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A Novel Auxiliary Edge-Resonant Snubber-Assisted Soft Switching PWM High Frequency Inverter with Series Capacitor Compensated Resonant Load for Consumer Induction Heating

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ABSTRACT

In this paper, a novel prototype of auxiliary switched capacitor assisted voltage source soft switching PWM Single-Ended Push Pull (SEPP) series capacitor compensated load resonant inverter with two auxiliary edge resonant lossless inductor snubbers is proposed and discussed for small scale consumer high-frequency induction heating (IH) appliances. The operation principle of this inverter is described by using switching mode equivalent circuits. The newly developed multi resonant high-frequency inverter using trench gate IGBTs can regulate its output AC power via constant frequency edge-resonant associated soft switching commutation by using an asymmetrical PWM control or duty cycle control scheme. The brand-new consumer IH products which use the newly proposed edge-resonant soft switching PWM-SEPP type series load resonant high-frequency inverters are evaluated using power regulation characteristics, actual efficiency vs. duty cycle and input power vs. actual efficiency characteristics. Their operating performance compared with some conventional soft switching high-frequency inverters for IH appliances is discussed on the basis of simulation and experimental results. The practical effectiveness of the newly proposed soft switching PWM SEPP series load resonant inverter is verified from an application point of view as being suitable for consumer high-frequency IH appliances.

Keywords: Single-ended push-pull inverter, High frequency inverter, Series capacitor compensated resonant load, Lossless inductor snubbers, Auxiliary switched capacitor, Soft switching PWM, Induction heating, Home power electronics

1. Introduction

In recent years, consumer power electronics relating to high frequency electromagnetic eddy current based induction heating (IH) technology have become more suitable and acceptable for small scale consumer food cooking and processing appliances such as multi-burner cooking heaters, rice and wheat cookers, hot water producers and steamers. In addition, the technology has been used for super heated vapour steamers including the IH fixing roller used in copy machines and printers[1-3].

In general, IH equipment for consumer power and energy applications in home and business use not only meet the practical demands of safety, cost effectiveness and cleanliness, but also has the following advantages:

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very high thermal conversion efficiency, rapid heating, local focusing heating, high power density, direct heating, high reliability environmental recycle non-acoustic noise and low electromagnetic noise.

These, IH appliances make use of eddy current oriented joule's heat based on Faraday's electromagnetic low noise induction law and need to supply high-frequency power to a variety of IH loads, which consist of planer (pancake) or cylindrical working coils with electromagnetic eddy current based heated materials. Some high-frequency inverters operating at ranges from 20 kHz to several MHz need cost effective high efficiency and high power density high-frequency power supplies. Among the various types of high-frequency inverter topologies, there are full bridge, half bridge, single-ended push-pull and center tap push-pull configurations, in which voltage source type lossless snubber inductor assisted zero current soft switching (ZCS) SEPP load resonant, voltage source type zero voltage soft switching (ZVS) SEPP resonant inverter and voltage source ZVZCS-SEEP multi resonant inverter. These high frequency soft switching inverters which have simple configurations, high efficiency, low cost and wide soft commutation operating ranges are indispensable for high frequency operation. The voltage source type ZCS high frequency inverter and its modifications match the practical operating requirements mentioned previously. However, these high frequency inverters are not able to regulate output power under constant frequency pulse modulations.

In this paper, a novel circuit topology of a voltage source ZCS-SEPP high-frequency multi resonant inverter using a constant frequency PWM control strategy with active auxiliary quasi- resonant lossless inductor snubbers and a switched capacitor is proposed for cost effective consumer IH food cooking and processing heater applications, which include practical outstanding features. The operating principles of the proposed high frequency inverter topology, the ZCS-PWM control scheme for power regulation and the actual efficiency characteristics for the PWM control strategy are illustrated and evaluated on the basis of simulation and practical experimental results. Also, the effectiveness of this proposed high frequency inverter is substantially proved for consumer induction heating.

2. Voltage Source ZCS-PWM SEPP High Frequency Inverter

2.1 Circuit Configuration

The newly developed multi-resonant ZCS-PWM-SEPP high-frequency inverter circuit using the latest trench gate IGBTs is shown in Fig. 1. This high frequency inverter is composed of two lossless snubber inductor-assisted series load resonant inverters with auxiliary switched capacitors for edge resonance commutation and uses a PWM control strategy. This high-frequency inverter circuit consists of the main switches; reverse conducting IGBTs; $Q_1(SW_1/D_1)$ and Q2(SW2/D2), a single auxiliary switch $Q_3(SW_3/D_3)$ in series with an auxiliary quasi-resonant capacitor C_r as an active snubber, ZCS-assisted lossless inductor snubbers L_{S1} and L_{S2} ($L_{S1} = L_{S2}$) in series with Q_1 and Q_2, a power factor compensation series load resonant capacitor C_s, and a highly inductive induction heated load represented by its equivalent series inductive circuit model of R_o and L_o. The proposed ZCS-PWM SEPP high-frequency inverter circuit is configured using a few circuit components and power semiconductor devices.

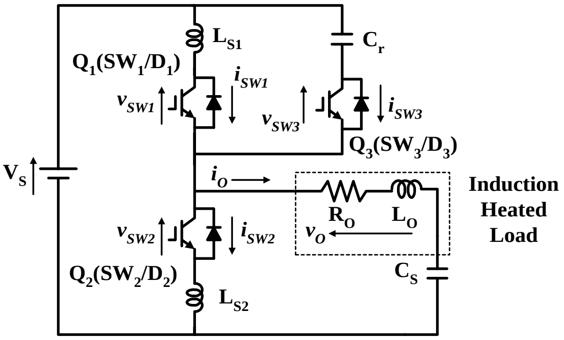


Fig. 1 Multi-resonant ZCS-PWM SEPP high-frequency inverter

2.2 High Frequency AC Control Scheme

The output high-frequency AC power of the proposed inverter circuit, which is delivered at the IH load, can be regulated by a constant frequency asymmetrical PWM (duty cycle) control scheme in a soft switching commutation mode. The proposed PWM gate pulse timing sequences of the active power switches Q_1, Q_2, and Q_3 are shown schematically in Fig. 2. The main active power switch Q_1 is first switched on for a period of time T_{on1}.

Before the main switch Q_1 is turned off by a time of T_o, the auxiliary switch Q_3 is turned on during a period T_{on3} inserting a current overlapping time of T_o between 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 constant frequency asymmetrical PWM control scheme or the duty cycle (defined as the sum of the conduction time T_{on1} of the main active switch Q_1 and the conduction time T_{on3} of the auxiliary power switch Q_3 divided by the total period operating time T of a high switching frequency pulse signal), the proposed high frequency inverter circuit can control the high-frequency output power using ZCS PWM soft switching. The conduction time T_{on1} of the main active switch Q_1 can be controlled while keeping the conduction time T_{on3} of the auxiliary active switch, the overlapping time T_o and the dead time T_{d1} constant to control the duty cycle D. As a control variable of the proposed asymmetrical PWM, the duty cycle D is defined by

$$D = (T_{on} + T_{d1}) / T \tag{1}$$

By varying the duty cycle, the high-frequency output power can be regulated. The voltage source ZCS-PWM SEPP high-frequency series load resonant inverter with two lossless inductor snubbers and a single switched capacitor can not only be controlled using the described constant frequency asymmetrical PWM strategy, but it can also be controlled using a constant frequency pulse density modulation(PDM) technique. By using hybrid dual mode control of asymmetrical PWM and PDM at a constant high frequency, the soft switching operating range can be effectively expanded from high power to low power settings.

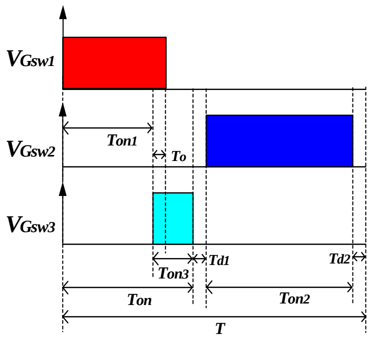


Fig. 2 Proposed PWM gate pulse timing sequence pattern

3. Steady-State Operation Principle

The operating mode transitions and their corresponding equivalent circuits for the proposed soft switching high frequency inverter circuit at 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 high-frequency soft switching multi-resonant inverter circuit includes eleven operating modes as shown in Fig. 3. The operation principle of the proposed soft switching inverter circuit can be explained as follows by using the corresponding equivalent circuits,

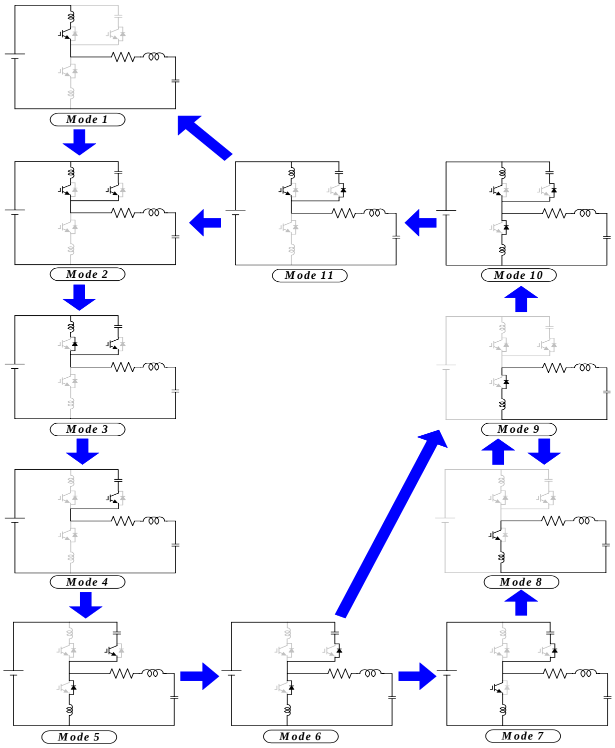


Fig. 3 Operating mode transitions and equivalent circuits at steady state during one switching cycle

The soft switching operation for the two main switches and the auxiliary switch in the proposed inverter circuit can be implemented using the gate pulse timing sequence pattern shown in Fig. 2. At the beginning of each switching cycle, the high side main switch SW_1 of Q_1 is conducting and high-frequency AC power is supplied to the IH load. After the switch current i_{SW1} through SW_1

naturally commutates to the switch anti-parallel diode D_1 of Q_1 by quasi-resonance due to the ZCS-assisted inductor snubber $L_{S1} = L_{S2}$ in series with the switch Q1, together with the auxiliary series load resonant tuned capacitor C_s, 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, a ZCS commutation at a turn-off switching mode transition can be implemented by the arbitrarily timing processing when turning off the main switch SW_1 of Q_1. At this time, since an auxiliary resonant current i_{SW3} flows through the switch SW_3 which increases slowly, 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 together with C_r, R_o-Lo inductive load circuitry with a power factor series load compensation tuned capacitor C_s, a ZCS commutation at a turn-off switching mode transition can be performed for the auxiliary active power switch SW_3 of Q_3. While the auxiliary 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, the diode D_2 of Q_2 becomes reverse biasing and begins to conduct. While the diode D_2 continues conducting, the current flowing through D_2 is naturally commutated to SW_2 of Q_2. Therefore, a complete ZVS and ZCS hybrid (ZVZCS) commutation can actually be 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 with the aid of the low side ZCS-assisted inductor snubber $L_{S1} = L_{S2}$, the induction heated load R_o-L_o and load power factor compensation series load resonant tuned capacitor C_s, the ZCS commutation can be performed at a turn-off switching mode transition 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 when a second switching cycle starts. At this time, a ZCS turn-on commutation can be realized with the aid of the ZCS-assisted inductor snubber L_{S1}.The operation modes of the proposed high-frequency soft switching inverter shown in Fig. 1 are divided into eleven operating modes as shown in Figs. 3 and 4. The proposed inverter offers a complete ZCS for all the switches and achieves ZVS and ZCS hybrid commutation even at turn-on switching mode transitions for the main switch SW_2.

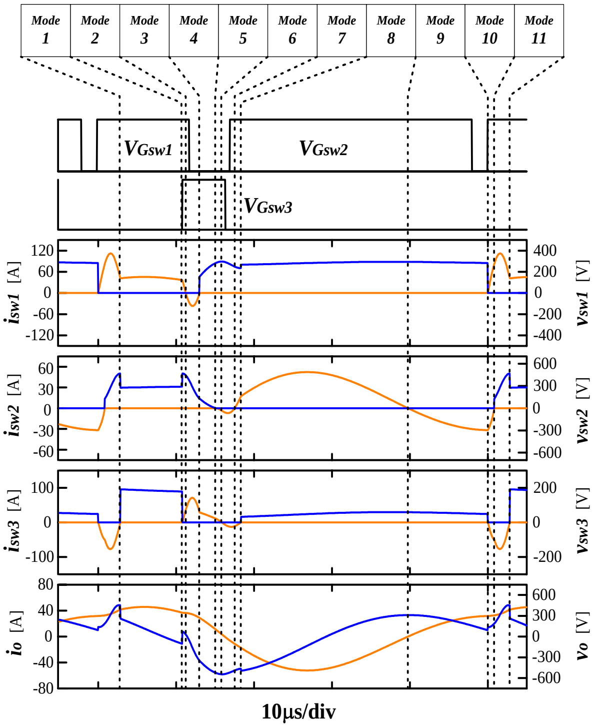


Fig. 4 One switching cycle operating modes and waveforms for a duty cycle of 0.34

4. Experimental Evaluations and Discussions

4.1 Design Specifications and Circuit Parameters

An experimental inverter set up is proposed to validate the steady state performance of the proposed high frequency soft switching inverter circuit. The design specifications and circuit parameters used in the experimental breadboard setup are indicated in Table 1. The high frequency inverter circuit proposed here is designed for consumer IH cooking heaters in home and business applications. An enamel pan with a diameter of 18 cm is used for the IH load as a heated object. The IH load consists of the enamel pan, a ceramic spacer as the top plate and a planer working coil composed of litz wire. The circuit parameters of this high frequency inverter are determined by considering the operating conditions of the soft switching commutation conditions and the output power ranges.

Table 1 Design specifications and circuit parameters

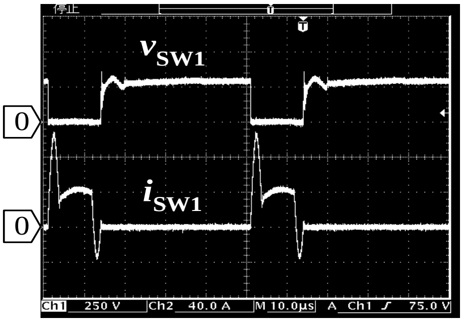
Item		Symbol	Value
DC Source Voltage		V_S	**282.8 V**
Switching Frequency		f_{SW}	**20 kHz**
Inductance of ZCS-assisted Inductor		L_{S1}	**2.09 μH**
Inductance of ZCS-assisted Inductor		L_{S2}	**2.01 μH**
Capacitance of Auxiliary Quasi-resonant Capacitor		Cr	**324 nF**
Capacitance of Power Factor Compensation Series Tuned Capacitor		Cs	**0.802 μF**
Enamel Pan	**Load Resistance**	R_O	**2.54 Ω**
	Load Inductance	L_O	**57.96 μH**

4.2 Experimental Results

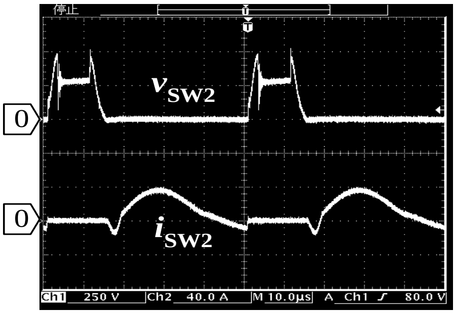
The steady state measured operating voltage and current waveforms for duty cycle D=0.34 under an input DC power of 2.7 kW are represented in Fig. 5. As it can be seen in this figure, all the main power switches Q_1, Q_2 and auxiliary active power switch Q_3 operate using a soft switching (ZCS) PWM strategy. All the power switches can achieve a ZCS commutation operation. In particular, it can be recognized that a complete ZVS and ZCS (ZVZCS hybrid) commutation can be performed at the turn-on switching mode transition for the switch 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 main power switch SW_1 of Q_1 during the conduction period of its anti-parallel diode D_3 of Q_3, the ZCS commutation at a turn-on switching mode transition can be achieved for the switch SW_1 of Q_1. Due to the inherent principle of soft switching operation in all the active power switches 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 soft switching PWM inverter circuit depicted in Fig. 1.

4.3 Power Regulation Characteristics

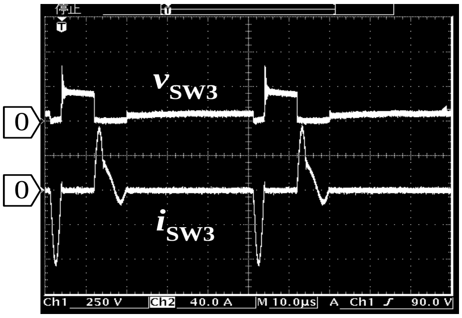
The input power (or output power) vs. duty cycle characteristics for the proposed ZCS-PWM SEPP high-frequency inverter using the trench gate IGBTs; which are based on a PWM control scheme are depicted Fig. 6. The solid line shows the simulation results and the dotted line gives the measured experimental ones. A good agreement is evident between the experimental and the simulation



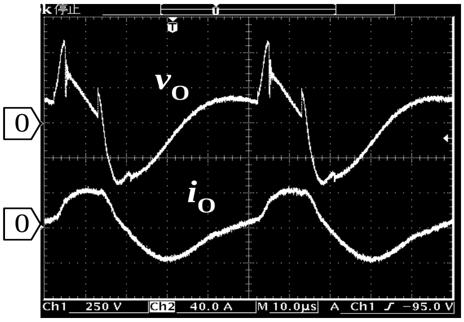
(a) Voltage and current waveforms of Q_1 (SW_1/D_1) v_{SW1} [250V/div], i_{SW1} [40A/div], t [10µs/div]



(b) Voltage and current waveforms of Q_2 (SW_2/D_2) v_{SW2} [250V/div], i_{SW2} [40A/div], t [10µs/div]



(c) Voltage and current waveforms of Q_3 (SW_3/D_3) v_{SW3} [250V/div], i_{SW3} [40A/div], t [10µs/div]



(d) Output voltage and current waveforms v_o [250V/div], i_o [40A/div], t [10µs/div]

Fig. 5 Measured voltage and current waveforms for D=0.34

results as shown in Fig. 6. In the proposed high-frequency soft switching inverter circuit, its input power can be regulated from a low value of approximately 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.

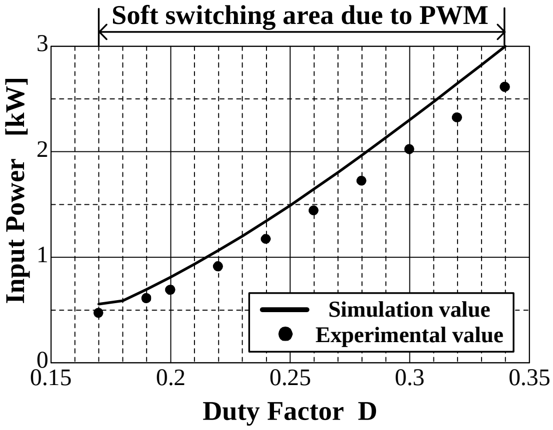


Fig. 6 Input power vs. duty cycle characteristics of the proposed multi-resonant ZCS-PWM SEPP high-frequency inverter.

4.4 Actual Efficiency Characteristics

The measured power conversion actual system efficiency characteristics of the proposed voltage source type ZCS-PWM SEPP high-frequency inverter for consumer IH cooking heaters are shown in Fig. 7. Under the rated output conditions, the measured actual efficiency of this soft switching inverter using the newly developed trench gate IGBTs with a low saturation voltage is estimated at about 94% for the entire system, since a zero current soft switching commutation operation can be completely achieved.

However, the proposed high frequency inverter operating using asymmetrical PWM control or duty cycle control achieves a complete soft switching commutation operation at the high output power settings. On the other hand, it becomes a hard switching commutation operation at certain low power settings and its actual efficiency is substantially reduced. In other words, this high frequency inverter still operates with considerably high efficiency. In the case of duty cycle D = 0.17, under a condition of the minimum output power setting using a soft switching PWM control scheme, the power conversion efficiency of the utility frequency AC to high frequency power conversion conditioning circuit system shown in Fig. 1 is sufficiently maintained at almost 86% on average as depicted in Fig. 7.

The soft switching operating area of the proposed high frequency power converter can actually be extended by the use of PDM controls at the low power settings or by the use of a dual mode implementation of PWM and PDM selection control. The soft switching operation can be completely realized over all the output power regulation ranges including low power settings.

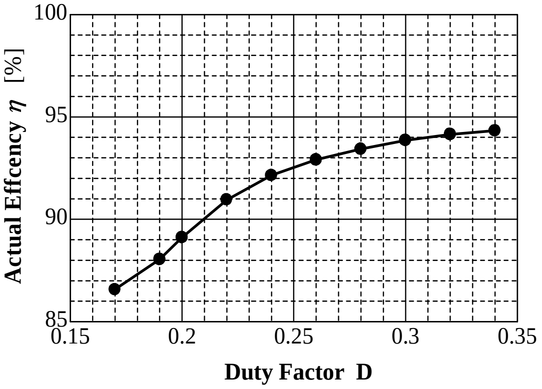


Fig. 7 Actual efficiency vs. duty cycle characteristics of newly proposed high frequency inverter.

4.5 Comparative Actual Efficiency Characteristics

The proposed high-frequency soft switching PWM-SEPP series capacitor compensated load resonant tank inverter is compared with a previously developed simple voltage source type lossless snubber capacitor assisted ZVS-PWM SEPP high-frequency inverter designed for IH cookers shown in Fig. 8. This inverter has a narrow soft switching operation performance using a constant frequency PWM control scheme.

The actual efficiency vs. the input power regulation characteristics of the newly proposed high frequency soft switching ZCS-PWM type and ZVS-PWM type are comparatively illustrated in Fig. 9. The power regulation characteristics for both high frequency inverters are based on the asymmetrical PWM control strategy. However, it must be noted that the soft switching commutated operation schemes are different for both high frequency inverters.

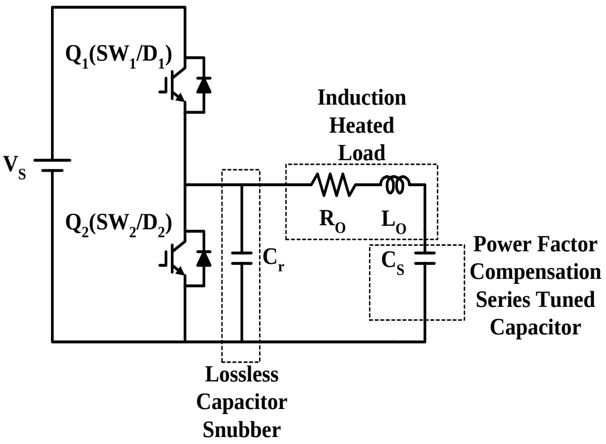


Fig. 8 Conventional ZVS-PWM-SEPP high-frequency inverter

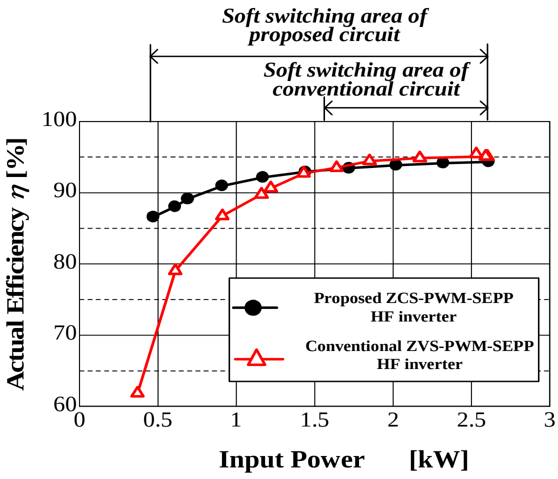


Fig. 9 Comparative actual efficiency vs. input power characteristics

The actual efficiency of the proposed voltage source ZCS-PWM SEPP high frequency power conversion circuit is higher than that of the previously developed ZVS-PWM SEPP for lower input power or output power ranges. For higher input power or higher output power ranges, the performance is almost the same as that of the previously developed power conversion circuit. This is due to the reason that the soft switching operation range of the newly proposed voltage source type ZCS-PWM SEPP high-frequency inverter power conversion circuit is much wider than that of the previously developed one in spite of the new pulse modulation control scheme based on the selectively controlled PWM and PDM approach. Since the newly proposed soft switching high-frequency power converter can also be regulated by introducing a simple PDM control scheme or dual mode implementation of PWM and PDM control strategies for low ranges in the duty cycle, it can maintain actual operating efficiency at a relatively high level by using a soft switching operation under low power conditions of output power less than 0.4 kW.

5. Conclusions

In this paper, a new topology for auxiliary quasi-resonant snubber-assisted voltage source type ZCS-SEPP high-frequency multi-resonant inverters used as utility frequency AC to high frequency AC power converters with active snubbers composed of an active auxiliary switched capacitor and two lossless snubber inductors has been proposed and developed originally for consumer IH cookers and steamers. The high frequency operation principle, the operation mode transitions, the operating characteristics and the practical effectiveness of the newly-proposed voltage source type ZCS-PWM SEPP high-frequency multi-resonant inverters using the latest trench gate IGBTs was illustrated and evaluated using simulations and experimental results by producing an actual breadboard setup for next generation consumer IH cooking heaters and IH steamers. A wide soft switching commutation operation range was obtained as compared with the previously-developed voltage source type ZVS-PWM SEPP inverter in spite of the PWM control strategy. The high-frequency power regulation range of this high frequency inverter can be efficiently supplied to the consumer high frequency IH cooking heater from full power to small power settings. Furthermore, a complete soft switching operation can be achieved even for lower power settings by introducing the high-frequency PDM control scheme or the dual mode operation of PWM at the higher power settings and by using a PDM control implementation in the lower power setting of this soft switching pulse modulated high-frequency multi-resonant inverter to expand the stable soft switching operation ranges as compared with previously developed ZVS-PWM high-frequency inverter system.

Therefore, it was substantially proved from an experimental point of view that the newly proposed ZCS

PWM/PDM high-frequency inverter for use in cost effective IH cooking heaters and IH steamers could actually achieve higher efficiency, high performance and wider soft switching operating ranges due to the introduction of a dual mode power control scheme based on PWM and PDM.

Acknowledgment

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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] Laknath Gamage, Tarek Ahmed, Hisayuki Sugimura, Srawouth Chandhaket and Mutsuo Nakoka,” Series Load Resonant Phase Shifted ZVS-PWM High-Frequency Inverter with a Single Auxiliary Edge Resonant AC Load Side Snubber for Induction Heating Super Heated Steamer”, Proceedings of 2003 International Conference on Power Electronics and Drive Systems (PEDS), Vol. 1, pp. 30-37, Singapore, November, 2003.

[5] 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.

[6] 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.

[7] Haruo Terai, Hideki Sadakata, Hideki Omori, Hidekazu Yamashita, Mutsuo 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 (PESC), Vol. 4, pp. 1874-1878 Cairns, Australia, June,2002.

[8] H. Kifune, Y. Hatanaka, and M. Nakaoka, “Latest Development of a Novel Fixed Frequency Power Controlled Soft Switching PWM High-Frequency Inverter with a Single Auxiliary Switch for Induction Heating Super Heated Steam Generator,” Transactions on The Institute of Electrical Installations Engineers-Japan, Transactions on IEEJ-IA (Industry Applications), Vol. 22, No.10, part D, pp. 797-804, October, 2002.

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Prof. Dr.-Eng. Nakaoka is a member of the Institute of Electrical Engineering Engineers of Japan, Institute of Electronics, Information and Communication Engineers of Japan, Institute of Illumination Engineering of Japan, European Power Electronics Association, Japan Institute of Power Electronics, Japan Society of the Solar Energy, Korean Institute of Power Electronics, IEE-Korea and IEEE.