A Novel Switched Capacitor Lossless Inductors Quasi-Resonant Snubber Assisted ZCS PWM High Frequency Series Load Resonant Inverter

Khairy Fathy, Tae Kyung Kang, Soon Kurl Kwon, Ki Young Suh, Hyun Woo Lee, and Mutsuo Nakaoka
EESRC, The graduate School of Electrical & Electronics Engineering,
Kyungnam University, Masan, Republic of Korea
Email: khairy_fathy@yahoo.ca

Abstract – In this paper, a novel type of auxiliary switched capacitor assisted edge resonant soft switching PWM series load resonant high frequency inverter with two auxiliary edge resonant lossless inductor snubbers is proposed for small consumer induction heating appliances. The operation principle of this high frequency inverter is described using the switching mode equivalent circuits. The practical effectiveness of the newly proposed soft switching inverter are discussed as compared with the conventional soft switching high frequency inverters based on simulation and experimental results from an application point of view.

keywords: Single-ended push-pull inverter, high frequency power conversion, zero current soft switching, induction heating.

I. INTRODUCTION

In recent years, the consumer comparative study power electronics relating to high frequency electromagnetic eddy current based induction heating (IH) becomes more suitable and acceptable for consumer food cooking and processing appliances, hot water producer, super heated steamer and fixing roller in copy and printer machines [1-3].

In general, consumer IH equipments for effective power and energy applications in home and business use not only meets the practical demands of safety, cost effectiveness and cleanliness, but also has excellent advantages of very high thermal conversion efficiency, rapid and direct local focusing heating, high power density, high reliability, non-acoustic environmental and low electromagnetic noise [4]-[5].

In this paper, a novel circuit topology of voltage source multi resonant ZCS-SEPP high frequency inverter with constant frequency PWM control strategy using active auxiliary quasi-resonant lossless inductor sunbbers and switched capacitor snubber is newly proposed for new generation cost effective consumer IH food cooking and processing applications. The operating principle of the proposed high frequency inverter topology incorporating ZCS-PWM control scheme for light AC power regulation and its actual efficiency characteristics for PWM control strategy are illustrated and evaluated on the basis of simulation and practical experimental results and the effectiveness of this proposed high frequency ZCS inverter using IGBTs are substantially proved for cost effective consumer IH appliances.

II. PROPOSED VOLTAGE SOURCE ZCS- SEPP PWM HIGH FREQUENCY INVERTER

A. Circuit Configuration: Fig. 1 shows the newly developed multi-resonant ZCS-SEPP PWM high-frequency inverter circuit using the latest trench gate IGBTs and operating with constant frequency PWM control strategy. This voltage-fed ZCS PWM high frequency inverter circuit consists of two main switches of reverse conducting IGBTs $Q_1(SW_1/D_1)$ and $Q_2(SW_2/D_2)$. a single auxiliary switch $Q_3(SW_3/D_3)$ in series with auxiliary edge-resonant switched capacitor C_r as an active snubber, two ZCS-assisted lossless inductor snubbers L_{S1} and L_{S2} connected in series with the main switches Q_1 and Q_2, power factor compensated series load resonant capacitor C_s, and highly inductive IH load represented by its R_o and L_o series inductive equivalent circuit model.

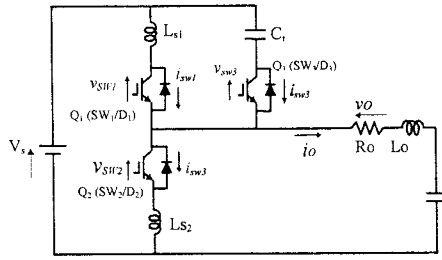

Fig. 1. Multi-resonant ZCS- SEPP PWM high frequency inverter.

B. High Frequency AC Power Control Scheme

The high frequency AC output power of the proposed inverter circuit, which is delivered to the IH load can be continuously regulated by a constant frequency asymmetrical PWM control scheme under a condition of zero current soft switching commutation mode. The proposed gate voltage pulse timing PWM sequences for the active power switches Q_1, Q_2, and the auxiliary power switch Q_3 are shown in Fig. 2. The main active power switch Q_1 is firstly switched on during period of time T_{on1} and before Q_1 is turned off the auxiliary switch Q_3 is turned on for a period T_{on3} inserting a an overlapping time of T_o between the switches Q_1 and Q_3. Then, the main switch Q_2 is turned on after turning off the auxiliary switch Q_3 by a dead time of T_{d1}. The main switch Q_1 is again switched on after a dead time T_{d2} as another period starts as depicted in Fig. 2. By adjusting the duty cycle, which is defined as $D = (T_{on} + T_{d1})/T$, the proposed high frequency ZCS-PWM inverter can regulate its high frequency output power continuously under a condition of soft switching; it can be controlled by a constant high frequency pulse density modulation (PDM) technique at low power settings. In addition, by using a dual mode hybrid control of asymmetrical PWM and PDM at a constant high frequency, soft switching operating range can be effectively expanded from high power to low power settings.

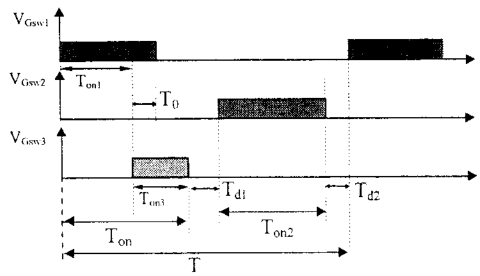

Fig. 2. Proposed PWM gate pulse timing sequences.

III. PRINCIPLE OF SOFT SWITCHING OPERATION

The switching operation mode commutation transitions and their corresponding equivalent circuits of the proposed zero current soft switching high frequency inverter in steady state during one switching cycle are shown in Fig. 3. The current operating waveforms and the relevant operating modes of this inverter in steady state are illustrated in Fig. 4 for a duty cycle D

= *0.34*. This multi resonant high frequency soft switching inverter circuit includes eleven operating switching modes. At the beginning of each switching cycle, the high side main power switch SW_1 of Q_1 is now conducting and high frequency AC effective power is supplied to the IH load. After the switch current i_{SW1} through SW_1 of Q_1 naturally commutates to the switch anti-parallel diode D_1 of Q_1 by quasi-resonance due to ZCS-assisted high side inductor snubber L_{S1}, together with the auxiliary series inductive load resonant tuned capacitor C_s, the auxiliary active power switch SW_3 of Q_3 is turned on and the main power switch SW_1 of Q_1 is turned off. As a result, a ZCS commutation at a turn-off switching mode transition can be achieved by the arbitrarily timing processing when turning off the main power switch SW_1 of Q_1. At this mode, since an auxiliary resonant current i_{SW3} flows through the switch SW_3 of Q_3 and increases softly, a ZCS commutation at a turn-on switching mode transition can be achieved for SW_3 of Q_3. Then, after i_{SW3} is commutated to the anti-parallel diode D_3 of Q_3 by the resonance formed by C_r, R_o-L_o inductive load circuitry and power factor series load compensated capacitor C_s, a ZCS soft switching commutation at a turn-off switching mode transition can be performed by turning off SW_3 of Q_3. While the auxiliary power switch SW_3 of Q_3 is conducting, the voltage v_{Q2} across the low side main switch SW_2 of Q_2 decreases toward zero. Before the low side main switch SW_2 of Q_2 is turned on as soon as the diode D_2 of Q_2 becomes reverse biasing state and begins to conduct naturally. While the diode D_2 continues conducting, the current flowing through D_2 of Q_2 is naturally commutated to SW_2 of Q_2. Therefore, a complete ZVS and ZCS (ZVZCS) hybrid commutation transition can be actually achieved for SW_2 of Q_2. On the other hand, after the current i_{SW2} through the low side main switch SW_2 of Q_2 is naturally commutated to D_2 of Q_2 with the aid of low side ZCS-assisted inductor snubber L_{S2}, the high inductive induction heating load R_o-L_o and load power factor compensation series load resonant tuned capacitor C_s, ZCS commutation at a turn-off switching mode transition can be performed by turning off the switch SW_2 of Q_2. While the diode D_2 of Q_2 is conducting, the current i_{D2} flowing through D_2 is commutated to the switch SW_1 of Q_1 by turning on the switch SW_1 of Q_1 when a second switching cycle starts. At this mode, a ZCS turn-on switching commutation can be realized with the aid of ZCS-assisted inductor snubber L_{S1}. The proposed edge

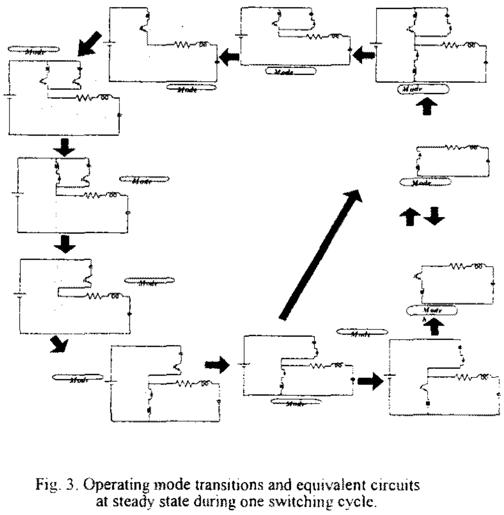

Fig. 3. Operating mode transitions and equivalent circuits at steady state during one switching cycle.

resonant ZCS PWM inverter offers a complete ZCS for all the main and auxiliary switches and achieves ZVZCS hybrid commutation at turn-on switching mode transition for the switch SW_2 of Q_2

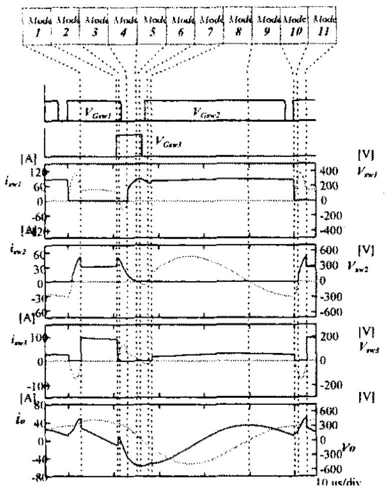

Fig. 4. Voltage and current waveforms during one switching cycle operating modes for a duty cycle of 0.34.

IV. EXPERIMENTAL EVALUATIONS AND DISCUSSIONS

A. Design Specifications and Circuit Parameters

An experimental setup assembly implementation by using trench gate reverse conducting IGBTs with low saturation voltage is proposed to validate the steady state performance evaluations of the proposed zero current soft switching high frequency inverter circuit. The design specifications and circuit parameters used in the experimental breadboard setup are respectively indicated in Table1. The ZCS-PWM high frequency inverter circuit proposed here is designed for consumer IH cooking heater in home and business applications. An enamel pan has a bottom diameter of 18 cm is used for the IH load as a heated object. The high frequency IH load consists of enamel pan, ceramic spacer as top plate and a planner working coil composed of litz wire assembly. The circuit parameters of this high frequency ZCS-PWM inverter are determined by considering the operating condition of zero current soft switching commutation condition and the required high frequency AC output power ranges.

Table 1. Design specifications and circuit constants.

Item		Symbol	Value
DC Source Voltage		V_s	282.8 V
Switching Frequency		f_{sw}	20 kHz
ZCS-assisted Inductor		L_{s1}	2.09 μH
ZCS-assisted Inductor		L_{s2}	2.01 μH
Auxiliary Quasi-resonant Capacitor		C_r	324 nF
Compensation series tuned capacitor		C_s	0.802 μF
Enamel Pan	Load Resistance	R_o	2.54 Ω
	Load Inductance	L_o	57.96 μH

B. Experimental Results

The steady state measured operating voltage and current waveforms for specified duty cycle $D = 0.34$ under an input DC power of 2.7 kW are represented in Fig. 5. As it can been noticed in this figure, all the main power switches Q_1, Q_2 and the auxiliary active power switch Q_3 can operate under a principle of

ZCS-PWM commutation operation. In particular, it can be recognized that a complete ZVZCS hybrid commutation at turn-on switching mode transition can be performed for the SW_2 of Q_2, because SW_2 is turned on during a conduction period of the diode D_2 of Q_2. Since the gate pulse voltage signal is given to the auxiliary power switch SW_1 of Q_1 during the conduction period of its anti-parallel diode D_1 of Q_1, the ZCS commutation at a turn-on switching mode transition can be achieved for the switch SW_1 of Q_1. In spite of the additional auxiliary switch SW_3 of Q_3, a high efficiency power conversion can be achieved in the proposed high frequency zero current soft switching PWM inverter circuit depicted in Fig. 1 due to the inherent principle of soft switching operation in all the active and auxiliary power switches.

C. High Frequency AC Power Regulation Characteristics

The input power or high frequency AC output power vs. duty cycle characteristic for the proposed ZCS-PWM high frequency SEPP inverter, which is based on duty cycle PWM control scheme is depicted Fig. 6. The solid line shows the simulation results and the dotted line gives the measured experimental ones. A good agreement between the experimental and the simulation results is evident as shown in Fig. 6. In the proposed zero current soft switching high frequency inverter circuit, its input power or the high frequency AC output power can be regulated approximately from a low value of 0.4 kW to 2.6 kW under a principle of zero current soft switching commutation. It is noted that the soft switching operating range becomes relatively large in the proposed voltage source ZCS-PWM SEPP high frequency inverter.

D. *Actual Efficiency Characteristics:* The measured actual power conversion efficiency vs. duty cycle characteristic of the proposed voltage source type ZCS- PWM high frequency inverter for consumer IH cooking heater is shown in Fig. 7. Under the rated output condition, the measured actual efficiency is estimated to be about 94% in total system, since a zero current soft switching commutation operation can be completely achieved for this high frequency inverter.

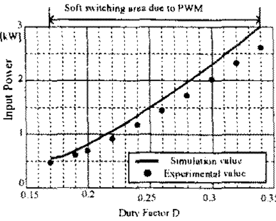

Fig. 6 Input power vs. duty factor characteristics

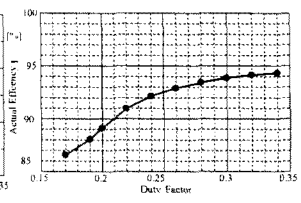

Fig. 7. Actual efficiency vs. duty factor characteristics

The zero current soft switching operating range of the proposed high frequency inverter can be actually extended by the use of high frequency pulse density modulation (PDM) control scheme under the low power settings or by the use of dual mode implementation of PWM and PDM selective control. Therefore, zero current the soft switching operation can be completely realized over all the output power regulation ranges including PDM in low power setting conditions and PWM in high power settings. The actual power conversion efficiency of the proposed voltage source ZCS-PWM high frequency inverter circuit is much higher than that of the previously developed ZVS-PWM one for lower output power setting ranges and the power conversion efficiency is almost the same for higher input power or higher output power ranges. This is due to the reason of the conduction power loss of the added auxiliary switch Q_3.

V. CONCLUSIONS

In this paper, a new topology of active auxiliary quasi-resonant snubber-assisted voltage source type ZCS-PWM SEPP high frequency series load resonant inverter using IGBTs, which is composed of an active auxiliary switched snubber capacitor and two lossless snubber inductors has been proposed and developed originally for consumer IH cooker, heated steamer, super heated steamer appliances and IH heat rollers. The practical effectiveness of the newly-proposed voltage source type ZCS-PWM SEPP high frequency multi resonant inverter using the latest trench gate IGBTs have been proved on the basis of the simulation and experimental results by producing an actual breadboard prototype. A wide soft switching commutation operation range of the newly proposed high frequency ZCS-PWM SEPP inverter has been obtained as compared with the previously developed voltage source type ZVS-PWM SEPP inverter. The high frequency power regulation strategy of this high frequency inverter could be efficiently supplied to the consumer high frequency IH cooking heater from full power to relatively small power settings. Applying a dual mode pulse modulation control strategy of the asymmetrical PWM in the higher power setting and the PDM in the lower power setting, the output power of this soft switching pulse modulated multi resonant high frequency inverter could be regulated under a condition of expanded stable soft switching operation ranges as compared with previously developed ZVS-PWM high frequency inverter. Therefore, the newly proposed dual mode ZCS PWM/PDM high frequency inverter could actually achieve higher efficiency, high performance and wider soft switching operating ranges.

ACKNOWLEDGMENT

This work was financially supported by MOCIE through IERC program

REFERENCES

[1] B. K. Lee, J. W. Jung, B. S. Suh, and D. S. Hyun, "A New Half-Bridge Inverter Topology with Active Auxiliary Resonant Circuit Using Insulated Gate Bipolar Transistors for Induction Heating Appliances," Proceedings of IEEE Power Electronics Specialists Conference (PESC), Vol.2, pp. 1232-1237, June, 1999.

[2] H. Terai, H. Sadakata, H. Omori, H. Yamashita, and M. Nakaoka, "High Frequency Soft Switching Inverter for Fluid-Heating Appliance Using Induction Eddy Current-based Involuted Type Heat," Proceedings of IEEE Power Electronics Specialists Conference, Vol 4, pp. 1874-1878, Cairns, Australia, June, 2002.

[3] H. Terai, T. Miyauchi, I. Hirota, H. Omori, Mamun A. Al, and M. Nakaoka, "A Novel Time Ratio Controlled High Frequency Soft Switching Inverter using 4th Generation IGBTs," Proceedings of IEEE Power Electronics Specialists Conference, (PESC), Vol. 4, pp. 1868-1873, Vancouver, Canada, June, 2001.

[4] H. Terai, I. Hirota, T. Miyauchi, H. Omori, K. Ogura, Y. Hirota, and M. Nakaoka, "Comparative Performance Evaluations of IGBTs and MCT in Single-Ended Quasi-Resonant Zero Voltage Soft Switching Inverter," Proceedings of IEEE Power Electronics Specialists Conference, (PESC), pp. 2178-2182, Vancouver, Canada, June, 2001.

[5] H. Tanaka, M. Kaneda, M. Ishitobi, E. Hiraki, and M. Nakaoka, "Electromagnetic Induction based Continuous Fluid Heating Appliance using Soft Switching PWM High Frequency Inverter," Proceedings of IEEE-IAS (Industry Application Society), International Appliance Technical Conference, (IATC), pp. 11-20, USA, May, 2000.