A Novel Utility AC Frequency to High Frequency AC Power Converter with Boosted Half-Bridge Single Stage Circuit Arrangement

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Abstract- This paper presents a novel soft-switching PWM utility frequency AC to high frequency AC power conversion circuit incorporating boost-half-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 switching mode 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 previously developed 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.

Index Terms- Utility frequency AC to high frequency AC conversion, Boost-half bridge one power stage, ZVS-PWM, Unity power factor correction, Sine wave current shaping in utility AC side, IH cooking appliance.

I. INTRODUCTION

With tremendous advances of 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 equipments using high frequency inverter topologies have the practical advantages of safety, cost effectiveness, energy saving, clean 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. Under the above technological situations, high frequency soft switching inverter topologies are indispensable for consumer IH appliances. The voltage source type ZCS high frequency inverter and its modifications match the practical operating requirements mentioned previously. However, this type of high frequency inverters could not able to regulate its output power under constant frequency PWM control strategy and has low power conversion efficiency.

In this paper, a novel prototype of a boost-half bridge single 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, and boost-half-bridge type zero voltage soft switching PWM high frequency inverter, and induction heated load with planer type litz wire working coil assembly is proposed.

II. INDUCTION HEATING APPLIANCE

Figure 1 demonstrates schematic configuration of a home and business use IH cooking and processing appliance. The solid-state high frequency inverter circuit delivers a high frequency power to the planer-working coil with mutual coupling secondary circuit of electromagnetic eddy current based heated materials. These electromagnetic 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 case of multi-burner type high-frequency IH equipments, the output

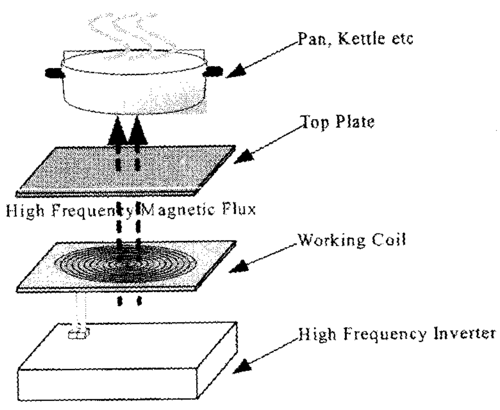


Fig. 1. Schematic configuration of IH cooking appliance.

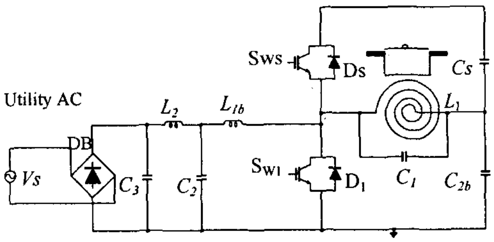


Fig. 2.Proposed one stage high frequency soft switching converter.

power of each burner has to be controlled under the same constant frequency, because of beat sound caused from difference 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 a condition of constant frequency pulse modulation should be developed and considered.

III. HIGH FREQUENCY INVERTER

A. Circuit Description

Figure 2 represents the circuit configuration of proposed single stage soft switching PWM power converter incorporating two switch only for boost chopper and half-bridge zero voltage soft switching (ZVS) high frequency PWM inverter. The boost-half bridge one stage high frequency inverter circuit topology includes two active power switch blocks $Q_1(S_{W1}/D_1)$, $Qs(S_{WS}/Ds)$, divided series capacitors C_s and C_{2b} and lossless snubbing capacitor C_l in parallel to the IH working coil L_l. In addition, the voltage boosted (charge-up) block composed of the boost inductor L_{1b} and active power switch Q_l (S_{W1}/D_l).

B. Principle of Operation

Figure 3 shows the operating voltage and current waveforms and the operation modes of the proposed one stage high frequency power converter during one switching cycle. The operating modes are simply explained in the following:

Mode 1 (S_{W1}: on, D_1: off, S_{WS}: off and Ds: off)

In this mode, the magnetic energy is stored into the boosting inductor L_{1b} through the loop of C_2-L_{1b}-Q_l-C_2, while the energy is delivered to the induction-heated load through C_{2b}-L_l-Q_l-C_{2b}.

Mode 2 (S_{W1}: off, D_1: off, S_{WS}: off and Ds: off)

In mode 2, the resonant energy is stored into C_l through the two loops composed of L_{1b}-C_l-C_{2b}-C_2-L_{1b} and L_l-C_l-L_l.

Mode 3 (S_{W1}: off, D_1: off, S_{WS}: off and Ds: on)

The energy is stored in Cs through the loop composed of L_{1b}-C_s-C_{2b}-C_2-L_{1b} and the energy is delivered to the IH load through the loop composed of Ds-C_s-C_2-L_{1b}.

Mode 4 (S_{W1}: off, D_1: off, S_{WS}: on and Ds: off)

In mode 4, the energy is delivered to the IH load through the loop composed of Cs-Qs-L_l-Cs and the energy is stored in the capacitor C_{2b} through the loop composed of L_{1b}-L_l-C_{2b}-C_2.

Mode 5 (S_{W1}: off, D_1: off, S_{WS}: off and Ds: off)

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 and the energy is stored in the capacitor C_{2b} through the loop composed of L_{1b}-L_l-C_{2b}-C_2 as in mode 4.

Mode 6 (S_{W1}: off, D_1: on, S_{WS}: off and Ds: off)

In mode 6, the energy in the IH working coil L_l is transferred into the capacitor C_{2b} through the loop composed of L_l-C_{2b}-L_l and the energy is stored in the capacitor C_{2b} through the loop composed of L_{1b}-L_l-C_{2b}-C_2 as in mode 5.

IV. PRACTICAL EVALUATIONS

A. Design Specification

A 3.5 kW prototype of the proposed boost half-bridge soft switching PWM high frequency power converter is practically implemented using the 4th generation IGBTs rated (60A, 950V) model GT60M322 as power switching devices Q_1 and Qs. Table 1 indicates the design specifications and circuit parameters.

B. Measured Voltage and Current Waveforms

Figure 4 shows the measured operating current and voltage waveforms of the power switches Q_1, Qs and IH working coil L_l. It is easy to recognize that the power switches Q_1 and Qs can operate under ZVS mode transition. Consequently, this zero voltage soft-switching operation reduces the switching losses and can allow high-energy conversion efficiency.

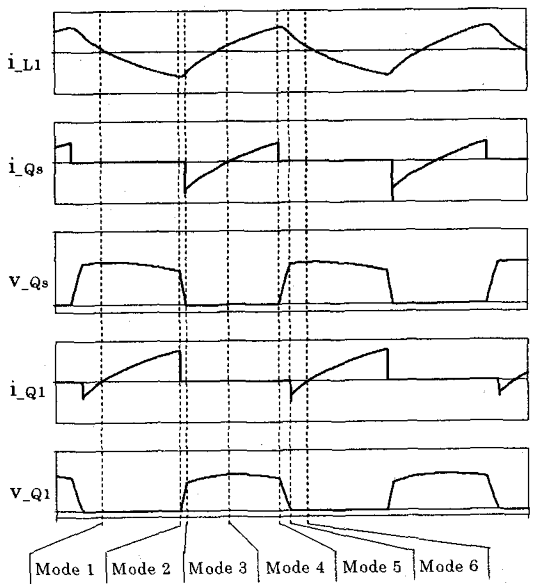


Fig. 3. Operating mode transitions and voltage-current waveforms.

TABLE I

DESIGN SPECIFICATIONS AND CIRCUIT PARAMETERS

Item	Symbol	Value
Working coil inductance with iron	L_l	58[μH]
pan resistance	R_L	2.5 [Ω]
Charge-up boost inductor	L_{lb}	500 [μH]
Filter inductor	L_2	200 [μH]
Losses snubbing capacitor	C_l	0.21[μF]
Filter capacitor	C_2	2 [μF]
	C_3	2 [μF]
Divided series capacitor	C_s	3 [μF]
	C_{2b}	4 [μF]

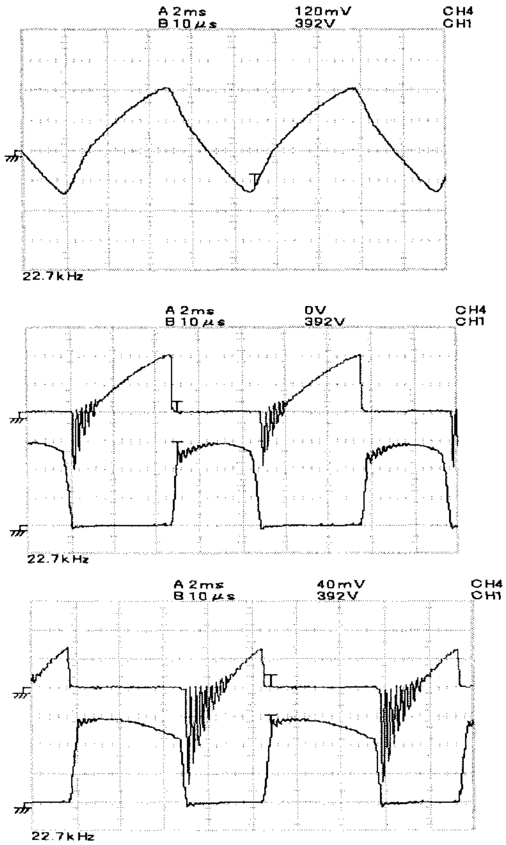


Fig. 4. Voltage and current waveforms of Q_1, Qs and L_1.

V. OPERATING CHARACTERISTICS

A. High Frequency Power Regulation

Figure 5 shows the input power regulation vs. duty cycle characteristics and ZVS operation ranges of the newly proposed and previously developed high-frequency inverter. Both high-frequency inverters are working at 200V 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 previously developed 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.

B. Actual Power Conversion Efficiency

Figure 6 shows the characteristics of the power conversion efficiency vs. the input power of the both high frequency inverter circuits. Efficiency of the newly developed one stage high-frequency inverter is below the previously developed inverter efficiency under a condition of the input power in range of 1kW or less. This is resulted from adding additional circuit components as the boost chopper inductor L_{1b}. However, for high bower setting more than 1kW, the proposed converter has high power conversion efficiency as compared to the previously developed one. Because the saving in the switching losses of semiconductor switching devices Q_1 and Qs due to the soft switching operation exceeds the losses in the boost inductor L_{1b}.

C. Zero Voltage Soft-Switching Commutation

Figure 7 illustrates the voltage and current waveforms of power switches Q_1 and Qs at turn on switching transition. It is clear that the voltage waveform is going up slowly due to the effect of the resonant capacitor C_l, while the current

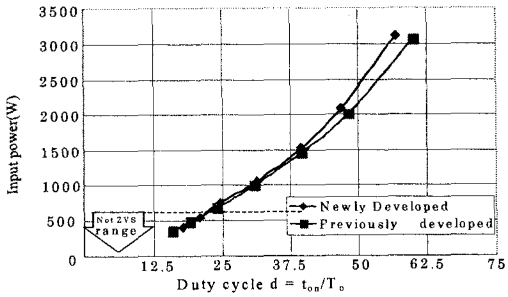
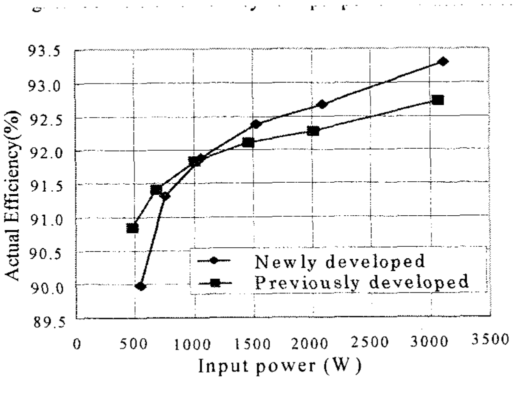


Fig. 5. Input power vs. duty cycle characteristics.



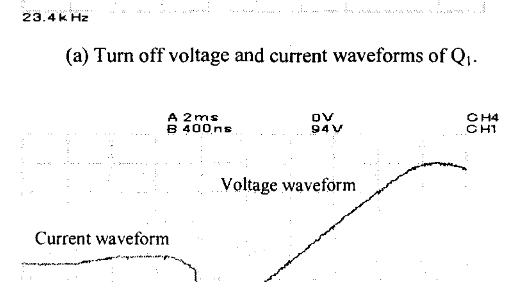
waveform decline sharp. As a result, turn-off power dissipations in power switches Q_1 and Qs are dramatically decreased. Turn-off power dissipations in the newly developed boost-half bridge one stage high frequency inverter are computed to be 20W for Q_1 and 8W for Qs. The maximum working voltage across Q_1 or Qs is computed as 700V. The power switches Q_1 and Qs are selected to have 950V rating.

D. Power Dissipation Analysis

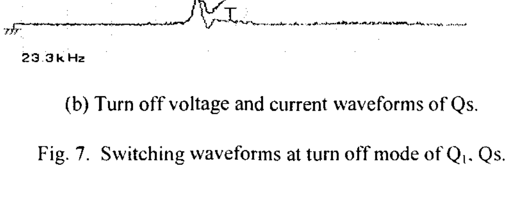
When the proposed one stage high frequency power converter and the previously developed one are operating under the condition of the maximum input power (3kW), the power dissipation of the newly developed one stage inverter is effectively estimated as about 6% lower than the previously developed two stages 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 Qs can be lowered in this boost-half-bridge one stage circuit topology and consequently the peak voltages of Q_1 and Qs are both reduced.

E. Unity Power Factor in Utility AC Side

Figure 8 shows the utility ac side voltage and input current waveforms of this boost half-bridge active clamp one-stage soft switching PWM high frequency inverter. The input current and utility ac side voltage become in-phase, in other word, unity power factor with sine wave current can



(a) Turn off voltage and current waveforms of Q_1.



(b) Turn off voltage and current waveforms of Qs.

Fig. 7. Switching waveforms at turn off mode of Q_1, Qs.

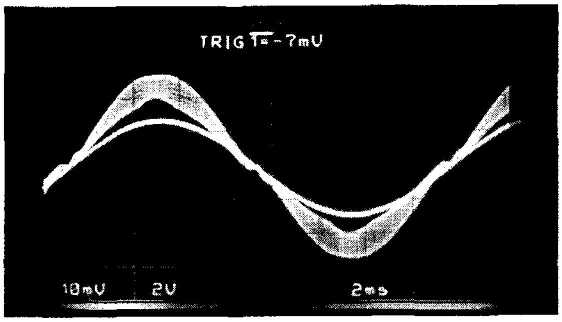


Fig. 8. Utility ac voltage and current waveforms.

be obtained. Therefore, although the switch of high frequency inverter and the switch of boost chopper converter are shared, the proposed boost-half bridge one stage power converter can operate as boost PFC converter.

V. CONCLUSIONS

In this paper, a novel circuit topology of utility frequency AC to high frequency AC power converter employing boost-half bridge single 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 two-stage high frequency power converter, which include high frequency AC power regulation, and power conversion efficiency based on the power loss analysis.

For further future work, the boost-half 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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