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Basic Study of a Phase-Shifted Soft Switching High-Frequency Inverter with Boost PFC Converter for Induction Heating

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ABSTRACT

This paper is mainly concerned with a high frequency soft-switching PWM inverter suitable for consumer induction heating systems. The proposed system is composed of a soft switching chopper based boost PFC converter stage with passive snubber and phase shifted PWM controlled full bridge ZVZCS high frequency inverter stage. Its fundamental operating performances are illustrated and evaluated in the experimental results. Its effectiveness is substantially proved on the basis of the experimental results from a practical point of view.

Keywords: Induction heating, Soft switching, High frequency power converter, Passive power factor correction

1. Introduction

In recent years, electromagnetic induction current based heat energy processing appliances using high frequency power conversion circuits have attracted special interest for consumer food cooking and processing applications. High frequency induction heating built-in appliances have been in development for consumer home use and business use in mass production for food cooking. The use of Industrial Heating (IH) for consumer home use and business use in food cooking power systems are indispensable when heating various metallic pans, such as aluminum, copper, stainless steel, iron cast and so on. High frequency switching is one solution for this problem. However, as the switching frequency becomes higher, the effective resistance of metallic materials, such as stainless steel and iron, becomes greater so as to supply sufficient cooking power.

To adapt various metallic pans, there are many approaches such as effectively using third harmonic currents, etc. Furthermore, it is important to correspond with the utility AC side current harmonic regulations of various countries.

In this paper, a phase-shifted soft switching high frequency inverter with a boost PFC converter is newly proposed for consumer cooking and processing appliances. The proposed system consists of two power stages, a voltage boost with PFC functional soft switching chopper stage for adapting various metallic materials and operating a phase-shifted high frequency inverter with ZVS and ZCS legs stage. The feasible operating characteristics of the proposed power system using IGBTs are evaluated and illustrated on the basis of simulation and experimental results.

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2. Induction Heated Cooking Appliance

Fig. 1 shows the schematic configuration of an IH cooking appliance. A high frequency inverter supplies high frequency current to a planer working coil, then inducted eddy currents directly flow into the pan or vessel on the basis of Faraday's electromagnetic induction law. For this reason, the IH method is able to realize high thermal conversion efficiency cooking. In the meantime, in case of a multi-burner type IH cooking heater, it is preferable to control the output power of each burner under constant frequency, because of a rising beat sound from the operating frequency differences of each inverter. This means the constant frequency power regulation method is indispensable for IH cooking appliances. Furthermore, to reduce input current harmonics, the soft switching voltage boost PFC converter stage is connected to reduce input current harmonics and meet regulations.

3. Circuit Description of High Frequency Soft-Switching Inverter with Boost PFC Converter

Fig. 2 represents the circuit configuration of the newly proposed power supply using a high frequency soft-switching phase-shift PWM inverter (HF-INV) with boost PFC converter. This circuit topology consists of a boost PFC stage comprising low pass filter L_f and C_f, boost inductor L_1, switching device Q_1 (S_1/ D_1) with its

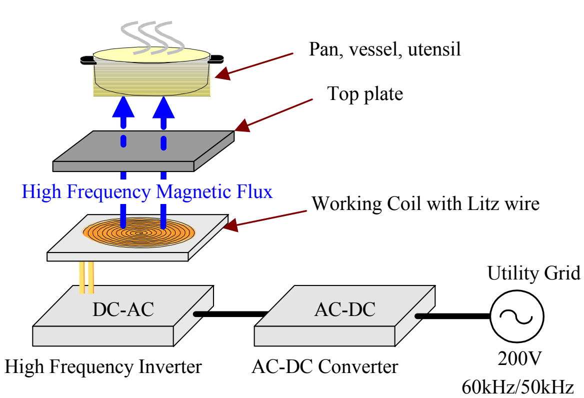


Fig. 1 A schematic configuration of IH cooking heater using power electronics circuit

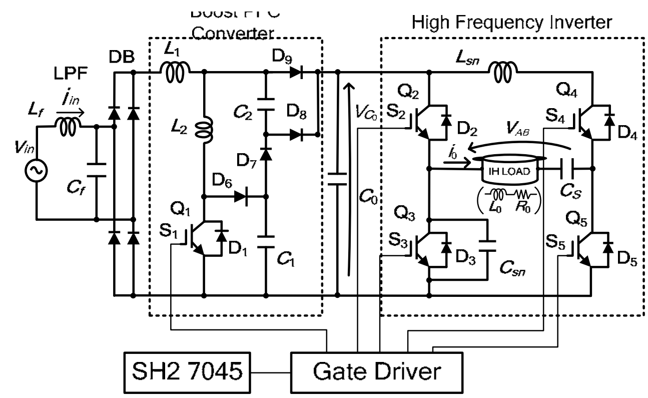


Fig. 2 Proposed phase-shifted soft switching high frequency inverter with boost PFC converter

lossless snubber inductor L_2 and lossless snubber capacitor C_1, C_2, intermediate DC smoothing capacitor C_0 and so on. Additionally, the high frequency inverter stage comprises ZVS side switching devices Q_2 and Q_3, lossless snubber capacitor C_{sn}, ZCS side switching devices Q_4 and Q_5, and lossless snubber inductor L_{sn}. The induction heated load with working coil is described as L_0 & R_0 with a series capacitor C_s. In addition, the commercial AC oriented lower frequency current components through the working coil is designed to be eliminated by intermediate DC smoothing capacitor C_0. The switching frequency of the proposed circuit is 60kHz.

High frequency output power to the IH load can be regulated by controlling the switching phase angle ϕ of the high frequency inverter stage, as well as intermediate DC voltage V_{Co} , which can be controlled by the boost PFC converter stage mentioned in the following subscripts.

3.1 Operation principle of phase-shifted high frequency inverter stage

Fig. 3 and Fig. 4 explain the circuit operation principle of the soft switching phase-shifted PWM inverter stage. This circuit includes ten operation modes during one switching period. Switching devices Q_2 and Q_3 in the current lagging leg operate under the conditions of ZVS & ZCS turn on and ZVS turn off by the lossless snubber capacitor C_{sn}. On the other hand, switching devices Q_4 and Q_5 in the current leading leg operate under ZCS turn on assisted by lossless snubber inductor L_{sn}, and ZCS & ZVS turn on.

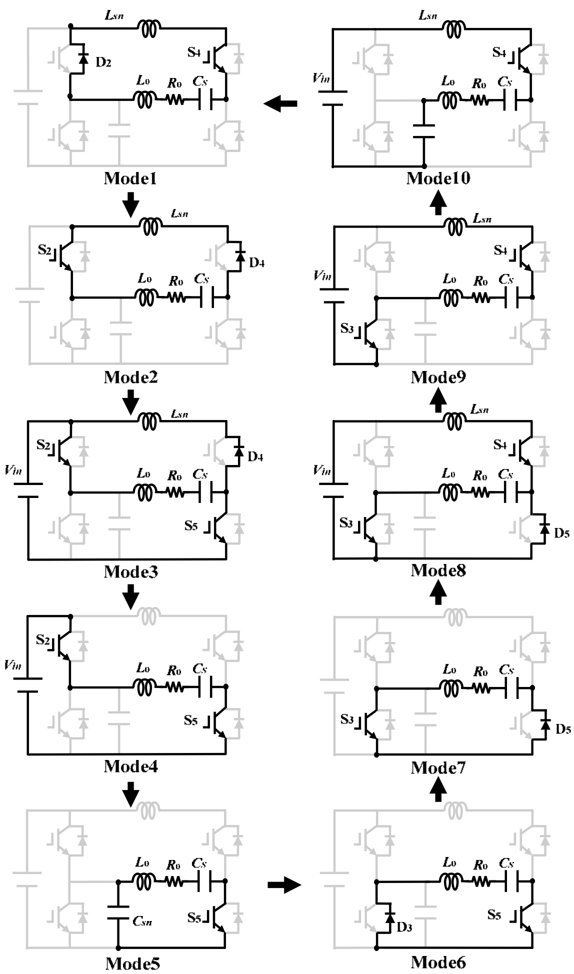


Fig. 3 Operating mode transitions and equivalent circuit of the phase shifted PWM inverter stage

The high frequency output power is regulated by the phase shift angle ϕ as shown in this figure.

The circuit operation in each operating mode is simply described as follows,

Mode1 : The switch S_4 is turned on under ZCS condition. The current begins to flow through the resonant circuit as S_4-Cs-R_0-L_0-D_2-L_{sn} loop. The gate signal of S_2 turns on while D_2 is conducting.

Mode2 : Due to load resonance, the current flowing to S_4 turns to zero and then the regenerative current flows through anti-parallel diode D_4. The gate signal of S_4 is turned off under ZVS&ZCS condition.

Mode3 : Switch S_5 is turned on. The current through D_4 reaches zero linearly due to continuous current of the lossless snubber inductor L_{sn}. This current has a gradient of constant value. Therefore S_5 is turned on under ZCS condition with the assistance of lossless snubber inductor L_{sn}.

Mode4 : Both switches S_2 and S_5 are conducting. The high frequency power is supplied from the DC voltage source to the load.

Mode5 : When switch S_2 is turned off, time point t_4, the lossless snubber capacitor C_{sn} starts to discharge. Therefore, S_2 is turned off under ZVS condition.

Mode6 : When C_{sn} is fully discharged, the current flows through the resonant loop S_5-D_3-L_0-R_0-C_s. At this time, the gate signal S_3 is turned on.

Mode7 : Due to the circuit resonance, the current through S_5 turns to zero and then the regenerative current flows through the anti-parallel diode D_5. The gate signal of S_5 is turned off under ZVS&ZCS condition.

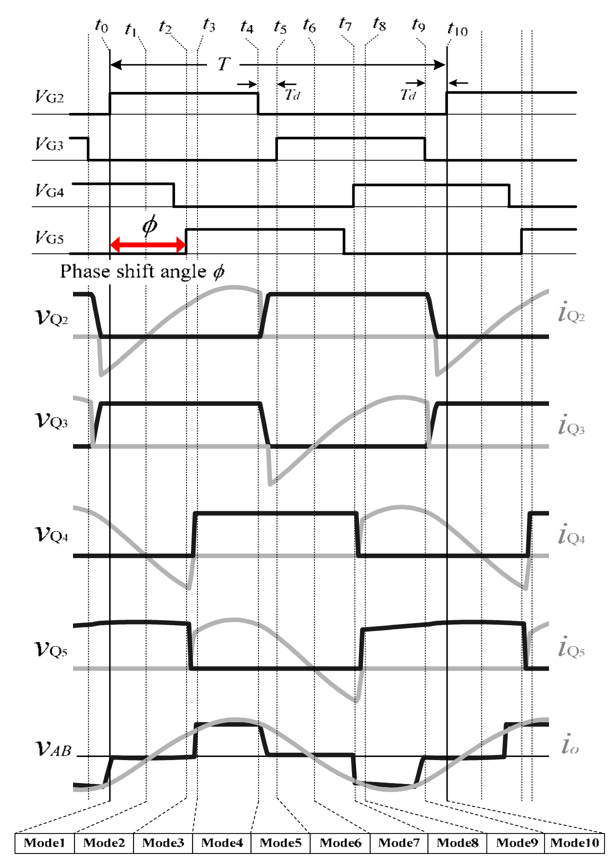


Fig. 4 Circuit waveforms of the phase shifted PWM inverter stage

Mode8 : Switch S_4 is turned on with ZCS condition. At the same time, the current through D_5 starts to decrease.

Mode9 : Both S_4 and S_3 are on state. The IH power is supplied from the DC voltage source to the IH load.

Mode10 : S_3 is turned off at the time point t_9 with ZVS condition by the assistance of the lossless snubber capacitor C_{sn}.

3.2 Operation principle of boost PFC converter stage

The primarily connected voltage boost PFC converter stage has two functions. One is power factor correction of the total system with discontinuous current mode operation; the other is the additional output power regulation for various metallic pans and kettles, by boosting intermediate voltage V_{Co}. This circuit stage includes 10 operating modes during one switching period, as shown in Fig. 5 and Fig. 6. In these figures, the following high frequency inverter stage with IH load is described as simple resistance R_S. The circuit operation in each operating mode is simply described as follows:

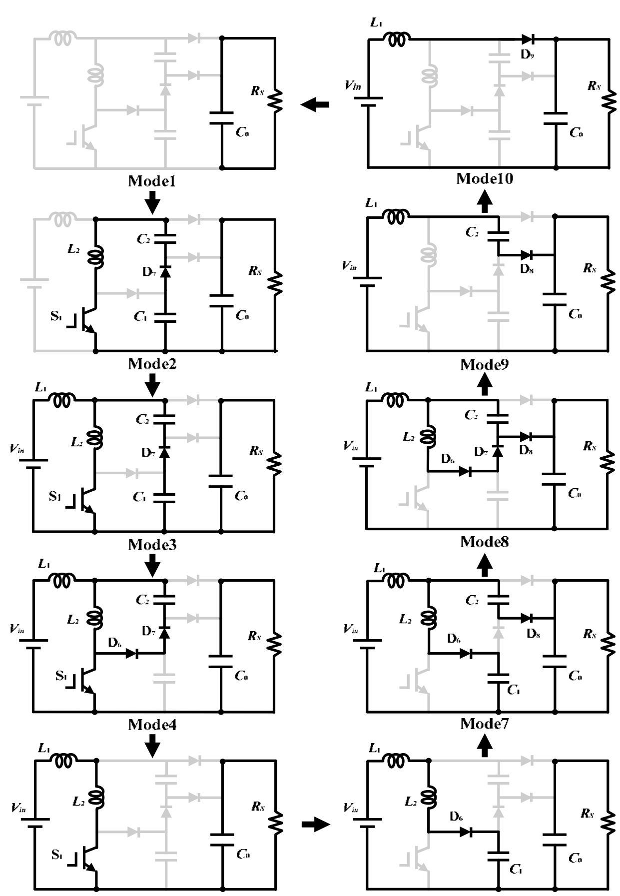


Fig. 5 Operating mode transitions and equivalent circuit of the boost PFC converter stage

Mode1 : At time point t_0, the boost inductor current is zero. So current only flows to resistance R_S and intermediate capacitor C_O. Then, capacitor C_1 is charged to output voltage V_{Co}, but capacitor C_2 is discharged.

Mode 2 : Switch S_1 is turned on with ZCS condition at t_1 and then C_1 starts to discharge through C_1-C_2-L_2-S_1 loop as shown in Fig. 5, producing a sinusoidal resonant current. The current of S_1 increases gradually by the effect of the lossless snubber inductor L_2.

Mode 3 : At time point t_2, the boost inductor current increases gradually. As a result, the current through inductor L_2 contains both the current of inductor L_1 and the resonant current.

Mode 4 : The voltage across capacitor C_1 reaches zero at time point t_3. The current starts flowing through the L_1-D_6-D_7-C_2 loop.

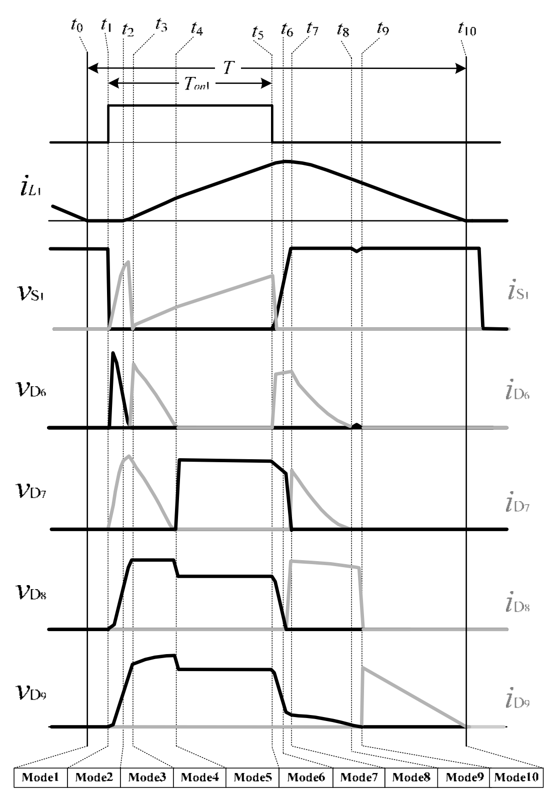


Fig. 6 Circuit waveforms of the boost PFC converter stage

Mode 5 : When C_2 is fully charged, switch current i_{S1} is equal to inductor current i_{L1}. The turn-on commutation process is completed. The converter circuit works as a conventional boost chopper type converter circuit.

Mode 6 : At time point t_5, active power switch S_1 is turned off. The current starts to charge capacitor C_1 through D_6. So switch S_1 is turned off under ZVS condition with the assistance of lossless snubber capacitor C_1.

Mode 7 : When the voltage across C_1 reaches to the output voltage V_{Co}, C_2 start to discharge through D_3. C_1 is still charged by the inductor current i_{L2}.

Mode 8 : When the capacitor C_1 voltage is charged up to the output voltage V_{Co} at time point t_8, i_{L2} flows through D_6-D_7-D_8. Thus, the current through L_2 decreases continuously.

Mode 9 : When the inductor current i_{L2} becomes zero, the current i_{L1} flows to C_2 via D_7.

Mode 10: When the voltage across C_2 goes to zero at time t_9, inductor current i_{L1} flows into R_S and Co through D_9.

In this operation principle, the boost switching device S_1 can operate under the condition of ZCS turn on and ZVS turn off.

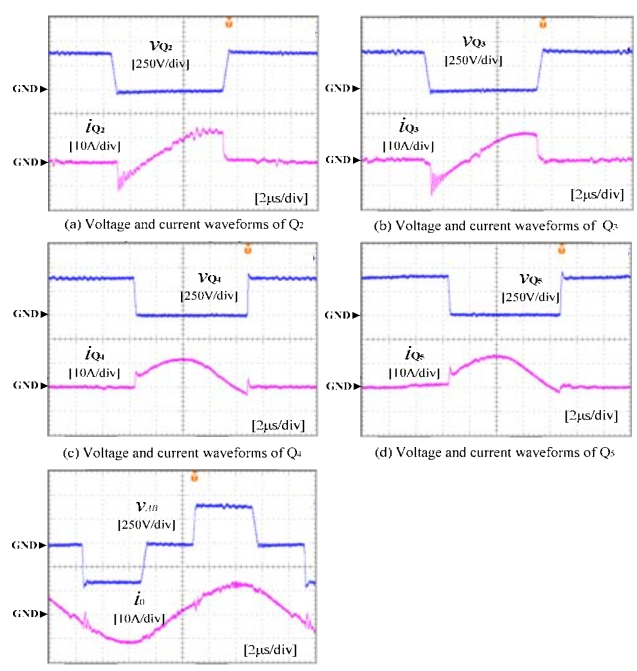
4. Steady state operating performance

To verify the performances of the proposed IH system, an experimental prototype was built and tested. The circuit parameters of the prototype are listed in Table 1. Two different materials based flat-bottomed pans were tested, a stainless steel pan, 18cm diameter, and a copper pan, 16cm diameter. The measured equivalent parameters of these pans are depicted in Table 1. Switching device; IGBTs in the inverter stage are trench gated 2 in 1 modules (Mitsubishi CM100DUS-12F), on the contrary, Mitsubishi CM100DY-24NF was selected for the boost PFC converter stage.

Fig. 7 (a) to (e) show the experimental waveforms of the phase-shifted HF inverter stage with the stainless steel pan, when the duty cycle of the PFC converter stage D = 0.26 and phase shift angle ϕ = 70 degrees. In this condition,

Table 1 Experimental circuit parameters

Item		Symbol	Value
Utility AC side Voltage		v_{in}	200V
Utility AC Frequency		f_{in}	60Hz
Switching Frequency		f_{SW}	60kHz
Filter Capacitance in Utility AC side		C_f	5μF
Filter Inductance in Utility AC side		L_f	900μH
Boost PFC Converter			
Boost Inductance		L_1	28μH
Lossless Snubber Inductance		L_2	2μH
Lossless Snubber Capacitance		C_1	0.043μF
Lossless Snubber Capacitance		C_2	0.7μF
DC Filter Capacitance		C_0	3900μF
Phase Shift High Frequency Inverter			
Lossless Snubber Inductance		L_{sn}	2μH
Lossless Snubber Capacitance		C_{sn}	0.01μF
Power Factor Compensation Capacitance		C_s	0.032μF
Load1 (Stainless steel pan)	Load Inductance	L_0	242.3μH
	Load Resistance	R_0	25Ω
Load2 (Copper pan)	Load Inductance	L_0	216μH
	Load Resistance	R_0	1.8Ω
Q1 :CM100DY-24NF(MITSUBISHI)			
Q2-Q5 :CM100DUS-12F(MITSUBISHI)			



(a) Voltage and current waveforms of Q2
(b) Voltage and current waveforms of Q3
(c) Voltage and current waveforms of Q4
(d) Voltage and current waveforms of Q5
(e)Voltage v_{AB} and current i_o waveforms

Fig. 7 Experimental voltage and current waveforms of phase shift HF-inverter stage (ϕ=70 degree) the intermediate DC voltage is 400 V, and input power is 2.45 kW. From Fig. 7 (a) and (b), it is clear that IGBT switching devices in the current lagging leg turn on under ZVS and ZCS turn on, and ZVS turns off as an effect of lossless snubber capacitor C_{sn}. From Fig. 7 (c) and (d), Q_4 and Q_5 in the current leading leg turn on under ZCS condition with the assistance of lossless snubber inductor L_{sn}, and ZCS & ZVS turn off. As a result, switching losses in each IGBT is dramatically decreased. Observed slight current spikes in Fig. 7 (c) and (d) are caused by the recovery current of the anti-paralleled diode connected to each IGBT switch.

Fig. 8 illustrates the operating waveforms of the boost PFC converter. From Figure 8 (a), boost switch Q_1 turns on under the condition of ZCS and turns off under the condition of ZVS, though slight turn off loss caused by tail current of the IGBT appeared in this figure. Observed voltage and current ringing may be mainly caused by the stray inductance in the hand-made circuit construction. The manufacture-based robust circuit design may be able to solve this problem.

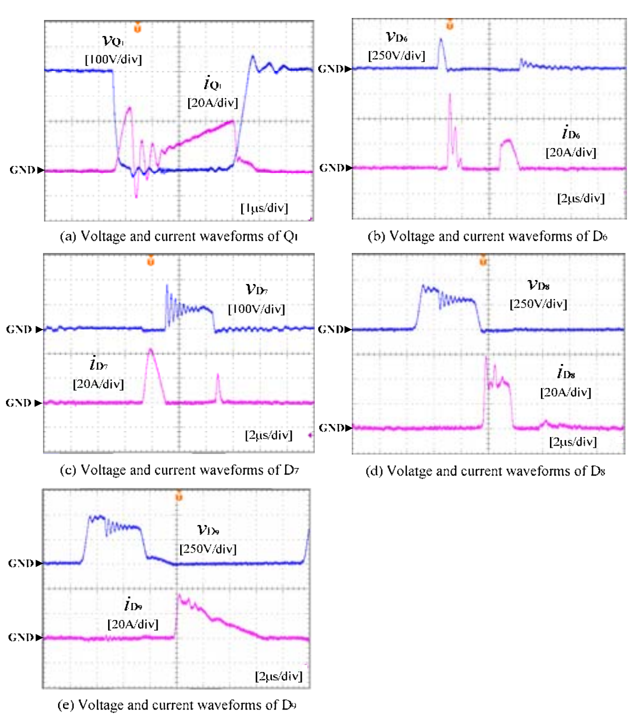


Fig. 8 Experimental voltage and current waveforms of boost PFC converter stage (D=0.26)

Fig. 9 shows the characteristics for power regulation by input power against duty factor D at the PFC converter stage and phase shift angle ϕ at the high frequency inverter stage. As seen in this figure, input power of the proposed inverter with Load 1 (stainless steel pan) can be regulated continuously from 0.5 to 2.45 kW by increasing the intermediate DC voltage boosted with PFC stage as well as by controlling the phase angle ϕ. On the contrary, in the case of Load 2 (copper pan) as IH load, the continuous power regulation area is 0.5 to 1.7 kW. The limitation of the output power 1.7 kW is the absolute ratings of the IH coil.

The power conversion efficiency in the proposed circuit vs. input power is shown in Fig. 10. From this figure power conversion efficiency at a condition of Pin = 2.45 kW with stainless steel pan is 81.7 %.

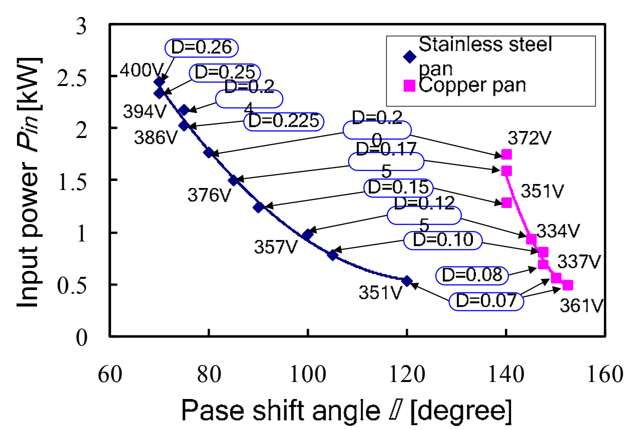


Fig. 9 Input power regulation characteristics and intermediate voltage

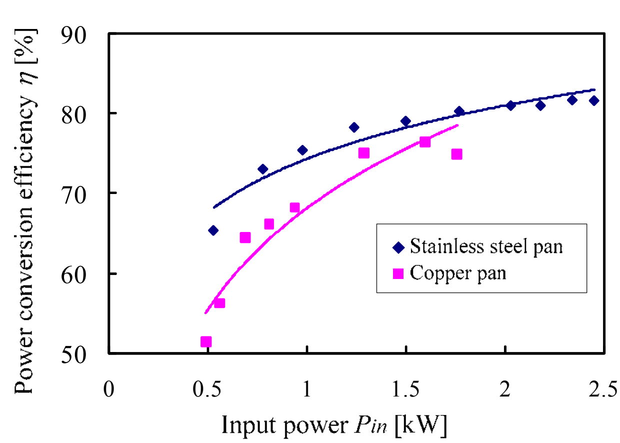


Fig. 10 Power conversion efficiency

Fig. 11 depicts the experimental waveforms of the input AC current controlled by the PFC stage with discontinuous current mode. Boost inductor current peak in each sampling period in Figure 11 (a) is settled by an input AC utility grid voltage. Fig. 11 (b) shows a magnified current waveform at the peak point. In this condition, Fig. 11 (c) indicates the relations between the AC utility grid voltage and the current of the total IH DCM operation is kept even. Fig. 12 depicts the utility AC side current harmonics analysis results comparison with current harmonics regulation (IEC61000-3-2, class A).

From these results, the third harmonics of the utility AC side current dose not meet regulations. To meet harmonic regulations perfectly, anti-third harmonic injected duty factor control in the boost PFC converter may be necessary.

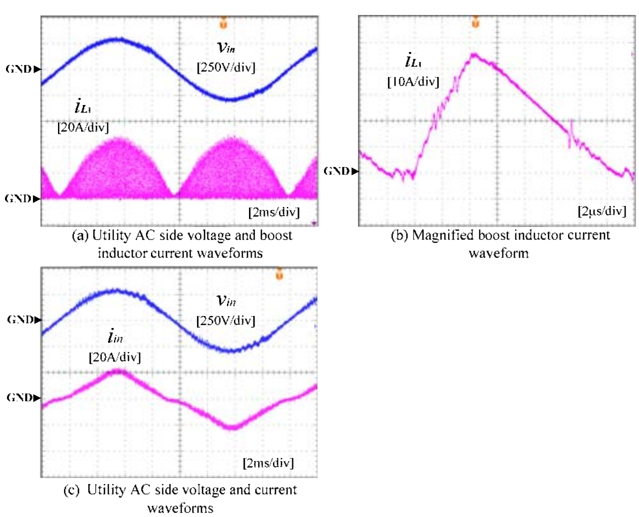


Fig. 11 Experimental waveforms in the boost PFC stage

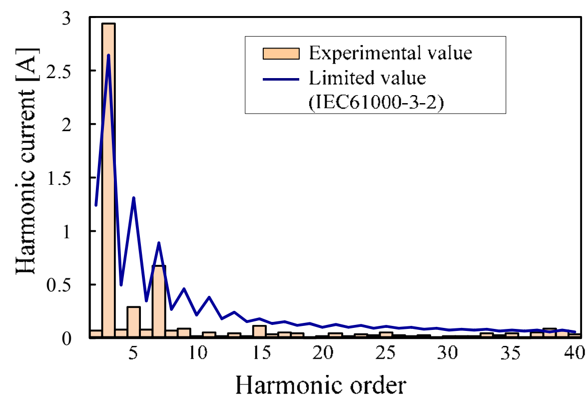


Fig. 12 FFT analysis of Utility AC side current

5. Conclusion

In this paper, a novel circuit topology of a utility frequency AC converted to high frequency AC power by employing a boost PFC converter stage and phase-shifted PWM high frequency inverter was proposed for consumer induction heating appliances. Its operating principle and unique features were presented, along with a phase-shifted PWM and boost chopper based on an intermediate voltage control scheme. The proposed high frequency IH power conditioning system, which can heat various metallic-cooking items, could reduce the switching losses generated in active components. The steady state operating performances were experimentally illustrated, which include high frequency power regulation, and current harmonic analysis.

Its practical effectiveness was proved from an experimental point of view.

References

[1] H.Kifune, T.Yamaguchi, D.Yoshida, Y.Hatanaka, M.Nakaoka, "Novel Load Adaptive Frequency Tracking Control Scheme for High Frequency Inverter Without PLL Scheme", Proceedings of the 35th IEEE Power Electronics Specialist Conference, 2004.

[2] H.Kifune, Y.Hatanaka, M.Nakaoka, "Cost effective phase shifted pulse modulation soft switching high frequency inverter for induction heating applications", Trans. on IEE Electric Power Applications, Vol. 151, No. 1, pp.19-25, January 2004.

[3] H.Tanimatsu, H.Sadakata, T.Iwai, H.Omori, Y.Miura, E.Hiraki, H.W.Lee, and M.Nakaoka, "Quasi-Resonant Inductive Snubbers-Assisted Series Load Resonant Tank Soft Switching PWM SEPP High-Frequency Multi Resonant Inverter with Auxiliary Switched Capacitor", The 6th International Conference on Power Electronics, pp II-299, Busan, Korea, October 2004.

[4] M.Helsper, F.W.Fuchs, M.Munzer, "Analysis and Comparison of Planae and Trench-IGBT-Modules under ZVS and ZCS Switching Conditions", Proc. of IEEE 33rd

Power Electronics Specialists Conference, Vol. 2, pp.614-619, 2002.
[5] Y.Miura, T.Ahmed, N.A.Ahmed, E.Hiraki, K.Yasui, T.Iwai, H.Omori, H.W.Lee, and M.Nakaoka, “Multi-resonant ZCS-PWM and PDM Hybrid Controlled High Frequency Inverter with Series Load Resonance and Active Edge Resonant Commutation,” Power Electronics Technology Exhibition and Conference, Baltimore, USA, October 2005.
[6] H.S.Choi and B.H.Cho, “Novel Zero-Current-Switching (ZCS) PWM Switch Cell Minimizing Additional Conduction Loss”, KIEE International Transactions on EMECS, 12B-1, pp.37-43, 2002.
[7] N.A.Ahmed, Y.Miura, T.Ahmed, E.Hiraki, A.Eid, H.W.Lee, and M.Nakaoka, “Quasi-Resonant Dual Mode Soft Switching PWM and PDM High-Frequency Inverter with IH Load Resonant Tank”, Proceedings of IEEE Power Electronics Specialists Conference, Brazil, pp.2830-2853, June 2005.
[8] M,Nakamura, M,Shimada, T.Myoui, H.Sadakata, S.Moisseev and M.Nakaoka, “Performance Evaluations on Soft-Switching Boost Power Converter with a Single Auxiliary Passive Snubber”, Proceedings of IEEE Power Electronics Specialists Conference, Canada, pp.1057-1062, June 2001.

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