JPE 7-3-8

Advanced Induction Heating Equipment using Dual Mode PWM-PDM Controlled Series Load Resonant Tank High Frequency Inverters

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ABSTRACT

In this paper, a novel type auxiliary active edge resonant snubber assisted zero current soft switching pulse modulation Single-Ended Push Pull (SEPP) series load resonant inverter using IGBT power modules is proposed for cost effective consumer high-frequency induction heating (IH) appliances. Its operating principle in steady state is described by using each switching mode's equivalent operating circuits. The new multi resonant high-frequency inverter with series load resonance and edge resonance can regulate its high frequency output power under a condition of a constant frequency zero current soft switching (ZCS) commutation principle on the basis of the asymmetrical pulse width modulation (PWM) control scheme. Brand-new consumer IH products using the proposed ZCS-PWM series load resonant SEPP high-frequency inverter using IGBTs is evaluated and discussed as compared with conventional high-frequency inverters on the basis of experimental results. In order to extend ZCS operation ranges under a low power setting PWM as well as to improve efficiency, the high frequency pulse density modulation (PDM) strategy is demonstrated for high frequency multi-resonant inverters. Its practical effectiveness is substantially proved from an application point of view.

Keywords: High frequency inverter, Series capacitor compensated resonant load, Lossless inductor snubbers, Auxiliary switched capacitor snubber, Zero current soft switching, Dual mode PWM and PDM control, Consumer IH appliances

1. Introduction

1.1 Technical Backgrounds

With great advances in high frequency power electronics technologies, an efficient electromagnetic eddy current based induction heating (IH) approach is more acceptable for consumer food cooking and processing appliances such as cooking heaters, rice cookers and warmers, hot water producers and steamers, along with super heated vapor steamers. A variety of small scale IH appliances not only fulfills the key demands of safety and cleanliness, but also has excellent advantages as high thermal conversion efficiency, rapid heating, local spot heating, direct heating, high power density, high reliability, low running cost and non-acoustic noise. The aforementioned IH home appliances using high frequency inverters make use of eddy current based Joule's heat and hysteretic loss heat due to Faraday's electromagnetic induction law and can supply high-frequency AC power to

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the IH load, which consists of a working coil and eddy current based heating materials. Some types of high-frequency multi resonant inverters operating over power frequency ranges from 20kHz to several MHz have some advantages as cost effectiveness, high efficiency and high power density. There are various high-frequency inverter circuit topologies, such as a full bridge, half bridge, single-ended push-pull, center tap push-pull and boost half bridge. Of these, the voltage source type ZCS (Zero Current Soft switching) SEPP (Single-Ended Push Pull) resonant and quasi-resonant high-frequency inverter topologies developed by the authors have remarkable features as simple configuration, high efficiency and wide soft commutation range.

1.2 Research Objective

In this paper, a voltage source type ZCS-SEPP high-frequency multi-resonant inverter with a constant frequency duty cycle PWM control function, which is composed of switched capacitor and two lossless inductors in series with the main switches, is newly proposed for consumer IH food cooking and processing applications. The operating principle of the proposed high frequency inverter circuit with a PWM control scheme for IH heated power regulation is described herein by using switching mode equivalent circuits. The feasible operating characteristics of this high frequency inverter using IGBTs are illustrated and evaluated on the basis of experimental results and simulation. Finally, in order to extend soft switching operating ranges under low power setting conditions, a pulse density modulation-based power regulation scheme is discussed for this ZCS-PWM controlled IH high frequency inverter.

2. Soft Switching High Frequency Inverters

2.1 Circuit Description

The newly developed voltage source type ZCS-PWM-SEPP high-frequency inverter circuit for consumer induction heaters is shown in Fig.1 and its modified topologies in Fig.2 (a), (b), (c), (d), which includes two lossless inductor-assisted series load resonant inverters with a single auxiliary switched capacitor to provide a constant frequency PWM strategy. This multi-resonant ZCS-PWM high-frequency inverter circuit consists of the main active switches $Q_1(SW_1/D_1)$ and $Q_2(SW_2/D_2)$, a single auxiliary active switch $Q_3(SW_3/D_3)$ in series with auxiliary quasi-resonant capacitor Cr, ZCS-assisted two inductor snubbers L_{S1} and L_{S2} in series with Q_1 and Q_2, IH load power factor compensation series resonant capacitor C_S, and IH load with *Ro* and *Lo* series circuitry represented by equivalent inductive circuit model, *Ro*; effective equivalent resistance of IH load, and *Lo*; effective equivalent inductance of IH load.

Because of constant frequency operation, the load parameters (*Ro & Lo*) are kept constant and seem to exhibit no skin effect. It is noted that the proposed soft switching PWM high-frequency inverter circuit consists of a few circuit components and low cost circuit configurations. Another Multi-resonant ZCS- SEPP PWM high frequency inverter topology is shown in Fig. 2a [Single-end half bridge topology and fig.2b divided capacitor single-end half bridge high frequency inverter] and Fig. 2c [Divided Capacitor double-ended half-bridge topology position of Q3 (SW3/D3)] and these can be interchanged to control the output to satisfy the load requirements.

2.2 High Frequency AC Power Regulation Scheme

The high-frequency AC effective output power of the proposed inverter circuit in Fig.1 can be continuously regulated by a constant frequency asymmetrical PWM control scheme under a condition of zero current soft commutation principle. The PWM gate pulse timing sequences of this high-frequency inverter are illustrated in Fig.3. By the constant frequency asymmetrical PWM control scheme which is based on varying the time ratio of total conduction times *Ton* of Q_1 and Q_3 to the operating switching period *T* of high-frequency AC output, the proposed multi-resonant high-frequency inverter circuit can control the high-frequency AC output power continuously.

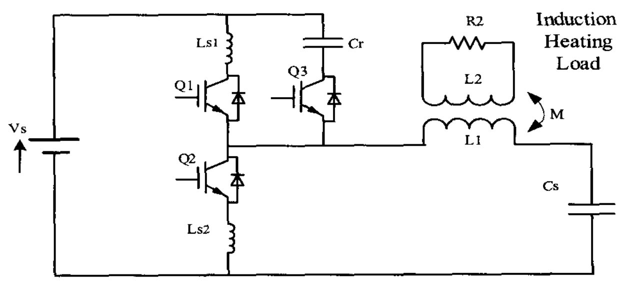
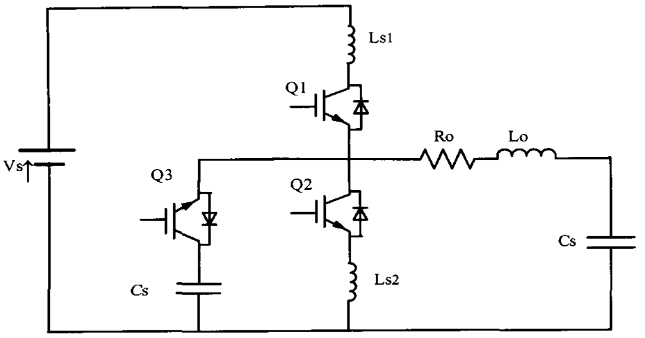
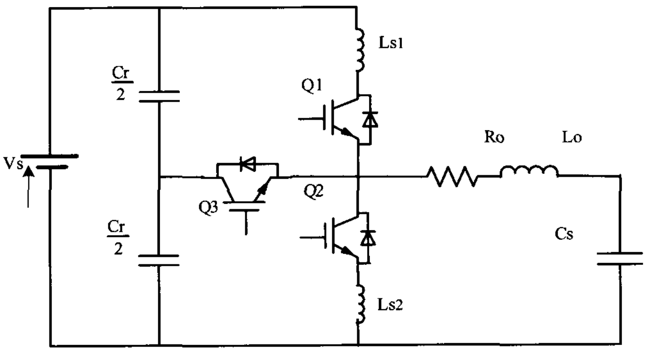


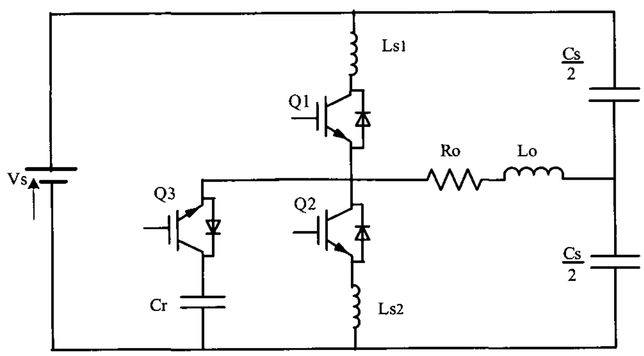
Fig. 1 Multi Resonant ZCS-PWM high frequency inverter topology (1) with low side load resonant circuit



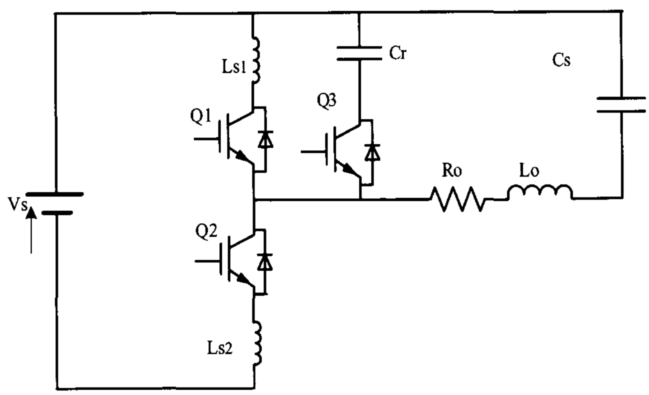
a) Single ended half bridge topology (2)



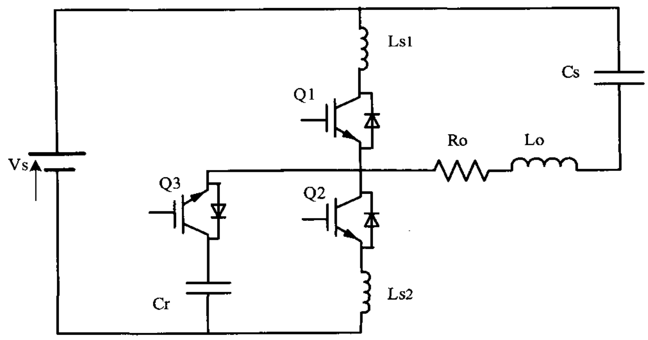
b) Divided Capacitor Single Ended half bridge Topology (3)



c) Divided Capacitor Double Ended half bridge Topology (4)



d) Single ended high side load resonant topology (5)



e) Single ended high side load resonant topology (6)

Fig. 2 Multi-resonant ZCS- PWM high frequency inverter topologies

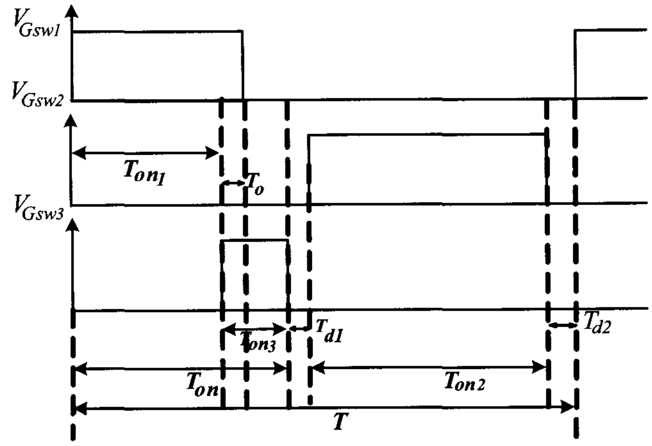


Fig. 3 Asymmetrical PWM gate pulse timing sequences

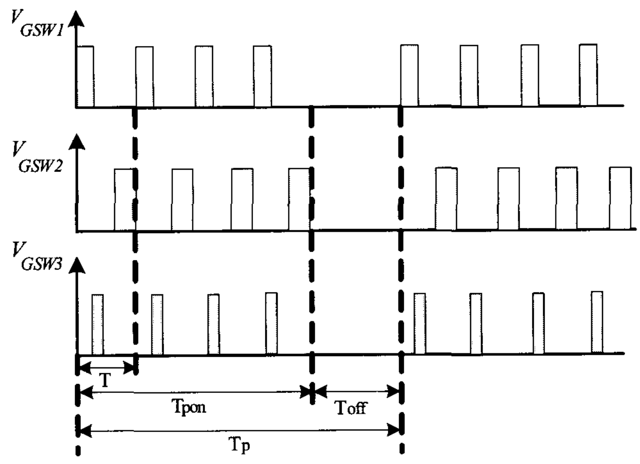


Fig. 4 Dual mode PWM/PDM gate pulse timing sequences

The external gate signal driver only changes the conduction time Ton1 of Q1 (SW1/D1). The overlapping time T_O determined by conduction time *Ton1* of Q_1 and conduction time *Ton3* of Q_3 is designed for a constant value. As a control variable in the proposed asymmetrical duty cycle PWM scheme, the Duty Factor *D* as a control variable is defined as follows,

$$D = \frac{Ton + Td1}{T} \quad (1)$$

By varying the duty factor *D* as a constant variable, the high-frequency AC output power of this multi-resonant inverter can be regulated continuously.

The voltage-fed ZCS-PWM high-frequency IH load resonant inverter can be controlled by not only the constant frequency asymmetrical PWM scheme but also the constant frequency dual mode PWM/PDM scheme. By using the PDM control scheme illustrated in Fig.4, the zero current soft switching operating range can be achieved even in low power setting ranges. As another control variable of the PDM scheme, Duty Factor *Dp* can be defined as:

$$D = \frac{Ton + Td1}{T} \quad (2)$$

The high frequency AC effective power regulation can be achieved by means of changing the PDM ratio as *Tpon* to one cycle period *Tp* specified here.

$$D_p = \frac{T_{pon}}{T_p} \quad (3)$$

2.3 Remarkable Features

The outstanding features of the newly developed soft switching multi-resonant high frequency inverter are summarized below;

- The DC component of the high frequency current through the working coil is zero because of the series capacitor compensated resonant tank.
- The zero current soft switching commutation range becomes much wider from high power to low power setting ranges.
- The actual efficiency of this high-frequency inverter is much higher over wider power regulation ranges from high power settings to low power settings because of the selective dual mode PWM and PDM control scheme.
- Constant frequency operation can be implemented. As a result, the IH load parameters are kept constant.

3. Steady State Operating Principle

3.1 Relevant Operating Waveforms

The operating mode transitions and equivalent circuits of the proposed high frequency inverter circuit in periodic steady state are represented in Fig.5. This multi-resonant high-frequency inverter circuit has eleven repeating operating mode transitions. The operation principle of the proposed inverter circuit is explained below.

3.2 Operating Principle

The zero current soft switching operation for all the active switches Q1, Q2, Q3 in the proposed multi-resonant inverter circuit can be achieved under a gate pulse sequence pattern as depicted in Fig.3. In Mode1, the first setting, the high side main switch SW_1 of Q_1 is now conducting and high-frequency AC power is supplied to the IH load. After the current i_{SW1} through SW_1 of Q_1 commutates to anti-parallel diode D_1 of Q_1 by quasi-resonance due to ZCS-assisted inductor snubber L_{S1} in the series with Q_1 together with the auxiliary resonant capacitor Cr, the auxiliary active switch SW_3 of Q_3 is turned on and the main switch SW_1 of Q_1 is turned off. As a result, ZCS commutation at a turn-off mode transition can be implemented by the arbitrarily timing processing in turning off the switch SW_1 of Q_1. At this time, since an auxiliary resonant current i_{SW3} flows through the switch SW_3 of Q_3 and increases softly, ZCS commutation at a turn-on mode transition can be achieved for SW_3 of Q_3.

After i_{SW3} flowing through SW_3 is commutated to anti-parallel diode D_3 of Q_3 by the quasi-resonance together with Cr, R_O-L_O inductive load circuitry with a series power factor compensation tuned capacitor C_S, ZCS commutation at the turn-off mode transition can be performed by turning off SW_3 of Q_3. While the auxiliary active switch SW_3 of Q_3 turns on, the voltage 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 turns on, D_2 of Q_2 begins to conduct. While D_2 of Q_2 continues conducting, the current flowing through the diode D_2 is naturally commutated to SW_2 of Q_2. Therefore, a complete ZVS and ZCS hybrid commutation 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 induction heated load represented by R_O-L_O series circuit and power factor compensation series load resonant tuned capacitor Cs, the ZCS commutation at a turn-off mode transition can be performed by turning off the switch SW_2 of Q_2. While D_2 of Q_2 is now conducting, the current i_{D2} flowing through D_2 of Q_2 is commutated to the switch SW_1 of Q_1 by turning on the switch SW_1 of Q_1. At this time, a ZCS turn-on commutation can be realized with the aid of the ZCS-assisted first inductor snubber L_{S1}.

3.3 Time Domain and Frequency Domain Analysis

Fig. 6 represents the equivalent circuit model of the proposed inverter. According to load current direction, it has two states: the first is Q1 or Q3 turn on state in which power transferred from source to Load. The second state is the Q2 turn on state, in which the compensating capacitor discharges through the load.

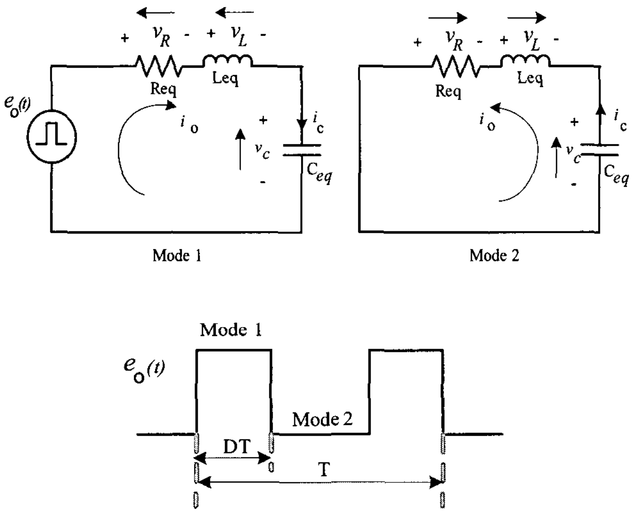


Fig. 6 Simplified equivalent circuits

Modes from 1 to 5, 10 and 11 provide the same circuit operation that the load current transfer from the source to Load through Q_1, Q_2, L_{s1} and C_r so these modes are represented as state 1. At this state the equivalent input voltage $e_0(t)$ is defined as:

$$e_0(t) = V_s \qquad \text{for} \quad 0 \le t \le DT \tag{4}$$

$e_0(t)$ is expressed by Quasi-square voltage determined through duty factor D, which is depicted by Fig. 6

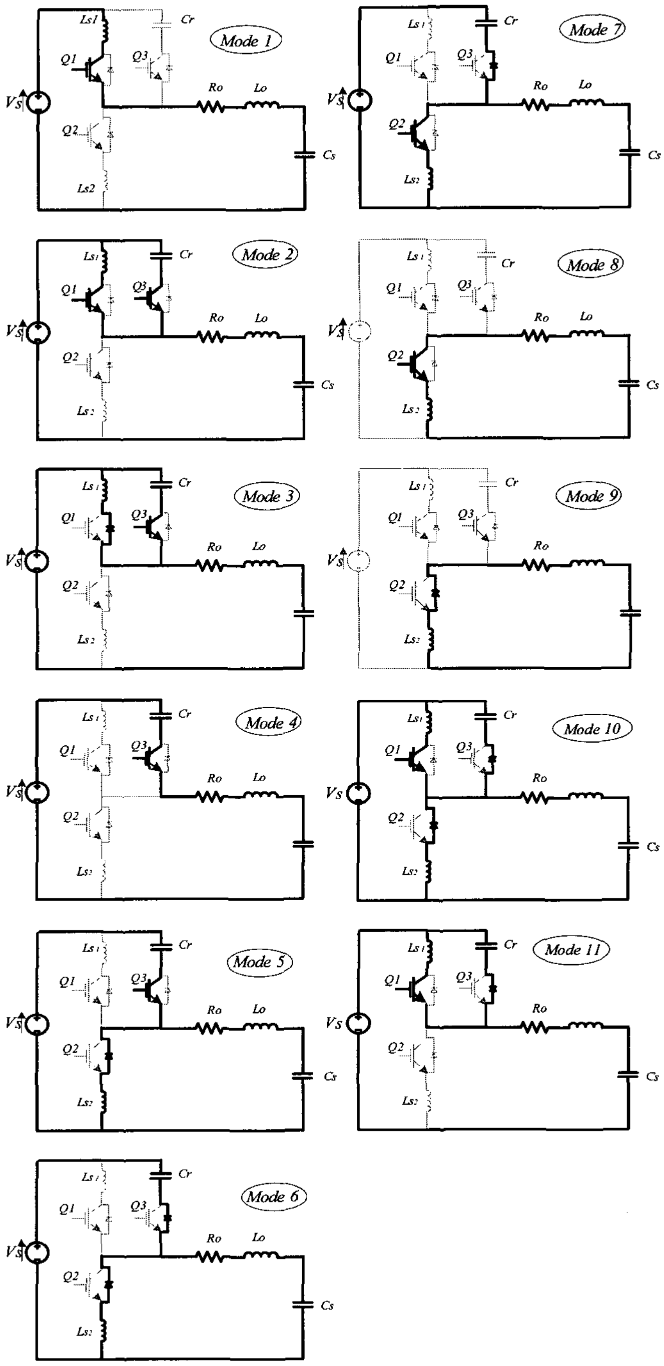


Fig. 5 Operating mode transition and equivalent circuits at steady state during one switching cycle

The current equations of the equivalent circuit in state are represented by:

$$R_{eq}i_o + L_{eq}\frac{di_o}{dt} + v_{cs} = V_s \quad (5)$$

$$i_o - C_{eq}\frac{dv_{cs}}{dt} = 0 \quad \text{, charging mode} \quad (6)$$

where $0 \le t \le DT$

Solving equations 5, 6 we get the value of load current, taking the under-damped case where $\frac{R_{eq}}{2L_{eq}} \le \sqrt{\frac{1}{L_{eq}C_{eq}}}$ For initial conditions current in the equivalent inductor with initial state variables; $i_o(0^-)$ and $V_{ceq}(0^-)$ are the compensating capacitor initial voltage, and the output current is calculated from:

$$i_o(t) = e^{-\alpha t}\left[A_1 \cos\omega_d t + A_2 \sin\omega_d t\right] \quad (7)$$

where ω_o is the resonant frequency and α the damping factor; in series resonant circuit

$$\alpha = \frac{R_{eq}}{2L_{eq}}, \ \omega_d = \sqrt{\omega_o - \alpha^2}, \omega_o = \sqrt{\frac{1}{L_{eq}C_{eq}}}$$

$$A_1 = i^{-0}, \ A_2 = \frac{V_s - V_{ceq}^{0-}}{\omega_d L_{eq}} - \frac{Ri_o^{0-})}{2\omega_d L_{eq}}$$

The mode transition conditions of the state variable are indicated as $i_o(0) = i_o(T) = i_o^{0-}, \ v_{ceq}(0) = V_{ceq}^{0-}$

For the second state which represents modes 7, 8, 9 the output current is given by

$$R_o i_o + L_{eq}\frac{di_o}{dt} + v_{ceq} = 0 \quad (8)$$

$$i_o + C_{eq}\frac{dv_{ceq}}{dt} = 0 \quad \text{, discharging mode} \quad (9)$$

$DT \le t \le T$

$$i_o(t) = e^{-\alpha t}\left[A_3 \cos\omega_d t + A_4 \sin\omega_d t\right] \quad (10)$$

$$A_3 = i_o(0^+), \ A_4 = \frac{V_s - V_{cs^+}}{\omega_d L_{eq}} - \frac{R}{2\omega_d L_{eq}} i_o(0^+)$$

where i_o^{+0}, V_{ceq}^{+0} are the initial state variable conditions of mode 2

$$i_o(DT) = i_o^{+0}, \ v_{ceq}^{+0}(DT) = V_{ceq}^{+0}$$

The initial values are estimated as a function of duty factor D by using a steady state variable (continuous and periodic state conditions of steady state variables)

The ratio α / ω_o is defined as the damping factor δ:

$$\delta = \frac{\alpha}{\omega_o} = \frac{R_o}{2\sqrt{L_{eq}/C_{eq}}}$$

The output voltage and load current due to frequency domain analysis can be expressed in terms of the Fourier series as follows:

$$v_o(t) = \frac{DV_s}{2} + \sum_{n=1,3,5,\dots}^{\infty} \frac{2V_s}{n\pi}\sin 2nD\pi \cos n(\omega t - D\pi) \quad (11)$$

$$i_o(t) = \sum_{n=1,3,5,\dots}^{\infty} \frac{2V_s}{n\pi|Z_n|}\sin 2nD\pi \cos n(\omega t - D\pi - \theta_n) \quad (12)$$

where Z_n is the load impedance at harmonic n and θ_n is the load angle

Power absorbed by the load with series resistance is determined from $I_{rms}^2 R_o$ where rms. The current can be determined from each component in the Fourier series by

$$I_{rms} = \sqrt{\sum_{n=1}^{\infty} I_{n,rms}^2} = \sqrt{\sum_{n=1}^{\infty}\left(\frac{I_n}{\sqrt{2}}\right)} \quad (13)$$

$$\text{where} \quad I_n = \frac{V_n}{Z_n} \quad (14)$$

$$P = \sum_{n=1}^{\infty} P_n = \sum_{n=1}^{\infty} I_{n,rms}^2 R_{eq} \quad (15)$$

4. Experimental Results and Evaluations

4.1 Design Specifications and Circuit Parameters

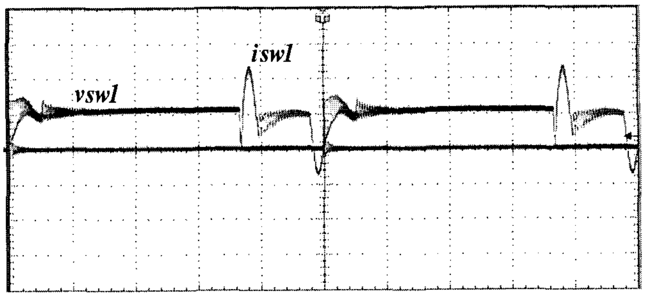
The evaluations and discussion in experiment prove the validity of the proposed multi-resonant high-frequency inverter circuit treated here. The design specifications and circuit parameters used in experiment are respectively listed in Table1. The proposed multi-resonant inverter circuit topology is designed for consumer IH food cooking heater applications in home and business use. Therefore, the stainless steel pan with its bottom diameter 18cm is used for IH load as a heated object. This IH load consists of a stainless steel pan, ceramic or plastic spacer, and working coil composed of litz wire. The circuit parameters of this multi-resonant inverter are determined by considering the soft switching condition and output power ranges.

Table 1 Design specifications and circuit constants

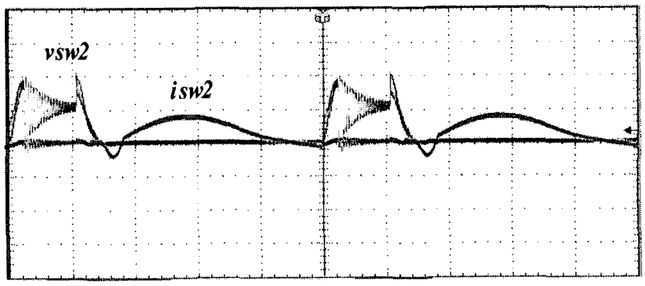
Item	Symbol	Value
DC Source Voltage	V_s	270 V
Switching Frequency	f_{sw}	20 kHz
ZCS-assisted Inductor	L_{s1}	2.01 Mh
ZCS-assisted Inductor	L_{s2}	2.01 Mh
Auxiliary Quasi-resonant Capacitor	C_r	330 Nf
Compensation series tuned capacitor	C_s	0.8 Mf
Load Resistance	R_o	2.1
Load Inductance	L_o	45 Mh

4.2 Measured Operating Waveforms and Verifications

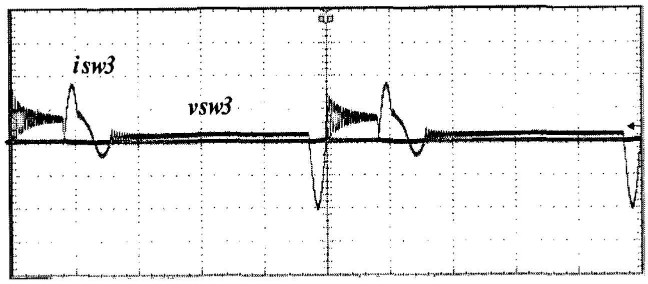
The steady state measured switching operating waveforms for duty factor D=0.34 under a condition of the input DC power 2.4kW for built-in burners are represented in Fig.7. As can be seen in Fig.7, it is noted that all the active main and auxiliary power switches can operate under a principle of zero current soft switching PWM strategy. All the power switches can achieve ZCS operation under PWM regulation. In particular, it can be recognized that complete ZVS and ZCS hybrid soft commutation at turn-on mode transition is performed for the main switch SW_2 of Q_2, because the main SW_2 of Q_2 turns on during a conduction period of D_2 of Q_2. Since the gate pulse voltage signal is not given to the auxiliary switch SW_3 of Q_3 during a conduction period of anti-parallel diode D_3 of Q_3, the ZCS commutation at a turn-on mode transition can be achieved for the main switch SW_1. Because of zero current soft switching operation in all the power switches, in spite of auxiliary switch SW_3 of Q_3, a high efficiency power conversion can be achieved in the proposed high-frequency inverter circuit in Fig.1.



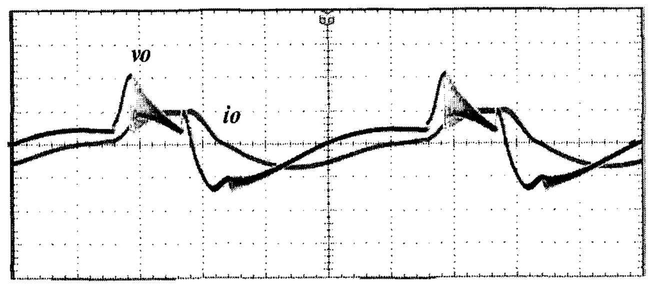
(a) Voltage and current waveforms of Q 1 (250V/div, 40A/div, 10 μs/ div)



(b) Voltage and current waveforms of Q 2 (250V/div, 40A/div, 10 μs/div)



(c)Voltage and current waveforms of Q 3 (250V/div, 40A/div,10 μs/div)



(d)Output voltage and current waveforms (250V/div, 40A/div,10 μs/div)

Fig. 7 Measured voltage and current waveforms in case of D=0.34

4.3 Power Regulation Characteristics

The input DC power (or output AC power) vs. duty factor characteristics for the proposed voltage source type ZCS-SEPP high-frequency multi-resonant inverter with PWM control scheme using the trench gate IGBTs is depicted Fig.8. In the high-frequency multi-resonant inverter circuit proposed here, the input DC power of this high-frequency inverter can regulate approximately from 0.5kW to 2.4kW under a principle of zero current soft switching commutation. The soft switching operating range is relatively large in the proposed ZCS-PWM-SEPP high-frequency inverter using IGBTs.

4.4 Actual Efficiency Performances

The actual power conversion efficiency characteristics of the proposed ZCS PWM-SEPP high-frequency inverter for the consumer IH food cooking heater are shown in Fig.9. Under the rated output condition, the actual efficiency of the proposed inverter using the IGBT power module is experimentally estimated as about 96%. Since a zero current soft switching operation in this multi-resonant high-frequency inverter can be completely achieved even in the case of duty factor D=0.16 under the condition of the minimum output AC power for PWM control, the actual power conversion efficiency can be sufficiently kept at 84%.

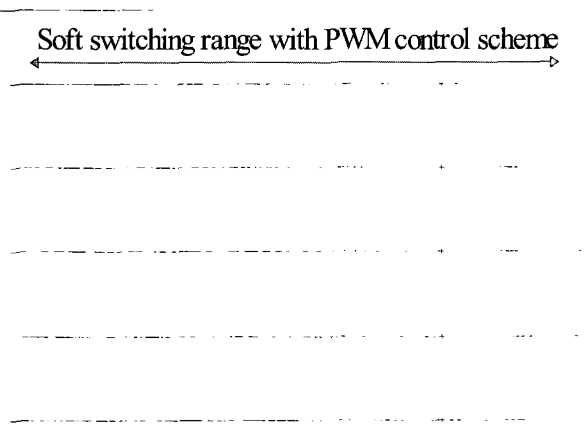


Fig. 8 Power vs. duty factor characteristics

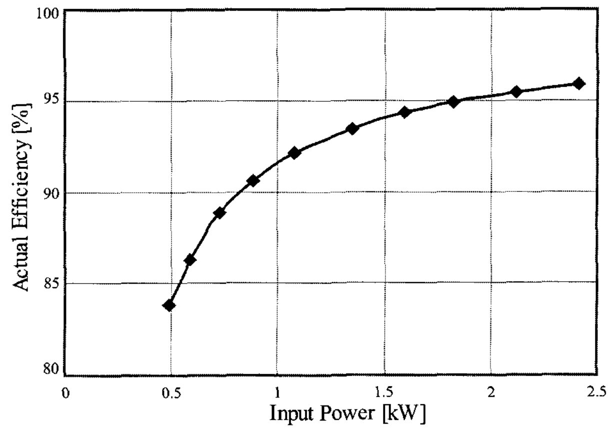


Fig. 9 Actual efficiency vs. input characteristic in case of PWM control scheme

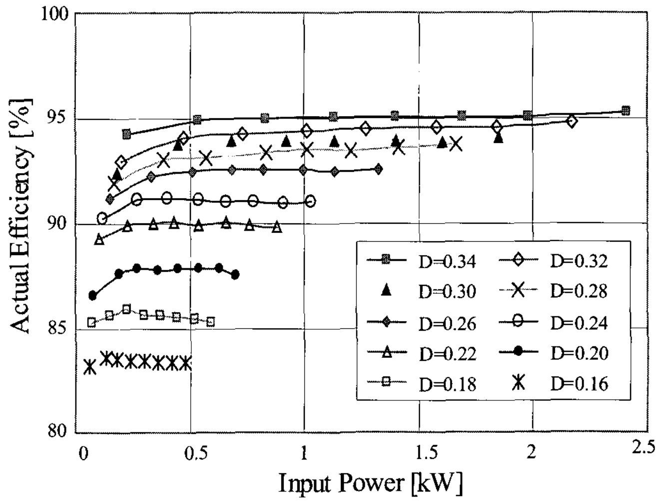


Fig. 10 Actual efficiency vs. input power characteristics in case of dual mode PWM/PDM hybrid mode control scheme

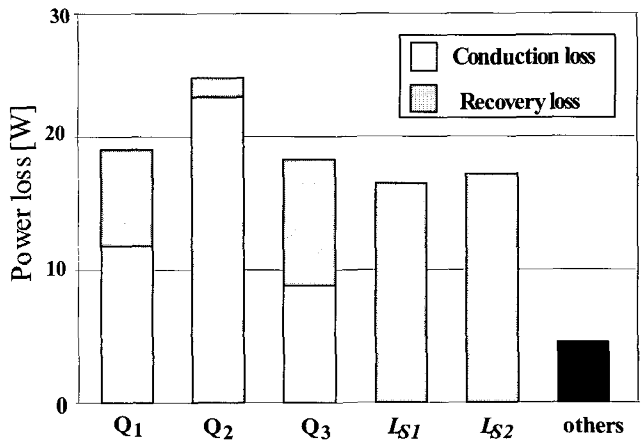


Fig. 11 Power conversion loss analysis in case of D = 0.34

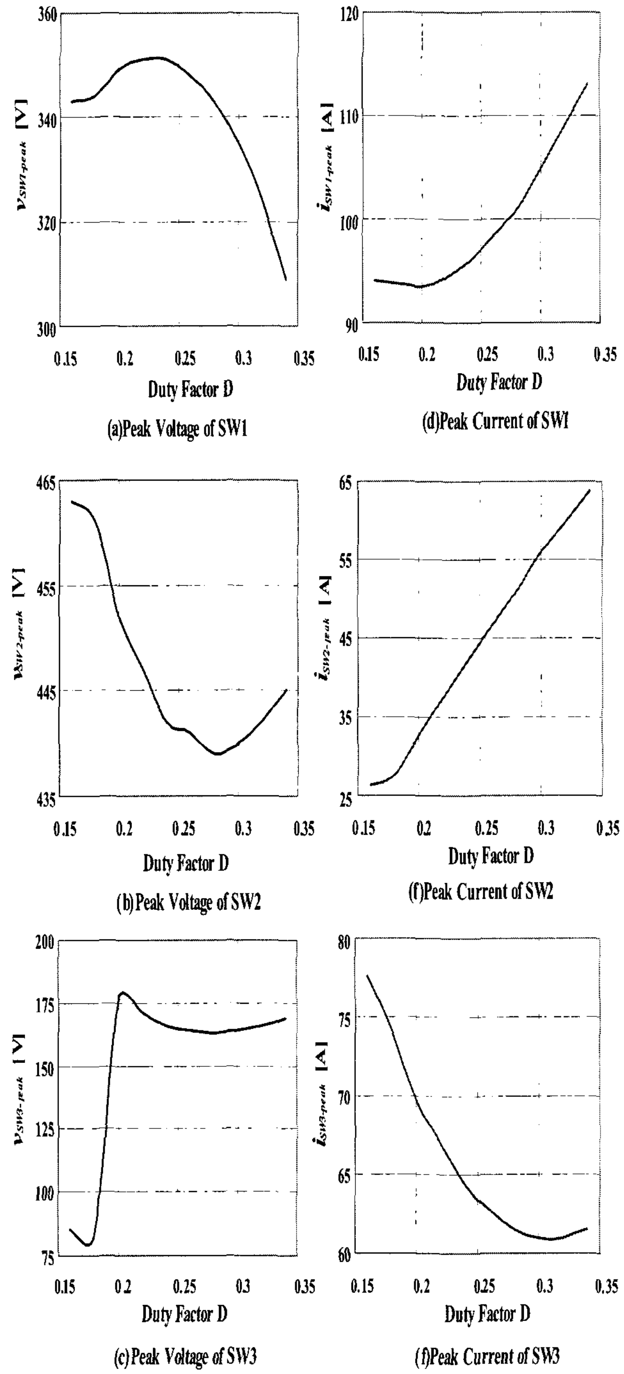


Fig. 10 Peak voltage and current characteristics

4.5 Dual Mode PWM and PDM Characteristics

The selective dual mode PWM and PDM control scheme is newly introduced in order to improve the actual efficiency under low power setting conditions. The actual efficiency vs. input power characteristics for an asymmetrical PWM control scheme and selective dual mode PWM and PDM control strategy are comparatively shown in Fig.10. The actual efficiency more than 90% ranging from high power settings to low power settings can be realized by introducing dual mode selective PWM and PDM control schemes.

4.6 Power Loss Analysis and Evaluations

Power conversion loss analysis of the proposed high-frequency multi-resonant inverter in case of D=0.34 (Input power 2.41kW) is shown in Fig.11. Conduction loss is composed of saturation voltage of switches (Q_1, Q_2, Q_3) and resistivity of ZCS assisted inductors (L_{S1}, L_{S2}). The loss of Q_3 is conjected to be constant despite of Duty Factor, because it is generated by soft switching PWM control. As can been seen in Fig.12, peak voltage of switchQ_3 is lower than switchQ_1 and switchQ_2. Therefore, it is possible to change switchQ_3 for improved power conversion efficiency.

5. Conclusions

In this paper, a new topology of active edge resonant snubbers assisted voltage source type ZCS-PWM-SEPP high frequency multi-resonant inverter with a series capacitor compensated IH load resonant tank was proposed for IH appliances originally. The operating principle and the operating characteristics of the new high-frequency circuit treated here were illustrated and evaluated on the basis of simulation and experimental results.

For a consumer IH food cooking heater, the practical effectiveness of the proposed multi-resonant inverter using the trench gate IGBT power module was proved on the basis of the simulation and the experimental results by the breadboard setup production. The zero current soft switching commutation range was much wider in spite of the pulse width modulation control as well as frequency modulation.

The high-frequency power of this inverter could be efficiently supplied to the induction heated load in the IH cooking heater from full power setting to small power setting. Furthermore, it was examined that the complete soft switching operation can be achieved even for a low power setting by introducing the high-frequency PDM control scheme. In the proposed high-frequency inverter treated here, the 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 high-frequency inverter could be introduced in order to extend soft switching operation ranges. Therefore, it was proved from an experimental point of view that the proposed zero current soft switching PWM high-frequency inverter for IH cooking heaters and IH steamers can actually achieve high efficiency and obtain wider soft switching range in selective PWM and PDM dual mode power control schemes.

In the future, the new PWM/PDM multi-resonant high frequency inverter topology using the latest Emitter Switched Bipolar Transistor (ESBT) and SiC-JFETs should be experimentally investigated and evaluated in order to realize much higher efficiency for consumer IH appliances.

Acknowledgment

This work supported by the Kyungnam University Research Fund.

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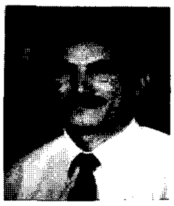

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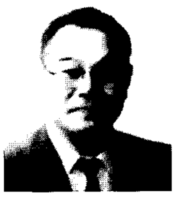

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