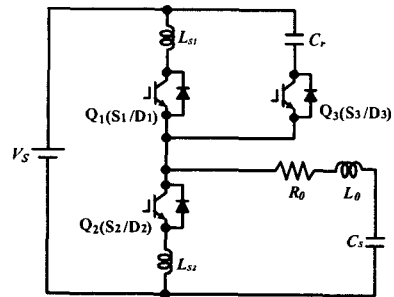

Fig. 4. RL Series Equivalent Circuit Model

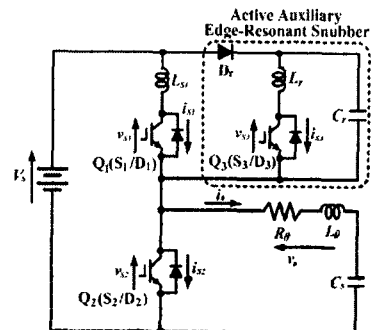Fig. 5. Conventional ZCS PWM SEPP High Frequency Inverter

Fig. 6. Proposed ZCS PWM SEPP High-frequency Inverter

Therefore, soft switching and power control are not be available at 0.5[kW] or below.

To resolve this issue, this study proposes an induction heating ZCS PWM high-frequency inverter that uses an active auxiliary edge-resonant snubber as shown in Fig. 6 above.

The proposed circuit has an active auxiliary resonant snubber circuit-added structure, consisting of auxiliary diode D_r, auxiliary switch $Q_3(S_3/D_3)$, auxiliary resonant inductor L_r, and auxiliary resonant capacitor C_r. If the auxiliary switch S_3 is turned on while switch S_1 is on, partial resonance occurs by ZCS inductor L_r and auxiliary resonant capacitor C_r. A partial auxiliary resonance then independently occurs by auxiliary resonant inductor L_r and auxiliary resonant capacitor C_r because the current on the main switch S_1 is supplied to the anti-parallel diode by force. Therefore, ZVS & ZCS are turned off. Because ZCS can be turned off by the main switch at a certain time, in other words, constant-frequency asymmetrical PWM control is available in an inverter circuit.
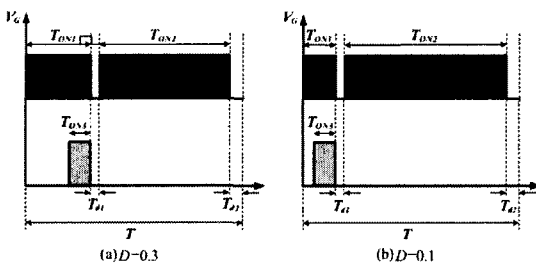

Fig. 7. Constant-frequency Asymmetrical PWM Gate Pulse Sequences

The proposed inverter circuit has a controlled high-frequency AC power supplied to the IH load in accordance with the asymmetrical PWM gate pulse sequences as shown in Fig. 7. If the turn-on time of main switch S_1 (T_{ON1}) during T cycle is authorized, power is consecutively controlled. On the contrary, if the turn-on time of auxiliary switch $S_3(T_{ON3})$ is confirmed, power stays constant. To consecutively control the IH load power by turning off the main and auxiliary switches at the same time, therefore, this paper defines the duty factor (power control variable in PWM mode) as follows:

$$D = \frac{T_{ON1} + T_{d1}}{T} \tag{7}$$

3.2 Simulation results and discussion

Table 1 states the circuit parameters used in the simulation and experiments of the proposed circuit. These parameters are designed in consideration of the output of a high-frequency inverter and the operational range of soft switching. The power factor correction capacitor set load resonant frequency to 21[kHz] under ZCS operation conditions.

Table 1. Circuit Parameters used in Simulation and Experiments

DC input voltage(V_{DC})		282.8[V]
Switching frequency(f_{sw})		20[kHz]
ZCS inductor(L_{S1})		5.6[uH]
Auxiliary resonant inductor(L_r)		2.3[uH]
Auxiliary resonant capacitor(C_r)		90[uF]
Power factor correction capacitor(C_S)		1.0[uF]
Induction heating	Load resistance(R_0)	1.8[Ω]
	Load inductor(L_0)	48[uH]
Model Type	Q_1, Q_2	CM75DU-24F
	Q_3	CM75DU-12F

Fig. 8 demonstrates the operation mode transition of the proposed high-frequency inverter circuit and the equivalent circuit of each operation

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mode. Each operation mode shall be as follows:

(1) Mode 0 ($t_{12} - t_0$)

Mode 0 is the mode in which DC load resonance occurs through anti-parallel diode (D_2) → IH load (R_0) → inductor (L_0) → power factor correction capacitor (C_S).

(2) Mode 1 ($t_0 - t_1$)

Mode 1 is the mode in which current on the anti-parallel diode D_2 is supplied to a main switch S_1 if the main switch S_1 turns on. The switch current i_{S1} rises smoothly by ZCS inductor L_{S1} and the main switch S_1 executes the ZCS turn-on operations. If the current of anti-parallel diode D_2 becomes 0 at t_1, Mode 1 transitions to Mode 2.

(3) Mode 2 ($t_1 - t_2$)

Mode 2 is the mode through which power is supplied from DC input voltage V_s to the load via the main switch S_1. DC load resonance then occurs through ZCS inductor L_{S1} → IH load (R_0) → inductor (L_0) → power factor correction capacitor (C_S).

(4) Mode 3 ($t_2 - t_3$)

Mode 3 is the mode in which auxiliary switch S_3 turns on. Auxiliary resonant capacitor C_r is then discharged and auxiliary partial resonance occurs through auxiliary switch S_3 → auxiliary resonant inductor L_r → auxiliary resonant capacitor C_r. The auxiliary switch current i_{S3} rises smoothly by auxiliary resonant inductor L_r and auxiliary switch S_3 executes the ZCS turn-on operations. In Mode 3, the voltage of the auxiliary resonant capacitor C_r becomes 0 at t_2. If the auxiliary diode D_r is conducted, Mode 3 transitions to Mode 4.

(5) Mode 4 ($t_3 - t_4$)

Mode 4 is the mode in which auxiliary diode D_r

is conducted. The auxiliary partial resonance occurs through auxiliary resonant capacitor C_r → ZCS inductor L_{S1} → auxiliary resonant inductor L_r while the main switch current i_{S1} and the auxiliary switch current i_{S3} decrease. If the main switch current i_{S1} becomes 0 at t_4, Mode 4 transitions to Mode 5.

(6) Mode 5 ($t_4 - t_5$)

Mode 5 is a mode in which auxiliary partial resonance occurs by ZCS inductor L_{S1} and auxiliary resonant capacitor C_r. The main switch current i_{S1} becomes 0 and the reverse diode D_1 is conducted. If the auxiliary switch current i_{S3} becomes 0 at t_5, Mode 5 transitions to Mode 6.

(7) Mode 6 ($t_5 - t_7$)

Mode 6 is a mode in which auxiliary partial resonance occurs by auxiliary resonant inductor L_r and auxiliary resonant capacitor C_r. The auxiliary switch current i_{S3} becomes 0 and the reverse diode D_3 is conducted. If the auxiliary resonant current on the reverse diode D_3 becomes 0 at t_7, Mode 6 transitions to Mode 7. Then, the main switch S_1 and auxiliary switch S_3 simultaneously perform the ZCS & ZVS turn-off operations at t_6.

(8) Mode 7 ($t_7 - t_8$)

Mode 7 is a mode in which auxiliary partial resonance occurs by ZCS inductor L_{S1} and auxiliary resonant capacitor C_r during $t_7 - t_8$ and auxiliary resonant capacitor C_r is charged. If the current on the reverse diode D_1 becomes 0 at t_8, Mode 7 transitions to Mode 8.

(9) Mode 8 ($t_8 \sim t_9$)

Mode 8 is a mode in which load resonance occurs by auxiliary diode D_r through auxiliary resonant capacitor C_r → IH load R_0 → inductor L_0 → power factor correction capacitor C_S. Voltage
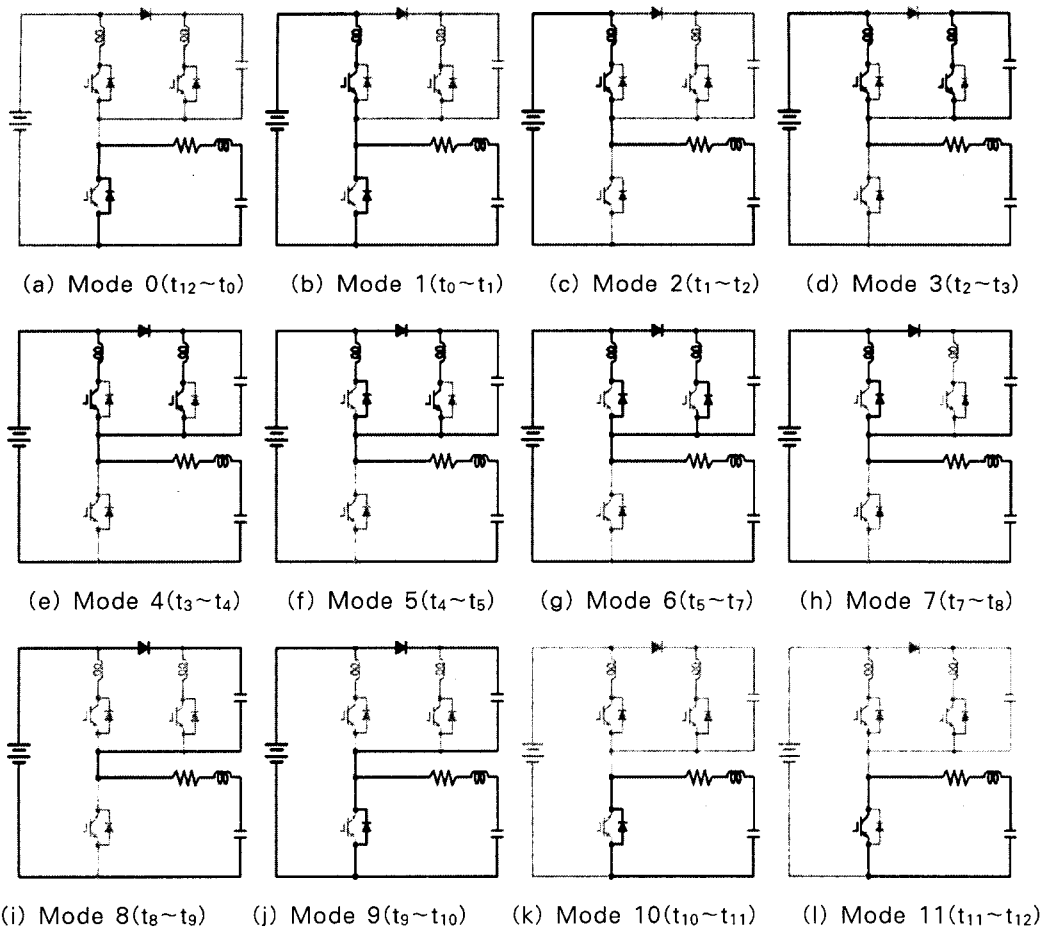
(a) Mode 0($t_{12}\sim t_0$)   (b) Mode 1($t_0\sim t_1$)   (c) Mode 2($t_1\sim t_2$)   (d) Mode 3($t_2\sim t_3$)

(e) Mode 4($t_3\sim t_4$)   (f) Mode 5($t_4\sim t_5$)   (g) Mode 6($t_5\sim t_7$)   (h) Mode 7($t_7\sim t_8$)

(i) Mode 8($t_8\sim t_9$)   (j) Mode 9($t_9\sim t_{10}$)   (k) Mode 10($t_{10}\sim t_{11}$)   (l) Mode 11($t_{11}\sim t_{12}$)

Fig. 8. Equivalent circuits of each operation mode in proposed inverters

VCr of auxiliary resonant capacitor C_r is then charged to input voltage V_s. If the reverse diode is conducted to t_9, Mode 8 transitions to Mode 9.

(10) Mode 9 ($t_9 - t_{10}$)

Mode 9 is a mode in which the reverse diode D_2 is conducted. The main switch S_2 is then turned on while the reverse diode D_2 is conducted and auxiliary resonant capacitor C_r is charged. If the current of diode D_r becomes 0, Mode 9 transitions to Mode 10.

(11) Mode 10 ($t_{10} - t_{11}$)

Mode 10 is a mode in which the main switch S_2

is turned on while the reverse diode D_2 is conducted. Main switch S_2 performs the ZCS & ZVS turn-on operations after the current is naturally commuted to the main switch S_2 from the reverse diode D_2 by load resonance.

(12) Mode 11 ($t_{11} - t_{12}$)

Mode 11 is a mode in which DC load resonance occurs by main switch S_2 through IH load $R_0 \rightarrow$ inductor $L_0 \rightarrow$ power factor correction capacitor C_s. Then, if current is naturally commuted to reverse diode D_2 from the main switch S_2 by load resonance, it transitions to Mode 0 and the operation is repeated.

Fig. 9 and Fig. 10 below demonstrate the voltage and current waveforms when the duty factor is 0.3 and 0.1, respectively. Fig. 11 shows each waveform when switch S_1 engages in turn-off operations ($t_2 - t_{11}$).
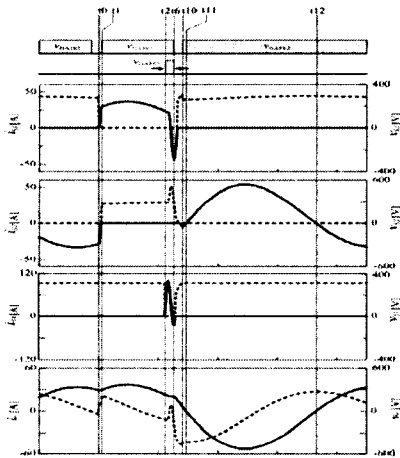

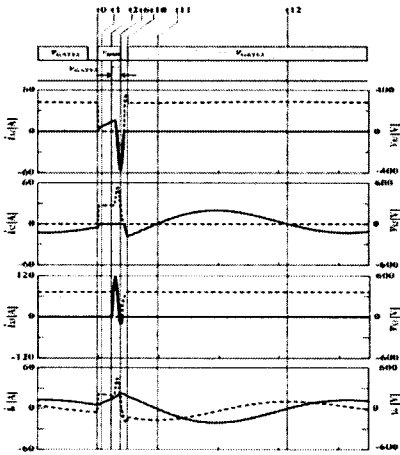**Fig. 9. Simulation waveforms of each voltage and current of proposed inverter(at D=3)**

Fig.10. Simulation waveforms of each voltage and current of proposed inverter(at D=0.1)
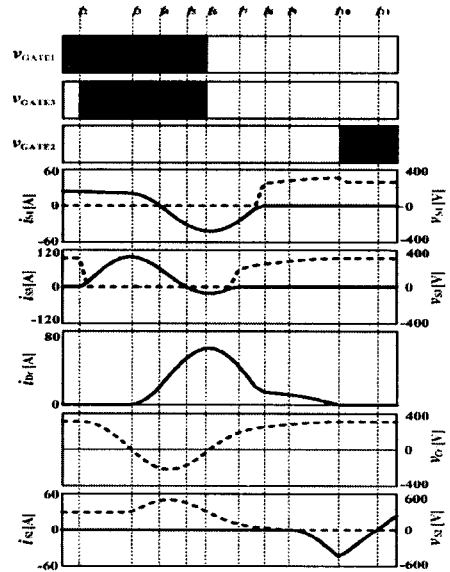
3.3 Experimental results and discussion

Fig. 12 and Fig. 13 describe the waveforms of

Fig. 11. Waveforms of each voltage and current between t_2 and t_{11}

each voltage and current of the proposed inverter circuit under different duty factors. The on-off operations for each switch as shown in Fig. 12 and Fig. 13 can be summarized as follows:

First, if the main switch S_1 is on, current rises smoothly via ZCS inductor L_s and ZCS turns on. On the contrary, if the main switch is off, ZVS & ZCS turn off while reverse diode D_1 is conducted.

Second, because the main switch S_2 turns off while reverse diode D_2 is conducted, ZVS & ZCS operate during both turn-off and turn-on situations.

Third, if auxiliary switch S_3 is on, current rises smoothly via auxiliary resonant inductor L_r and ZCS turns on. On the contrary, if the auxiliary switch is off, ZVS & ZCS turn off while reverse diode D_1 is conducted.

In sum, it was confirmed that power loss is reduced by soft switching and high-frequency switching throughout all operations in the inverter circuits proposed by three switch on-off operations.
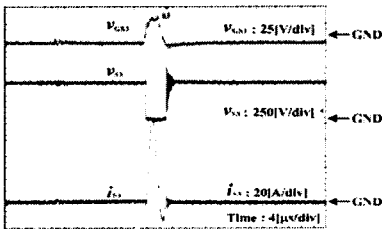
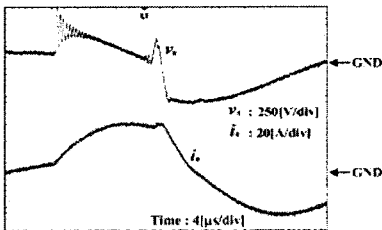Induction Heating PWM High Frequency Inverter using New Active Auxiliary Resonant Snubber
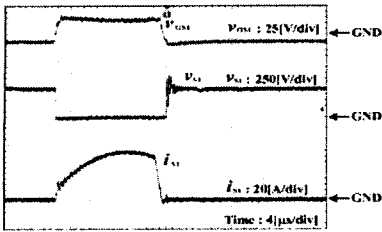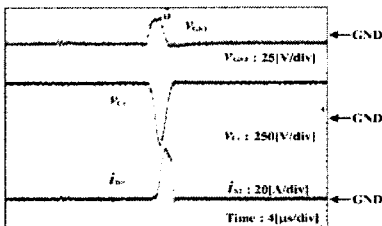
(a) Waveforms of voltage and current of switch Q₁
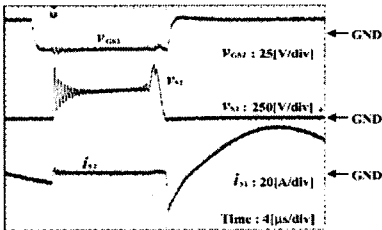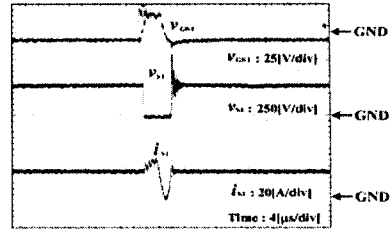
(b) Waveforms of voltage and current of switch Q₂
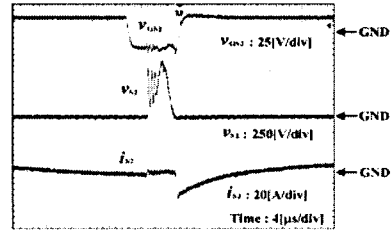
(c) Waveforms of voltage and current of switch Q₃

(e) Waveforms of voltage and current of IH load
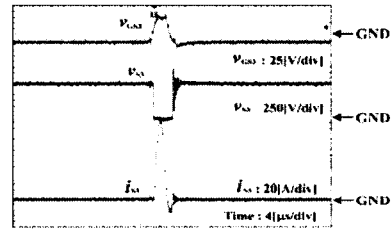
(f) Waveforms of voltage and current of Q₁ Cᵣ and Dᵣ

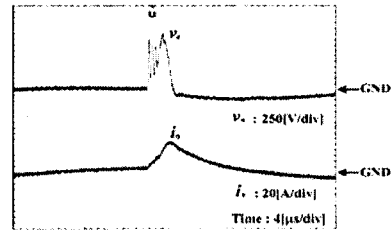Fig. 12. Experimental waveforms of each voltage and current (at D=0.3)
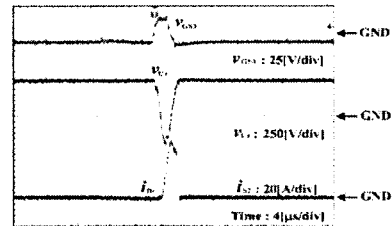
(a) Waveforms of voltage and current of switch Q₁

(b) Waveforms of voltage and current of switch Q₂

(c) Waveforms of voltage and current of switch Q₃

(e) Waveforms of voltage and current of IH load

(f) Waveforms of voltage and current of Cᵣ and Dᵣ

Fig. 13. Experimental waveforms of each voltage and current (at D=0.08)

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Fig. 14 demonstrates the characteristics of power input and output by the duty factor of a ZCS PWM SEPP high-frequency inverter. In the proposed high-frequency inverter, as shown in Fig. 14, power regulation is possible continuously from 0.25[kW] until 2.84[kW] where the duty factor (D) changes from 0.08 to 0.3 while ZCS is on by asymmetrical PWM. In the proposed inverter circuit, it has been confirmed that power is consecutively controllable with a wide range for IH apparatus applications.

Fig. 15 describes the characteristics of efficiency of the power conversion in the proposed ZCS PWM SEPP high-frequency inverter. In the figure, it can be observed that even though high efficiency (95[%]) was observed at the maximum power 2.84[kW], efficiency decreased somewhat at low power. Because the auxiliary switch operates constantly regardless of the duty factor at low electricity, the fixed loss of an active auxiliary resonant snubber circuit becomes greater than the total system power.

Fig. 16 compares efficiency characteristics for the input power of both the proposed and conventional ZCS PWM SEPP high-frequency inverters. Because power supply mode time cannot be set to a lower level than the auxiliary partial resonant cycle in the conventional ZCS PWM SEPP high-frequency inverter, as shown in the figure, the minimum power supply mode time becomes greater. If power is set to 0.5[kW] or lower, soft switching will not be available. In the proposed high-frequency inverter, on the contrary, the auxiliary partial resonant cycle can be set with the active auxiliary resonant snubber circuit only. Therefore, the minimum power supply mode time may be lowered. Because consecutive control is possible with constant frequency using the asymmetrical PWM method, soft switching is available up to 0.25[kW] in IH apparatus

applications. Because highly efficient high-frequency power can be supplied to the IH load, it may be the best power conversion system for IH apparatus applications.
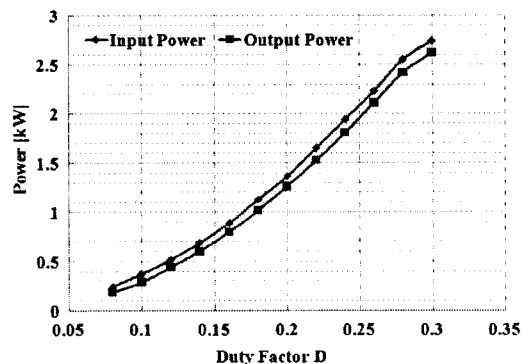

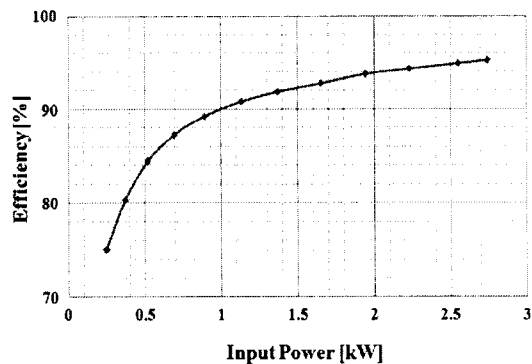Fig. 14. Input & Output Power Characteristics for duty factor

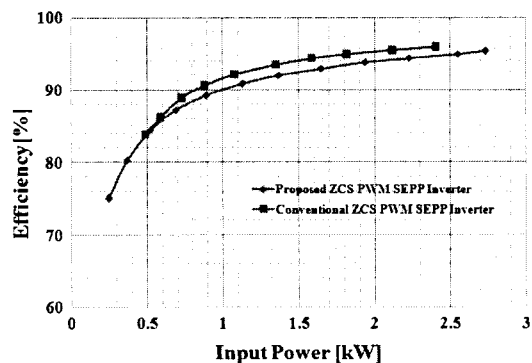Fig. 15. Efficiency for Input Power Characteristics

Fig. 16. Efficiency Characteristics for Input Power

4. Conclusion

This paper has proposed an induction heating ZCS PWM high-frequency inverter using a new active auxiliary resonant snubber in order to resolve issues (i.e., difficult soft switching and power control at a minimum power supply) that occur in ZCS SEPP high-frequency inverter circuits, which are widely used in IH apparatus applications. The following results were found:

(1) The characteristics of an electromagnetic induction heating system, the equivalent circuit model of an induction heating load, and how to measure load parameters are stated.

(2) It was determined that the inverter circuit proposed by switch on-off operations reduced power loss by soft switching and high-frequency switching throughout the entire operation.

(3) It was determined that constant power regulation is possible from 0.25[kW] to 2.84[kW] where the duty factor (D) changes from 0.08 to 0.3 under zero current switching operating by an asymmetrical pulse width modulating control. Therefore, it was found that power can be consecutively controlled with a wide range in IH apparatus applications.

(4) In terms of the efficiency of power conversion in induction heating ZCS PWM high-frequency inverters using the proposed active auxiliary resonant snubber, although high efficiency (95[%]) was observed at the maximum power 2.84[kW], efficiency decreased somewhat at low power. Because the auxiliary switch operates constantly regardless of the duty factor at low electricity levels, the fixed loss of active auxiliary resonant snubber circuit becomes

greater than the total system power.

(5) In the proposed high-frequency inverter, the auxiliary partial resonant cycle can be set with the active auxiliary resonant snubber circuit only. Therefore, the minimum power supply mode time can be lowered. Because consecutive control is possible with constant frequency using an asymmetrical PWM method, soft switching is available up to 0.25[kW] in IH apparatus applications.

Due to these results, the active auxiliary resonant snubber for induction heating with a PWM high frequency inverter will be effective as a power source for induction heating equipment.

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