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Zero Voltage Switching Boost H-Bridge AC Power Converter for Induction Heating Cooker

Soon-Kurl Kwon* · Bishwajit Saha

Abstract

This paper presents a novel soft-switching PWM utility frequency AC to high frequency AC power conversion circuit incorporating boost H-bridge inverter topology, which is more suitable and acceptable for cost effective consumer induction heating applications. The operating principle and the operation modes are presented using the switch mode equivalent circuits and the operating voltage and current waveforms. The performances of this high-frequency inverter using the latest IGBTs are illustrated, which includes high frequency power regulation and actual efficiency characteristics based on zero voltage soft-switching(ZVS) operation ranges, and the power dissipation as compared with those of the conventional type high frequency inverter. In addition, a dual mode control scheme of this high frequency inverter based on asymmetrical pulse width modulation(PWM) and pulse density modulation(PDM) control scheme is discussed in this paper in order to extend the soft switching operation ranges and to improve the power conversion efficiency at the low power settings. The power converter practical effectiveness is substantially proved based on experimental results from practical design example.

Key Words : Utility frequency AC to high frequency AC power conversion, Boost half-bridge single power stage, ZVS-PWM, Unity power factor correction, IH cooking appliances

1. Introduction

With the tremendous advances in power semiconductor switching devices, the electromagnetic induction current based directly heated energy processing products and applications using solid-state high frequency power conversion circuits; inverters, cyclo-inverters and cyclo-converters have attracted special interest for consumer food cooking and processing applications and hot water producers [1-3]. Recently, cost effective induction heating(IH) appliances using high frequency inverters have been rapidly developed as utility frequency AC to high-frequency AC power conversion system for consumer power and energy applications in home and business use. The IH equipment using high frequency inverter topologies have the practical advantages of safety,

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environment, very high thermal conversion efficiency, rapid and direct local focusing heating process, high power density, high reliability, environmental non-acoustic and low electromagnetic noise [4-7]. These unique advantages vantages are practically brought in accordance with great progress in power semiconductor switching devices, digital and analogue control devices and high frequency soft switching inverter circuits. Under the above technological situations, high frequency soft switching inverter topologies are indispensable for consumer IH appliances. These high frequency soft switching inverters must have the advantages of simple configuration, high efficiency, low cost and wide soft commutation operating ranges, which are necessary for high frequency operation. The voltage source type ZCS high frequency inverter and its modifications match the practical operating requirements mentioned previously. Integrated one stage configuration of high frequency power conversion can be established by combining both boost converter and half-bridge inverter in one conversion stage.

In this paper, a novel prototype of a boost H-bridge one-stage high frequency soft switching PWM inverter, which converts the utility frequency AC power into high frequency AC power with voltage boosting. This one-stage high frequency inverter composed of single phase diode bridge rectifier, non-smoothing filter, boost H-bridge type zero voltage soft switching PWM high frequency inverter, and induction heated load with planer type litz wire working coil assembly has been proposed. Also, we discussed control in this paper in order to extend the soft switching operation ranges and to improve the power conversion efficiency.

2. Induction Heating Appliances

Figure 1 demonstrates schematic configuration of a home and business use IH cooking and processing appliance. The solid-state high frequency inverter circuit delivers high frequency power to the planar-working coil with mutual coupling secondary circuit of electromagnetic eddy current based heated materials. These electro-magnetic induction eddy currents directly flow through the pan or vessel. In accordance with Faraday's electromagnetic induction law, a high thermal heating is produced with high conversion efficiency. In the case of multi-burner type high-frequency IH equipment, the output power of each burner has to be controlled under the same constant frequency, because of beat sound caused from different frequencies of operating inverters. In order to alleviate power dissipation of working coil, it is necessary to block lower frequency current components that are not effective for induction heating. In particular, the power dissipation reduction due to lower frequency coil current components and an improved soft-switching high frequency inverter operating under

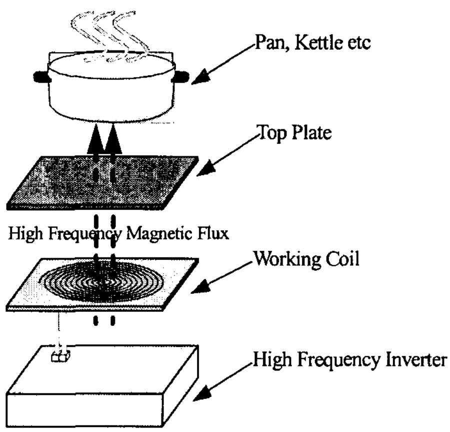


Fig. 1. A schematic configuration of induction heating cooking appliances

a condition of constant frequency pulse modulation should be developed and considered.

3. Proposed Boost H-Bridge High Frequency Inverter

3.1 Circuit Description

Figure 2 represents the novel circuit configuration of the proposed one stage soft switching PWM power converter incorporating two switch only for boost chopper and H-bridge zero voltage soft switching(ZVS) high frequency PWM inverter. The boost H-bridge one stage high frequency inverter circuit topology includes two active power switch blocks Q_1; Q_s, divided clamped series capacitors C_s and C_b, and lossless snubbing capacitor C_l in parallel to the IH load working coil L_1. In addition, the voltage boosted (charge-up) block is composed of the boost inductor L_b and active power switch Q_1. As we can see from the circuit configuration of proposed topology, the switching block Q_1 shares and performs the operation of both single-phase boost chopper converter and high frequency ZVS high frequency PWM inverter. In addition, the divided series capacitors C_s and C_b are used to block the lower frequency current components flowing through the induction heating(IH) load working coil L_1 which is assembled from litz wire.

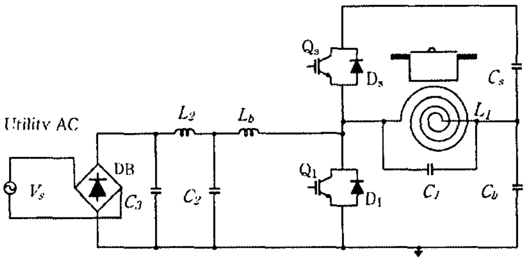


Fig. 2. Proposed single stage high frequency soft-switching inverter

3.2 Operation Switch Modes and Equivalent Circuits

Figure 3 shows the operating voltage and current waveforms and the operation modes of the proposed single stage high frequency power converter during one switching cycle. The corresponding equivalent circuits are shown in Fig. 4. The operation modes include six operating modes during one switching period, which will be explained simply in the following:

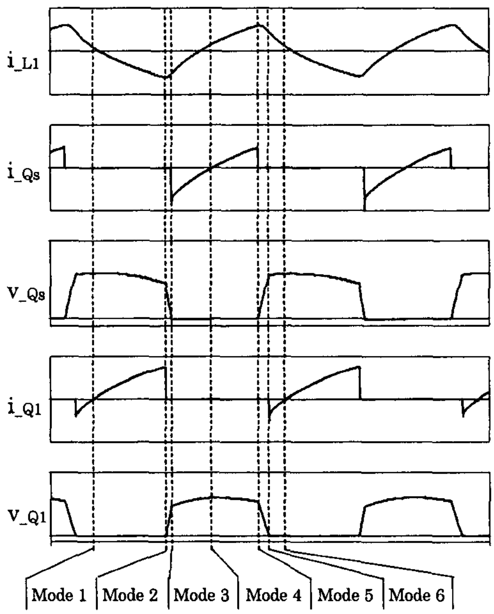


Fig. 3. Operating mode transitions and voltage and current waveforms

Mode 1(Q_1: on, D_1: off, Q_s: off and D_s: off)

This switching mode equivalent circuit is shown in Fig. 4 (a). In this mode, two current loops in the equivalent circuit are composed. The magnetic energy is stored in the boosting inductor L_b through the loop of C_2-L_b-Q_1-C_2 (1), while the energy is delivered to the induction-heated load through C_b-L_1-Q_1-C_b (2).

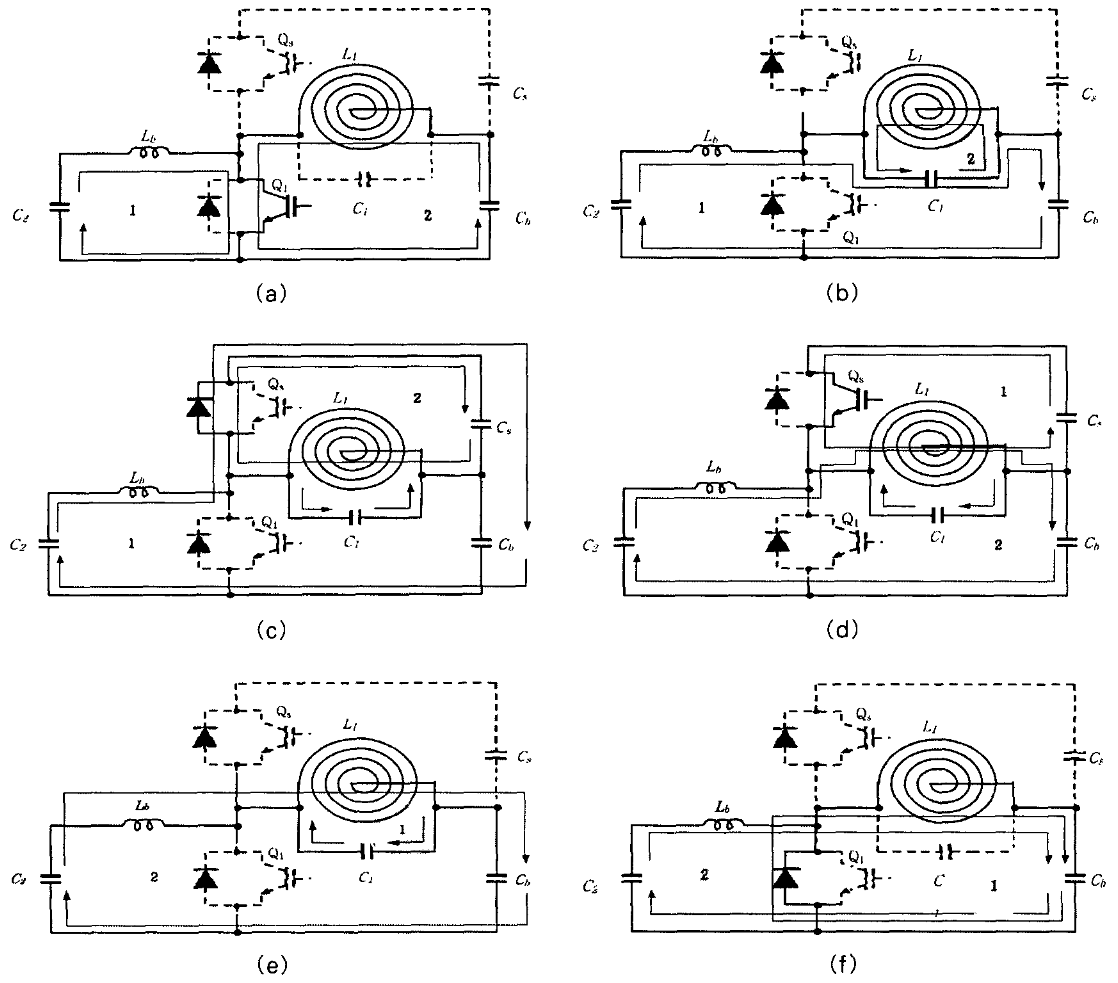


Fig. 4. Operating mode transitions and equivalent circuits

Mode 2(Q_l: off, D_l: off, Q_s: off and D_s: off)

The equivalent circuit of mode 2 is shown in Fig. 4 (b). In mode 2, the resonant energy is stored into C_l through the two loops composed of L_b-C_l-C_b-C_2-L_b (1) and L_l-C_l-L_l (2).

Mode 3(Q_l: off, D_l: off, Q_s: off and D_s: on)

The energy is stored in C_s through the loop composed of L_b-C_s-C_b-C_2-L_b (1) and the energy is delivered to the IH load through the loop composed of C_s-D_s-L_l-C_s (2). The equivalent circuit of mode 3 is shown in Fig. 4 (c).

Mode 4(Q_l: off, D_l: off, Q_s: on and D_s: off)

The equivalent circuit of mode 4 is shown in Fig. 4 (d). In mode 4, the energy is delivered to the IH load through the loop composed of C_s-Q_s-L_l-C_s (1) and the energy is stored in the capacitor C_b through the loop composed of L_b-L_l-C_b-C_2-L_b (2).

Mode 5(Q_l: off, D_l: off, Q_s: off and D_s: off)

This equivalent circuit of mode 5 is shown in Fig. 4 (e). During this operating mode, the energy is transferred to the IH load-working coil L_l through the loop composed of L_l-C_l-L_l (1) and the energy is stored in the capacitor C_b through the loop composed of L_b-L_1-C_b-C_2-L_b (2) as in mode 4.

Mode 6(Q_1: off, D_1: on, Q_s: off and D_s: off)

The mode equivalent circuit is shown in Fig. 4 (f). In mode 6, the energy stored in the IH working coil L_1 is transferred into the capacitor C_b through the loop composed of L_1-C_b-D_1-L_1 (1) and the energy is stored in the capacitor C_b through the loop composed of L_b-L_1-C_b-C_2-L_b (2) as in mode 5.

4. Experimental Circuit Evaluations And Results

4.1 Circuit Configuration and Design Specifications

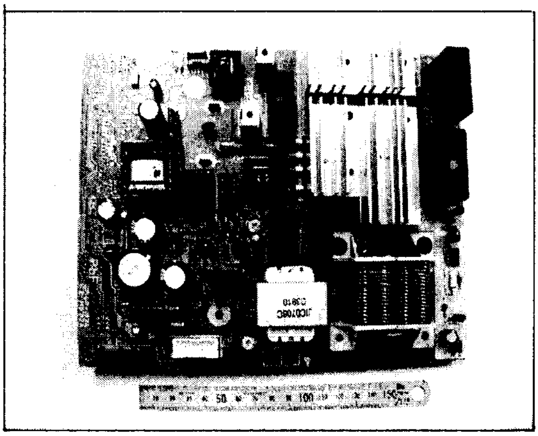
A 3.5[kW] prototype of the proposed boost H-bridge soft switching PWM high frequency power converter is practically implemented using the high frequency IGBTs rated(60[A], 950[V]) model GT60M322 produced by Toshiba Semiconductor Co., Ltd as power switching devices Q_1 and Q_s. Table 1 indicates the design specifications and circuit parameters of the newly developed high frequency inverter with boost H-bridge topology.

Table 1. Design Specifications and Circuit Parameters

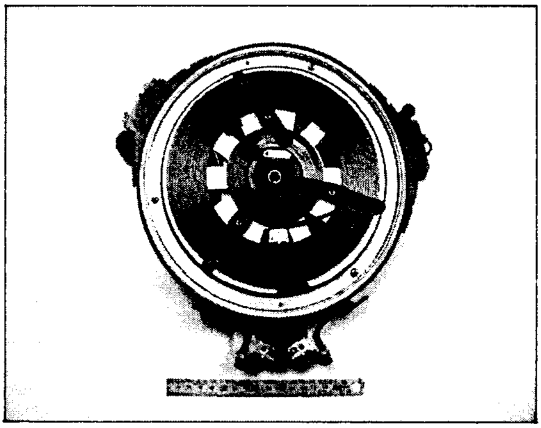
Item	Symbol	Value[Unit]
Working coil inductance with iron pan resistance	L_1	58.0[μH]
	R_L	2.5[Ω]
Charge-up boost inductor	L_b	500.0[μH]
Filter inductor	L2	200.0[μH]
Lossless snubbing capacitor	C_1	0.21[μF]
Filter capacitor	C_2	2.0[μF]
	C_3	2 .0[μF]
Divided series capacitor	C_s	3.0[μF]
	C_b	4.0[μF]
Switching frequency	f_s	22[kHz]

4.2 Implementation of Printed Circuit Board

Figure 6 (a) demonstrates the overall appearance of the newly developed single stage high frequency inverter for IH cooking heater with voltage boosting function, while Fig. 6 (b) shows the exterior view of the litz wire assembled IH working coil. The power converter circuit and the control circuit are built on the same printed circuit board.



(a) Exterior view of the newly developed power converter for IH cooking heater

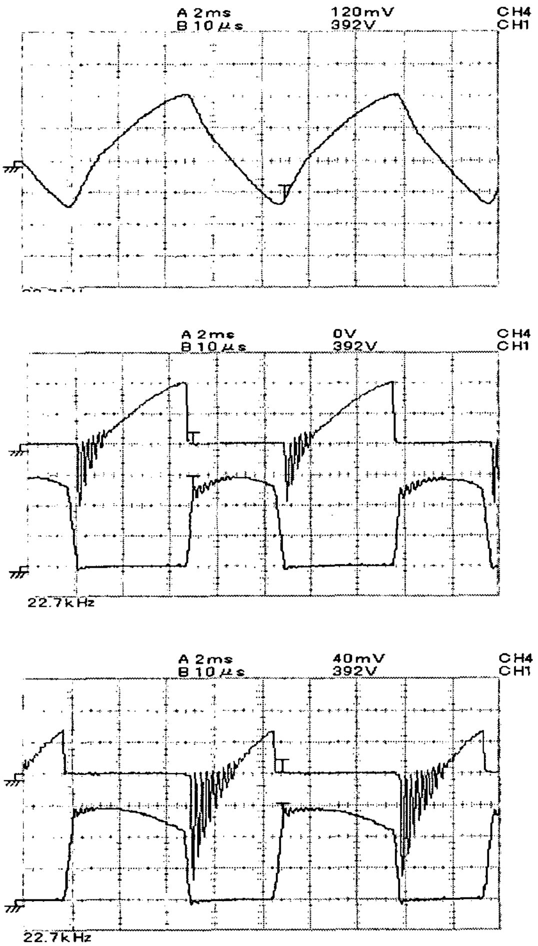


(b) Exterior view of the air-cooled litz wire type working coil assembly

Fig. 6. Appearance of the newly developed power converter

4.3 Measured Voltage and Current Waveforms

Figure 7 shows the measured operating current and voltage waveforms of the power switches Q_1, Q_s and IH load working coil L_1. It is easy to recognize that the power switches Q_1 and Q_s can operate under ZVS mode transition. Consequently, this operation reduces the switching losses and can allow high-energy conversion efficiency.



Current axis: 40(A/div), Voltage axis: 100(V/div), Time axis: 10(us/div)

Fig. 7. Voltage and current switching waveforms of Q_1, Q_s, L_1

5. Power Regulation Characteristics

5.1 High Frequency Power Regulation

Figure 8 shows the input power regulation vs. duty cycle characteristics and ZVS operation ranges of the newly developed and conventional type high frequency inverter. Both high frequency inverters are working at 200[Vrms] utility frequency AC voltage source and can regulate its power continuously by asymmetrical PWM control scheme with a constant switching frequency. It is recognized that the ZVS operation range of newly developed high frequency inverter is similar to that of the conventional type high-frequency inverter. Both high-frequency inverters could not operate with ZVS mode in the area of duty cycle below 22[%], where pulse density modulation(PDM) control technique can be used for the proposed power converter to extend its soft switching operation range. From experimental result, the proposed ZVS high frequency inverter could operate under 0.16 to 0.6 duty cycle at zero-voltage turn-on and turn-off transitions(see Fig. 8).

5.2 Actual Power Conversion Efficiency

Figure 9 shows the characteristics of the power conversion efficiency vs. the input power of both high frequency inverter circuits. Efficiency of the newly developed one stage high-frequency inverter is below the conventional type inverter efficiency under a condition of the input power in range of 1[kW] or less. This results from adding additional circuit components as the boost chopper inductor L_b. However, for high power settings more than 1[kW], the newly developed converter has high power conversion efficiency as compared to the conventional one. Because the saving in the switching losses of semiconductor switching devices Q_1 and Q_s due to the soft switching operation exceeds the losses in the boost inductor L_b. As we can see in Fig. 9 the lower power ranges efficiency is low. In this case, PDM control is proposed.

5.3 Zero Voltage Soft-Switching Commutation

Figure 10 illustrates the voltage and current waveforms of the power switches Q_1 and Q_s at turn-off switching transition. It is clear that the voltage waveform is rising slowly due to the effect of the resonant capacitor C_1, while the current waveform declines sharply. As a result, turn-off power dissipations in power switches Q_1 and Q_s are dramatically decreased. Turn-off power dissipations in the newly developed boost H-bridge one stage high frequency inverter are computed to be 20[W] for Q_1 and 8[W] for Q_s reduced. The maximum working voltage across Q_1 or Q_s is computed as 700[V]. The power switches Q_1 and Q_s are selected to have 950[V] rating.

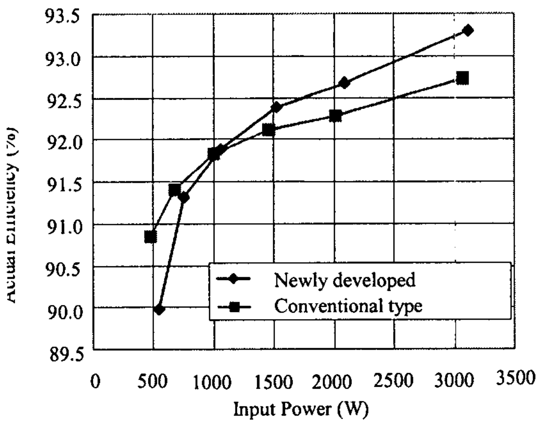


Fig. 8. Input power vs. duty cycle characteristics

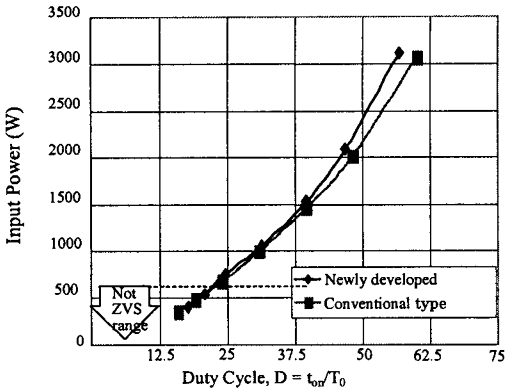
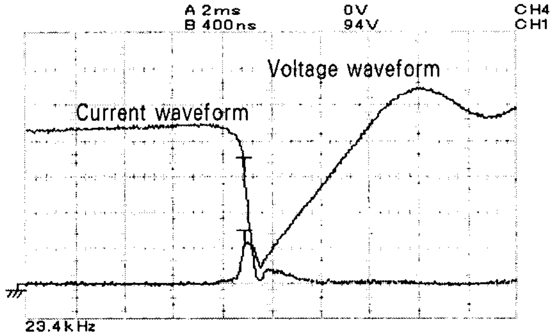
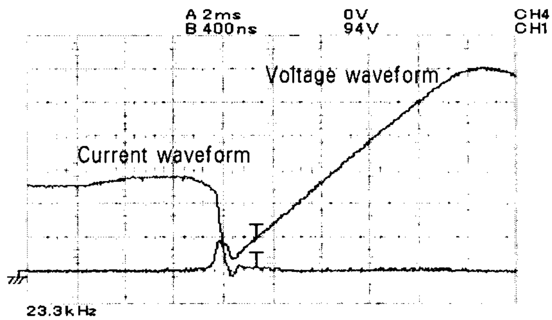


Fig. 9. Conversion efficiency vs. input power characteristics



(a) Turn off voltage and current waveforms of Q_1



(b) Turn off voltage and current waveforms of Q_s

Current axis: 20(A/div), Voltage axis: 100(V/div), Time axis: 400(μs/div)

Fig. 10. Switching waveforms at turn off mode of Q_1 and Q_s

5.4 Power Dissipation Analysis

When the proposed one stage high frequency power converter and the conventional one are operating under the condition of the maximum output power(3[kW]), the power dissipation of the newly developed one stage inverter is effectively estimated as about 6[%] lower(see Table 2) than the conventional type power conversion circuit. This reason is due to the elimination of the power loss on dc and lower-frequency working coil current components. The working voltage across Q_1 as well as Q_s can be lowered in this boost H-bridge one stage circuit topology and consequently the peak voltages of Q_1 and Q_s are both reduced.

5.5 Unity Power Factor in Utility AC Side

Figure 11 shows the utility ac side voltage and input current waveforms of this boost H-bridge one-stage soft switching PWM high frequency inverter. The input current and utility ac side voltage become in-phase, in other words, unity power factor with sine wave current can be obtained. Therefore, although the switch of high frequency inverter and the switch of boost chopper converter are shared, the proposed boost H-bridge one stage power converter can operate as boost PFC converter.

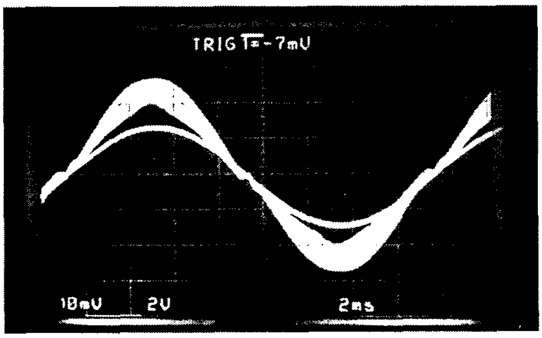


Fig. 11. Utility ac voltage and current waveforms

Table 2. Power Losses in the Circuit Components

Devices and components	Power Dissipation	
--	Proposed	Conventional
Switch Q_1	45[w]	65[w]
Switch Q_s	22[w]	30[w]
Filter inductor(L_2)	21[w]	25[w]
Boost inductor(L_b)	30[w]	--
Load(L_1)	53[w]	60[w]
Capacitors(C_2, C_3, C_s, C_b)	15[w]	15[w]
Bridge rectifier(DB)	23[w]	28[w]
Total	209[w]	223[w]

6. Conclusions

In this paper, the new circuit topology of utility frequency AC to high frequency AC power converter employing boost H-bridge one stage soft switching PWM high frequency inverter has been proposed for consumer induction heating appliances. The new one stage high frequency IH inverter using boosted voltage function can eliminate the dc and low frequency components of the working coil current and reduce the power dissipation of the circuit components. The operating principle, the operation modes and its unique features have been presented and discussed based on experimental and simulation results. The steady state operating performances have been experimentally illustrated as compared with conventional type high frequency power converters, which include high frequency AC power regulation, and power conversion efficiency based on the power loss analysis. At the soft-switching ranges, highest efficiency is above 93[%] and the lowest is about 90[%]. We proposed the pulse density modulation scheme for less than 1[kW] power ranges.

For further future work, the boost H-bridge one stage high frequency power converter using the promising power switching devices ESBTs and

SiC-JFETs will be evaluated and discussed in order to improve the overall power conversion efficiency.

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References

(1) H. Muraoka, M.Nakaoka, K. Sakamoto, "High-Frequency PWM Forward Converter with Auxiliary Active Clamped Capacitor for Low Voltage High Current Operation", Proceedings of IEEE PELS- Power Electronics Specialists Conference, Vol. 3, pp. 1523-28, Vancouver, Canada, July, 2001.

(2) S. Hishikawa, M. Serguei, M. Nakaoka, I. Hirota, H. Omori, H. Terai, "New Circuit Topology of Soft Switching Single-Ended High Frequency Inverter using IGBTs", Technical Report of IEICE-J Energy Electronics Professional Meeting, Vol. 100, No. 628, pp. 19-24, February, 2000.

(3) M. Kaneda, H. Tanaka, M. Nakaoka, "A Novel Prototype of Single-Ended Push-Pull Soft-Switching High-Frequency Inverter using a Single Auxiliary ZVS-PWM Switch", Technical Report of IEICE-J Energy Electronics Professional Meeting, Vol. 100, No. 628, pp. 31-37, February, 2000.

(4) H. Sadakata, H. Terai, H. Omori, H. Yamasita, M. Nakaoka, "The Development of ZCS-PWM-SEPP Inverter with Complexed Control Method" IEEJ SPC-03-30. February 2003.

(5) K. Yasui, T. Kitaizumi, D. Bessyo, H. Omori, H. Terai, Mamun Abdullah Al, M. Nakaoka, "Latest Development of Soft Switching Inverter Power Supply Using Active Clamp Scheme with A Charge Up Function for Magnetron Drive", IEEJ PCC-Osaka, Vol. 3, pp. 1484-1489, April, 2002.

(6) Nabil A. Ahmed, D. Bessyo, K. Yasui, H. Omori, H. Terai, M. Nakaoka, "The Inverter Circuit Skills to Realize Low-Cost, Compact-Size Power Supply for Microwave Oven, and the Advantages of Improved Defrosting" Proceedings of IEEE-IAS International Appliance Technical Conference, April, 2000.

(7) Hisayuki Sugimura, Nabil A. Ahmed, Tarek Ahmed, Hyun-Woo Lee, Mutsuo Nakaoka, "Utility AC Frequency to High Frequency AC Power Conversion Circuit with Soft Switching PWM Strategy", KIEE International Transactions on Electrical Machinery and Energy Conversion Systems, Vol. 5-B No. 2, pp. 181~188, 2005.

Biography

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He received a Ph. D(Dr-Eng) degree in Electrical Engineering from Young-Nam University, Daegu, Republic of Korea. He joined the Electrical Engineering Department of Kyungnam University, Masan, Republic of Korea in 1983 and has served as a professor. He was a visiting professor of VPEC in VPI & SU, UAS in 1997. His research interests include application developments of power electronics circuits and system. He is a member of the KIEE, KIPE, KIIEE, and IEEE.

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