KIEE International Transactions on Electrical Machinery and Energy Conversion Systems, Vol. 5-B No. 2, pp. 181~188, 2005 **181**

Utility AC Frequency to High Frequency AC Power Conversion Circuit with Soft Switching PWM Strategy

Hisayuki Sugimura*, Nabil A. Ahmed*, Tarek Ahmed,**
Hyun-Woo Lee† and Mutsuo Nakaoka*

Abstract - In this paper, a DC smoothing filterless soft switching pulse modulated high frequency AC power conversion circuit connected to utility frequency AC power source is proposed for consumer induction heating hot water producer, steamer and super heated steamer. The operating principle of DC link filterless utility frequency AC-high frequency AC (HFAC) power conversion circuit defined as high frequency cycloinverter is described, which can operate under a principle of ZVS/AVT and power regulation based on alternate asymmetrical PWM in synchronization with the utility frequency single phase AC positive or negative half wave voltage. The dual mode modulation control scheme based on high frequency PWM and commercial frequency AC voltage PDM for the proposed high frequency cycloinverter are discussed to enlarge its soft switching commutation operating range for wide HFAC power regulation. This high frequency cycloinverter is developed for high frequency IH Dual Packs Heater (DPH) type boiler used in consumer and industrial fluid pipeline systems. Based on the experiment and simulation results, this high frequency cycloinverter is proved to be suitable for the consumer use IH-DPH boiler and hot water producers. The cycloinverter power regulation and power conversion efficiency characteristics are evaluated and discussed.

Keywords: AC frequency, High frequency, Cycloinverter, Smoothing filterless, Soft switching PWM, Pulse density modulation, Dual pack heater.

1. Introduction

In general, the electromagnetic induction heating (IH) is concerned with non-contact, high efficiency, and clean electric heating method due to the energy conversion heated device by induction eddy current based on Faraday's law of electromagnetic induction principle in addition to Joule's heating principle. Attractive IH technology used for industrial and consumer applications can be roughly classified into low frequency and high frequency (over 20 kHz) [1]–[5]. The latest technology developments of IH application products emphasized on the environment have attracted special interest in the consumer application fields as IH cooking devices, rice cooker and warmer, boiler, hot-water producer, floor and wall fluid heater, fryer, dryer, wastes treatment and soil sterilization equipments and drying of atmospheric pressure super heated steamer [6]. Under these technological requirements, research and development of circuits and control schemes of the high frequency power supply equipment for the electromagnetic IH by a variety of high efficiency voltage source type series capacitor compensated and parallel capacitor compensated load resonant high frequency inverter which incorporate soft switching pulse modulation technologies using the latest MOS gate controlled power semiconductor switching devices (IGBTs and CSTBTs) are actively proceeded from a practical point of view [7], [8].

However, the harmonic distortion inherently produced in the commercial AC input grid side due to the rectified DC smoothing voltage link with capacitor input filter. In addition, the significant problems on power conversion efficiency, volumetric physical size as reliability and life of the electrolytic capacitor DC link power stage have actually appeared by using the electrolytic capacitor bank or assembly for the DC voltage smoothing.

This paper proposes a novel utility frequency AC - high frequency AC power conversion circuit defined as high frequency cycloinverter or cycloconverter, which does not include DC smoothing filter stage. The circuit operation principle of the proposed soft switching PWM AC - high frequency (HF) AC power cycloinverter is described for the hot-water producer and steamer using new IH Dual Packs Fluid Heater (DPH). The experimental and simulated

---

This paper was received the best paper award from ICEMS 2004, which held in Jeju, Korea from Oct. 31 to Nov.3, 2004

† Corresponding Author: The Electric Energy Saving Research Center, Kyungnam University, Masan, Korea

* The Electric Energy Saving Research Center, Kyungnam University, Masan, Korea (lhwoo@kyungnam.ac.kr)

** The Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan

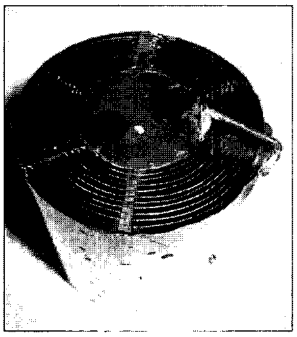
Received June 28, 2004 ; Accepted May 16, 2005

verification of operation of high frequency cycloinverter is carried out. Finally, the power regulation and power conversion efficiency characteristics of high frequency cycloinverter is evaluated and discussed. The feasible effectiveness and practicability of soft switching PWM controlled high-frequency cycloinverter treated here are substantially proved on the basis of experimental results applied for consumer IH-DPH applications in pipeline systems.

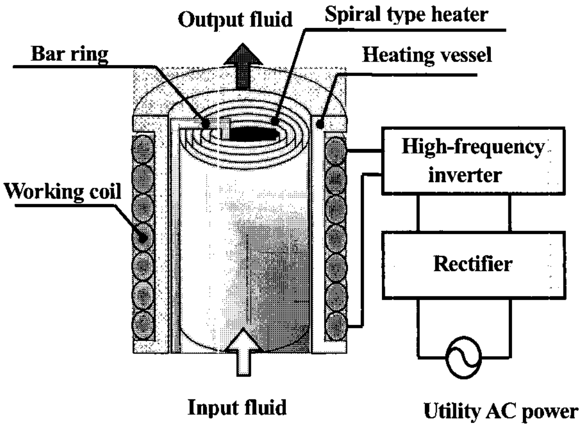
2. Novel Type of IH Dual Packs Fluid Heater

The appearance of proposed commercial use IH-DPH driven by the proposed high frequency inverter is shown in Fig. 1. This new spiral structure DPH device newly works as a heat exchanger, with the end ring from a low resistance material, formed spirally by the thin plate of nonmagnetic stainless steel SUS316, which is inserted into the non metal vessel. The non-magnetic material SUS304 is selected as a material for the IH-DPH device due to the advantages it has such as uniform temperature distribution, excellent corrosion protection for fluid (water, vapor, gas, powder), clean low pressure moving fluid in pipeline.

The work coil uses enamel copper wire twisting together and isolated from each other. This work coil is called litz wire for power. In this IH heating device(see Fig.3), thermally stable temperature of this wire is about 170 degrees centigrade. Actually, the water tube part is not over 120 degrees centigrade, because the heat insulating material is packed in IH-DPH hot-water producer between work coil and IH heating element. Therefore, the security of enough thermally stable temperature is possible for fluid heating container made of ceramics and nitrogen resin. This IH heating element is based on the mechanism, which heats the low pressure continuous movement fluid in the pipeline tube by the heat exchange action between IH heating element and fluid. Therefore, thermally stable temperature is also necessary for the pipeline tube. The fluid heating vessel tube uses the polycarbonate, and the thermally stable temperature is below 120 degrees centigrade.



(a) Top view.

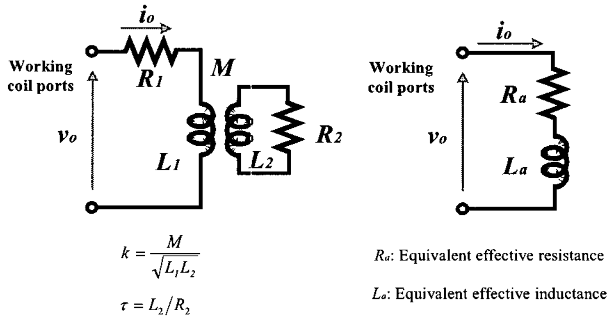


(b) Internal structure.

Fig. 1 IH stainless plate spiral dual packs fluid heater.

2.1 Equivalent Circuit of IH Load

The equivalent circuit modeling of IH-DPH load is shown in Fig. 2. This linear model of the induction heated load circuit is represented by equivalent effective inductor L_a in series with equivalent effective resistor R_a in the input side of working coil terminals of the induction heater or IH-DPH load. R_a and L_a are respectively determined by the self-inductance L_1 and internal resistance R_1 of the work coil, self-inductance L_2 of eddy current heated device in electromagnetic induction transformer secondary side and mutual inductance M between L_1 and L_2. It is considered that these circuit parameters are kept constant in spite of output power regulation of the IH-DPH load.



(a) Transformer type equivalent circuit model

(b) R_a-L_a series equivalent circuit model

Fig. 2 Equivalent circuit modeling of IH load.

2.2 Measurement of Circuit Parameters

Measured methods of circuit parameters R_a and L_a in the IH-DPH load can be achieved by applying a high frequency AC voltage to the IH-DPH load via the working coil by a high frequency inverter or high frequency linear power amplifier. The effective value V_{rms} of high frequency

AC voltage and effective value I_{rms} of high frequency AC current with electrical angular frequency ($\omega = 2\pi f$), power factor $\cos\theta$ ($\cos\theta$: difference angle between output voltage and output current) are measured for IH-DPH load and working coil. Eq. (1) is obtained on the basis of the sine wave alternating current theory.

$$\left\{\begin{aligned} &\frac{V_{rms}}{I_{rms}} = Z_{rms} = \sqrt{R_a^{\,2} + (\omega L_a)^2} \\ &\cos\theta = \frac{R_a}{\sqrt{R_a^{\,2} + (\omega L_a)^2}} \\ &\sin\theta = \frac{\omega L_a}{\sqrt{R_a^{\,2} + (\omega L_a)^2}} \end{aligned}\right. \tag{1}$$

The impedance of the induction heating load Z_{rms} for the angular frequency ω of measured voltage and current is calculated using. By using measured power factor, the equivalent parameters R_a and L_a of IH-DPH load with working coil is estimated. In case of considering internal resistance R_l of the work coil, the equivalent effective resistance value becomes $R_a + R_l$.

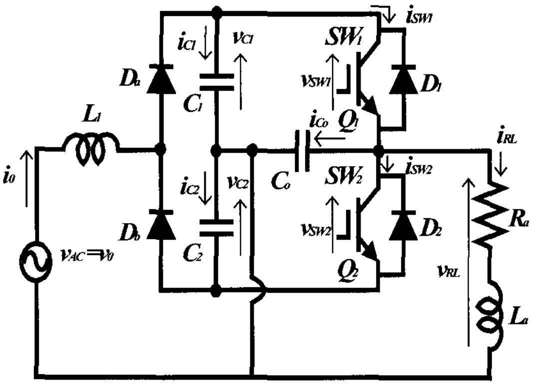


Fig. 3 Soft switching utility frequency AC-high-frequency AC power conversion circuit.

3. Utility Frequency AC - High Frequency AC Power Conversion Circuit

3.1 Circuit description

The circuit configuration of the proposed AC - HFAC power converter or high frequency cycloinverter which converts AC utility frequency into high frequency AC without use an electrolytic capacitor DC link or completely without DC smoothing bus line is shown in Fig. 3. The proposed power frequency conversion circuit as a high frequency cycloinverter is a one stage power frequency changing circuit topology which converts the utility frequency AC into high frequency AC voltage over 20 kHz This circuit topology is called a high frequency cycloinverter to differentiate it from the conventional high frequency inverter uses the Dc link bus line. The main power conversion circuit is composed of two power switching devices Q1 (SW1/D1) and Q2 (SW2/ D2), filter inductor L_1 in utility AC input-side, two capacitors C_1 and C_2 as active clamp resonance in accordance with IH-DPH load, low pass filter, lossless quasi-resonant snubber capacitor C_o and, induction heated DPH load.

3.2 Dual mode control of asymmetrical PWM and utility frequency AC PDM

The conventional asymmetrical PWM control can be used for gating the cycloinverter power switching devices SW_1 and SW_2. The gating pulses are exchanged every half cycle in synchronism with the polarity of the utility AC voltage to supply the desired AC power for IH-DPH load. Also, a dead time T_d is necessary to avoid a shout through.

The gate pulse signal timing sequences are shown in Fig. 4. The PWM duty cycle d_{PWM} as a control variable is defined as given in Eq. (2), by the duration proportion of on time T_{on1} of the main power switch to the high frequency switching period T. By introducing this control strategy, the high frequency cycloinverter enables to supply the desired output AC high frequency power with ZVS for the IH-DPH load.

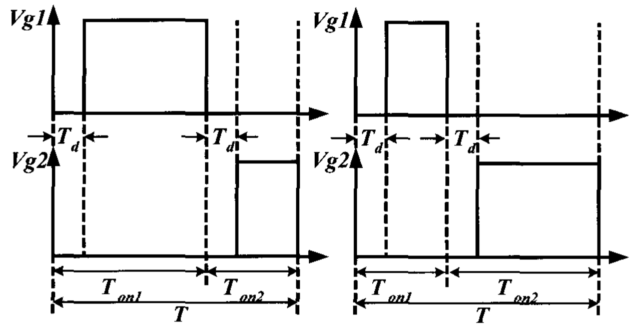


Fig. 4 Gate voltage pulse signal sequences of asymmetrical PWM control scheme.

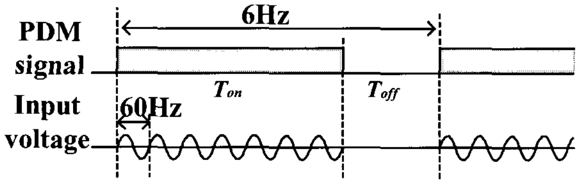


Fig. 5 Utility AC frequency-based pulse density modulation control strategy (dPDM =0.7).

$$d_{PWM} = \frac{T_{on1}}{T} \tag{2}$$

In addition to the asymmetrical PWM control strategy, the utility frequency AC pulse density modulation (AC-PDM) - ZVS control scheme or utility AC voltage cycle control scheme can be used. The utility frequency AC-PDM-ZVS controls the output AC effective power by changing the discrete cycle numbers of utility frequency AC voltage pulse trains in some intervals T_{PDM} to IH-DPH load. New concepts of the utility frequency AC-PDM-ZVS control strategy in a period of 10 cycles utility AC power source is shown in Fig. 5. The ZVS-based utility frequency AC-PDM time ratio as a control variable d_{PDM} is defined as given in Eq. (3).

$$d_{PDM} = \frac{T_{on}}{T_{on} + T_{off}} \tag{3}$$

The proposed high frequency cycloinverter circuit topology depicted in Fig. 3 can also adjust the high-frequency AC output power on the basis of dual-mode control of asymmetrical PWM and utility frequency AC-PDM under a condition of complete zero voltage soft switching commutation.

4. Simulation and Experimental Results

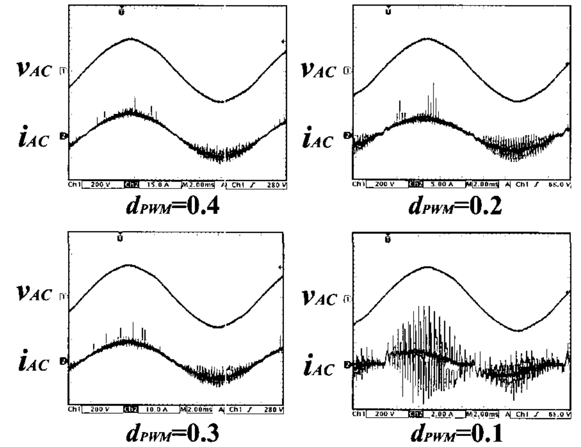
The design specifications and circuit parameters of the experimental setup of the proposed high frequency cycloinverter using IGBT module are indicated in Table 1. The simulation and experimental results are described in the following.

Table 1 Design Specification and Circuit Parameters.

Item	Symbol	Value
Utility AC voltage (RMS)	V_{AC}	single phase 60Hz 200V
Switching frequency	f	21kHz
Dead time	T_d	2μs
Filter and resonant capacitors	C_1, C_2	5μF
Lossless snubbing quasi-resohant capacitor	C_o	0.1μF
Inductance of utility AC side filter inductor	L_1	1mH
Effective resistance component of IH load	R_a	1.65Ω
Effective inductance component of IH load	L_a	34.2μH

Figure 6 shows input voltage and current waveforms of the proposed high frequency cycloinverter for different values of duty cycles d_{PWM} of 0.4, 0.3, 0.2 and 0.1 respectively.

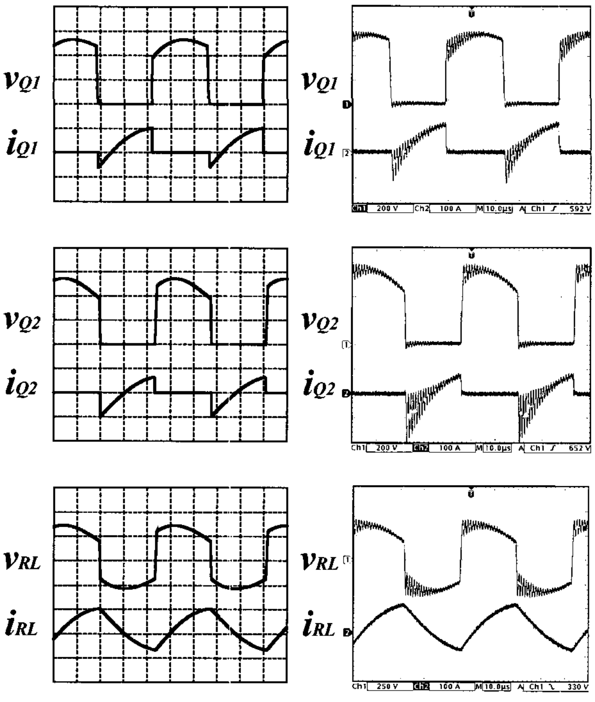
The relevant simulated and measured soft switching operating voltage and current waveforms near the peak value of utility AC sine waveform for asymmetrical PWM control of the high frequency cycloinverter set up in case of a duty factor d_{PWM} = 0.5 are shown in Fig. 7. A very good agreement is obtained between the simulation and experimental voltage and current operation waveforms.



d_{PWM}=0.4 d_{PWM}=0.2

d_{PWM}=0.3 d_{PWM}=0.1

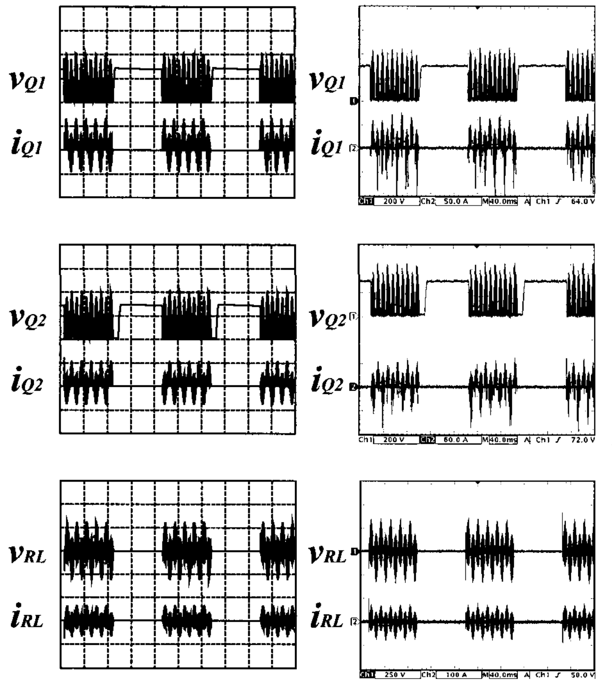
Fig. 6 Input voltage and current waveforms.



v_{Q1}, v_{Q2}: 200[V/div], v_{RL}: 250[V/div],
i_{Q1}, i_{Q2}, i_{RL}: 100[A/div], Time: 10[μs/div]

Fig. 7 Soft switching voltage and current waveforms in asymmetrical ZVS-PWM control, d_{PWM}=0.5(Left trace:s Simulation, Right traces: Experiment)

The input current waveform is much distorted at aduty cycle d_{PWM}=0.1. Therefore, the asymmetrical PWM control is more effective for the high output power ranges of the proposed high frequency cycloinverter. However, the zero voltage soft switching commutation operation can be realized over all the output power regulation area on the basis of dual mode control implementation in case of low power setting area using the utility frequency AC-PDM-ZVS control and the asymmetrical PWM control in case of high power setting area. The changing point of asymmetrical PWM and utility frequency AC PDM in this high frequency cycloinverter is set to be at a duty ratio of $d_{PWM} = 0.3$. In all the high frequency AC power regulation ranges, this high frequency cycloinverter operates in soft switching commutation by changing the control scheme changing from asymmetrical PWM control to PDM control at low duty ratios. The simulated and measured operating waveforms in case of dual-mode control in case of d_{PWM} = 0.3 and $d_{PDM} = 0.5$ are comparatively illustrated in Fig. 8.



v_{Q1}, v_{Q2}: 200[V/div], v_{RL}: 250[V/div], i_{RL}: 100[A/div], i_{Q1} 50[A/div], i_{Q2}: 60[A/div], Time: 40[μs/div]

Fig. 8 Soft switching voltage and current waveforms in case of dual-mode control, d_{PWM} =0.3, d_{PDM} =0.5. (Left traces:Simulation Right traces: Experiment)

The input power vs. the duty factor characteristics of this high frequency cycloinverter under asymmetrical PWM control is depicted in Fig. 9. While, Fig. 10 shows the input power vs. the pulse density modulation characteristics of this high frequency cycloinverter under the principle of dual-mode of asymmetrical PWM and pulse density control in case of $d_{PWM} = 0.3$.

The soft switching operation area of the high frequency cycloinverter is lso illustrated in Figs. 9 and 10. In Fig. 9, the high frequency cycloinverter controlled by the asymmetrical ZVS-PWM technique operates in a hard

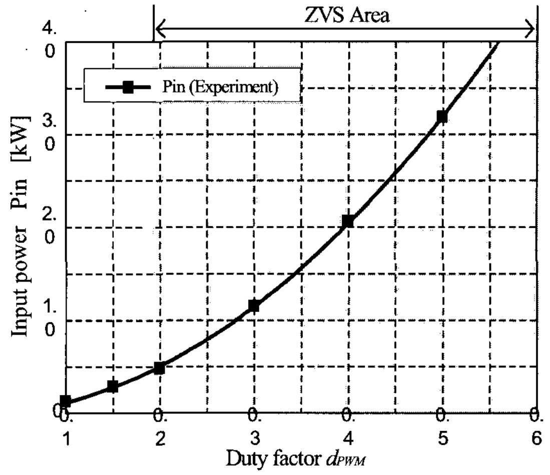


Fig. 9 Input power vs. duty cycle characteristics in case of asymmetrical ZVS-PWM control.

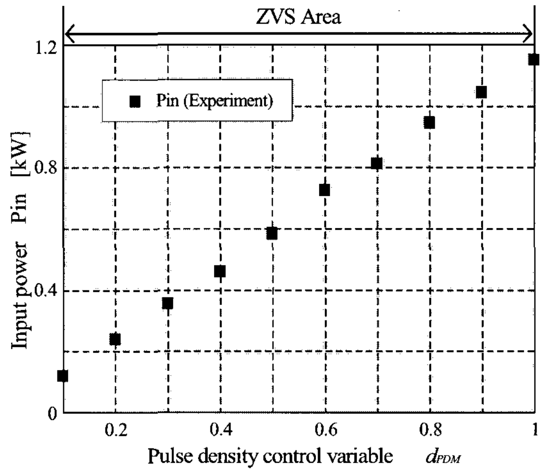


Fig. 10 Input power vs. ZVS-PDM characteristics in case of dual-mode control, d_{PWM}=0.3.

switching commutation operation mode in low power setting area. The soft switching operation range can be expanded as shown in Fig. 9. The high frequency cycloinverter controlled by dual-mode control of the asymmetrical PWM control and the utility frequency AC-PDM control operates completely in soft switching operation mode even in low power setting area. Therefore, the output power of this proposed high frequency cycloinverter can be regulated up to about 150 W in the ZVS soft switching operation, when the utility frequency AC-PDM-ZVS control is implemented in addition to the asymmetrical ZVS-PWM.

Fig. 11 illustrates the power conversion efficiency characteristics of the proposed high frequency cycloinverter under asymmetry PWM control and dual-mode control. It is clear to note that the actual efficiency of the high frequency cycloinverter using asymmetrical ZVS-PWM control might be reduced in the low power setting area, due to the hard switching operation in low power setting range. The high conversion efficiency over 90% can be almost maintained

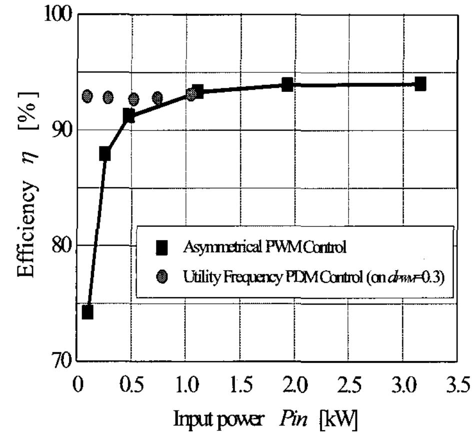


Fig. 11 Actual power conversion efficiency vs. output power characteristics in Asymmetry PWM control and dual-mode control.

when the dual-mode of asymmetrical PWM and utility frequency pulse density control (AC-PDM-ZVS) is used for low power setting area and the proposed high frequency cycloinverter can operate under a condition of complete soft switching commutation in all high frequency power regulation area. Therefore, the dual mode pulse modulation control scheme using asymmetrical ZVS-PWM and utility frequency AC-ZVS-PDM is more effective to put it into practical use for the high-efficient power control implementation.

5. Conclusions

In this paper, high frequency zero voltage soft switching cycloinverter based on utility frequency AC - high frequency AC power converter without the electrolytic capacitor DC smoothing filter link has been newly proposed, which can implement compactness, low cost, high reliability, high efficiency and long life. The sot soft switching circuit operation principle and features of the high frequency cycloinverter were clarified for unique consumer induction heating applications based on new type Dual Packs Fluid Heater as IH heat exchanger. A high power conversion efficiency could be achieved from an experimental point of view in the proposed utility frequency AC - high frequency AC cycloinverter using the dual-mode pulse modulation control implementation of asymmetrical ZVS-PWM and utility frequency AC-ZVS-PDM over a wide power regulation range.

In the future, the optimum circuit parameter design method of the input filter part of the proposed high frequency soft switching cycloinverter will be investigated, and the power loss analysis of high frequency soft switching cycloinverter using experimental v-i characteristics of power semiconductor switching devices (IGBTs; CSTBTs) will be analyzed and the actual efficiency and conventional efficiency characteristics will be compared experimentally.

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, 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, vol4, pp.1874-1878, Cairns, Australia, June, 2002.

[3] L. Gamage, T. Ahmed, H. Sugimura, S. Chandhaket and M. 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), pp. 30-37, Singapore, November, 2003.

[4] H. Tanaka, M. Kaneda, S. Chandhaket, M. Aubdallha AL, M. Nakaoka “Eddy Current Dual Packs Heater based Continuous Pipeline Fluid Heating using Soft Switching PWM High Frequency Inverter”, Proceedings of International Symposium on Industrial Electronics (ICPE), Mexico, pp306-311, December, 2000

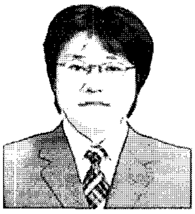
[5] H. Sugimura, H. Muraoka, K. Soushin, M. Matsuda, and M. Nakaoka” Dual Mode ZVS-PWM High Frequency Load Resonant Inverter with Auxiliary Edge resonant Snubber for Super Heated Steamer”, Proceedings of The 29th Annual Conference of the IEEE Industrial Electronics Society (IECON), pp. 1679-1684, Virginia, USA, November, 2003.

[6] H. Tanaka, H. Sadakata, Hi. Muraoka, E. Hiraki and M. Nakaoka, “Innovative Electromagnetic Induction Eddy Current based Far Infrared Rays Radiant Heater using Soft Switching PWM Inverter with Duty Cycle Control Scheme”, Proceedings of KIPE-ICPE (Korean Institute Power Electronics-International Conference on Power Electronics)-Korea, Vol.1, pp64-68, October, 2001.

[7] T. Nakamizo, Bin Guo, M. Nakaoka, “New Generation Electromagnetic Induction-based Fluid-Heating Energy Processing Appliance using Voltage-Fed PWM Resonant Inverter”, Proceedings of PCIM(Power Conversion and Intelligent Motion)-Japan, Vol.1, pp.

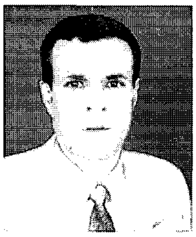
597-607, April, 1998.

[8] H. Sadakata, M. Nakaoka, H. Yamashita, H. Omori and H. Terai "Development of Induction Heated Hot Water Producer using Soft Switching PWM High-frequency Inverter", Proceedings of IEEE-IAS PCC (Power Conversion Conference)-Osaka, Vol.2, pp452-455, April, 2002.



Hisayuki Sugimura

He was born in Kyoto Prefecture, Japan in 1977. He received the Bachelor of Science Degree in Electrical and Electronics Engineering, Yamaguchi University, Japan, in 2003. He joined Power Electronics System Engineering Laboratory, Division of Electrical and Electronics Engineering, The Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. His interest research is concerned with high-frequency soft switching inverters and soft switching DC-DC converters. He is a member of IEEJ and IEEE.



Nabil A. Ahmed

He received the B.Sc. and M.Sc degrees in Electrical Engineering from the Electrical and Electronics Engineering Department, Faculty of Engineering, Assiut University, Egypt in 1989 and 1994 respectively and the Dr.-Eng. degree in Electrical Engineering from Toyama University, Japan in 2000. Since 1989, he has been with the Department of Electrical and Electronics Engineering, Faculty of Engineering, Assiut University, where he is currently an Assistant Professor. He is now a post doctor fellow at the Electric Engineering Saving Research Center, Kyungnam University, Korea. His research interests are in the area of power electronics, variable speed drives, soft switching converters and renewable energy systems. Dr.-Eng. Nabil is recipient of Japanese Monbusho scholarship, the JSPS fellowship and the best presentation award from ICEMS 2004.

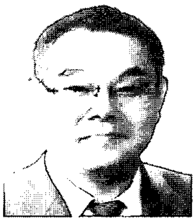
Tarek Ahmed

He received his M.Sc. degree in electrical engineering from the Electrical Engineering Department, Faculty of Engineering, Assiut University, Assiut, Egypt in 1998. He is currently working toward the Ph.D. degree in the Power Electronic System and Control Engineering Laboratory, the Division of Electrical and Electronic Systems Engineering, the Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. He is an Assistant Lecturer in the Electrical Engineering Department, Faculty of Engineering, Assiut University. His research interests are in the new applications of advanced high frequency resonant circuits and systems with the renewable energy related soft switching PWM rectifier and sinewave PWM inverter power conditioner.

Mr. Ahmed is a student-member of the Institute of Electrical and Electronics Engineers of USA (IEEE-USA), the Institute of Electrical Engineering and Installation of Engineers (IEIE-Japan), the Institute of Electrical Engineers (IEE-Japan) and Japan Institute of Power Electronics (JIPE). He was the recipient of prize paper awards from the Institute of Electrical Engineers of Japan (IEE-J) in 2003 and in 2004 and both the best presentation and student awards from IECON 2005.

Hyun-Woo Lee

He received the B.E. degrees in electrical engineering from Dong-A University, Pusan, Korea, in 1979 and received the M.S. degrees in electrical engineering from Yuing-Nam University, Kyungbook, Korea, in 1984 and the Ph.D. degrees in electrical engineering from Dong-A University, Pusan, Korea, in 1992. Since 1985 he has been with the Division of Electrical Electronics Engineering, Kyungnam University, Masan, Korea, where he is a Professor. He is interested in the area of Power electronics and new power generation system. He is a member of the KIEE (academic director), IEEE.



Mutsuo Nakaoka

He received his Dr.-Eng. degree in Electrical Engineering from Osaka University, Osaka, Japan in 1981. He joined the Electrical and Electronics Engineering Department of Kobe University, Kobe, Japan in 1981 and served as a professor of the Department of Electrical and Electronics Engineering, the Graduate School of Engineering, Kobe University, Kobe, Japan until 1995. Now he is working a professor in the Electrical and Electronics Engineering Department, the Graduate School of Science and Engineering, Yamaguchi University, Yamaguchi, Japan. His research interests include application developments of power electronics circuits and systems. He has received more than ten Awards such as the 2001 premium prize paper award from IEE-UK, the 2001 and 2003Best Paper Award from IEEE-IECON, the 2000 third paper award from IEEE-PEDS, 2003 James Melcher Prize Paper award from IEEE-IAS. He is now a chairman of IEEE Industrial Electronics Society Japan Chapter.

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.