Utility AC Frequency to High Frequency AC Power Frequency Converter

without Electrolytic Capacitor Link for Consumer Induction Heating Appliances

H. Sugimura, A. Eid, H. W. Lee, S. K. Kwon, K. Y. Suh and M. Nakaoka
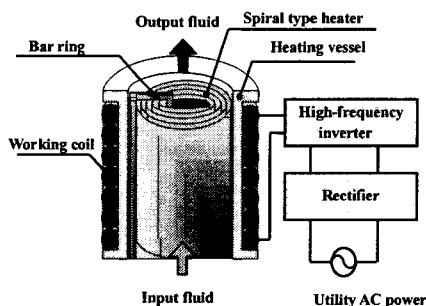(Electric Energy Saving Research Center, Kyungnam University, Masan, Korea)

Abstract- In this paper, a novel prototype topology of soft switching PWM controlled high frequency AC power conversion circuit without DC voltage smoothing chemical capacitor filter link from the voltage grid of utility frequency AC power supply source with 60Hz-100V or 60Hz-200V is proposed and introduced for innovative consumer induction heating (IH) boiler applications as hot water producer, steamer and super heated vapor steamer.

It is actually verified on the basis of experiment and simulation results in the steady state operation of the high frequency power frequency converter using IGBTs which is suitable for the business-use IH boiler using new electromagnetic induction heating dual packs fluid heater. Finally, the power regulation characteristics in addition to utility AC side line current harmonic components and power factor characteristics and power conversion efficiency characteristics of this high frequency power frequency converter operating under a principle of soft-switching PWM and PDM are evaluated and discussed from an experimental point of view.

Keywords-High frequency power frequency converter, High frequency cycloinverter, Soft switching PWM, Utility AC-PDM, Dual mode pulse modulation control strategy, Non DC smoothing electrolytic capacitor DC link, Induction heating, Spiral type dual packs fluid heater

1.Introduction

In recent years, the latest technology developments of IH application products and equipment emphasized on the environment have attracted special interest in the consumer application fields as demonstrated below; IH cooking device, rice cooker and warmer, boiler, hot-water producer, floor and wall fluid heater, fryer, dryer, wastes treatment and soil sterilization equipment using cleaning and drying of atmospheric pressure super heated steamer. Under these technological requirements, research and development of circuits and control schemes of the high frequency power supply equipment for the electromagnetic induction heating 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 are actively proceeded from a practical point of view.

However, the harmonic current distortion inherently causes in the commercial AC input grid side of high frequency inverter power supplies because of rectified DC smoothing voltage link with electrolytic capacitor input filter. In addition, the significant problems on power conversion efficiency, volumetric physical size, 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 the utility frequency AC to high frequency AC power conversion circuit defined as high frequency power frequency converter or cycloconverter, which does not include DC smoothing filter stage. In addition, the circuit operation of the soft switching PWM high frequency (HF) AC power converter as high frequency power frequency supply is described for the hot-water producer and steamer using IH Dual Packs Fluid Heater (DPH) developed newly. Then, the circuit operation verification of high frequency power frequency converter is carried out in experiment and simulation. Finally, the power regulation characteristics and power conversion efficiency characteristics of high frequency power frequency converter is evaluated and discussed, along with active filtering characteristics on harmonic line current components and

(b) Spiral heater structure

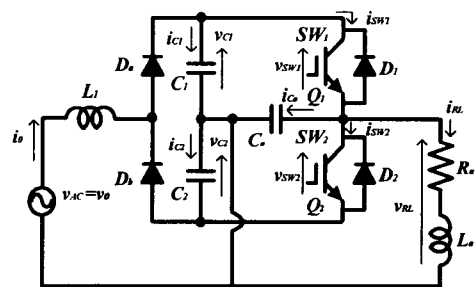Fig. 1. Internal structure of IH spiral type dual packs heater.

Fig. 2. Soft switching pulse modulated utility frequency AC-high frequency AC power conversion circuit without electrolytic capacitor.

total harmonic power factor in utility AC power grid side

2.Novel Type of Induction Heating Dual Packs Fluid Heater

The structure of business use IH-DPH driven by the high frequency inverter is shown in Fig.1. This spiral IH-DPH device developed newly works as a heat exchanger of the new spiral structure with the copper end ring with a low resistance, which is basically formed spirally by the thin plate of nonmagnetic stainless steel SUS316, which is inserted into the non metal vessel. The material of the IH-DPH device must consider the followings: temperature distribution is uniformity, corrosion protection for fluid (water, vapor, gas, powder) is excellent. The low pressure moving fluid in pipeline becomes clean. SUS316 is the stainless steel plate which is especially more excellent in corrosion protection than non-magnetic material SUS304 used most widely. In this case, the working coil uses enamel copper wire twisting together of the insulation to each other. This working coil is called power litz wire. In this developed IH heating device (see Fig.1), 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 tightly packed in IH-DPH hot-water producer between working coil and IH heating element part. Therefore, the security of
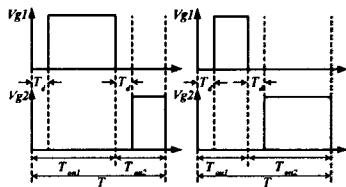

Fig. 3. Gate voltage pulse signal sequences of asymmetrical PWM control scheme.
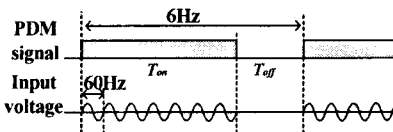

Fig. 4. Utility AC frequency-based pulse density modulation control strategy (d_{PDM} =0.7).

enough thermally stable temperature is possible for high temperature fluid heating container made of ceramics and nitrogen resin. This IH-DPH heating element is based on the mechanism, which heats the low pressure continuous movement fluid in the pipeline tube by the heat exchange behavior between IH heating element and fluid. Therefore, thermally stable temperature is also actually necessary for the pipeline tube. The fluid heating vessel tube uses the polycarbonate, and the thermally stable temperature is below 120 degrees centigrade.

3.Utility Frequency AC to High Frequency AC

Power Conversion System

3.1 Main Circuit Description The circuit structure of the AC to HFAC power converter or high frequency power frequency converter in which converts utility frequency AC

Table 1. Design specifications and circuit parameters

Item	Symbol	Value
Utility AC voltage (RMS)	V_{AC}	single phase 60Hz 200V
Switching frequency	f	21kHz
Dead time	T_d	$2\mu s$
Filter and resonant capacitors	C_1, C_2	5μF
Lossless snubbing quasi-resonant 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

power into high frequency AC power without the electrolytic capacitor DC link is shown in Fig.2. The proposed power frequency conversion circuit as a high frequency power frequency converter without electrolytic capacitor filter for DC smoothing stage defined as high frequency cycloinverter is a power frequency changing circuit topology which converts the utility frequency AC voltage into high frequency AC voltage over 20 kHz. This one power processing stage circuit structure is defined as high frequency power frequency converter which is different from the conventional high frequency inverter topology. The main power conversion circuit structure is basically composed of: two power switching blocks Q_1 (SW_1/D_1) and Q_2 (SW_2/D_2), filter inductor L_1 in utility frequency AC input-side, two capacitors C_1 and C_2 as active clamp resonance in accordance with high frequency IH-DPH load and low pass filter, lossless quasi-resonant snubber capacitor C_o and, IH-DPH load. This cycloinversion circuit operation for positive or negative utility AC voltage is equal to that of active clamp quasi-resonant inverter due to the lossless snubbing capacitor C_o in parallel with the induction heated DPH load. In case of using each $C_o/2$ in parallel with Q_1 and Q_2, the active clamp inverter also becomes the same equivalent as depicted in Fig.2.

3.2 Dual mode control of asymmetrical PWM and utility frequency AC PDM The gate pulse signal timing sequences for asymmetrical PWM control scheme of the
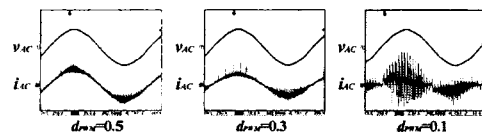

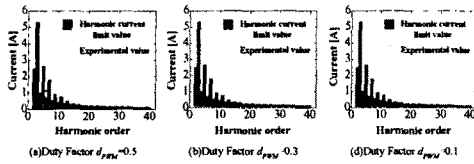Fig 5 Voltage and current waveforms in utility AC power side high

Fig. 6 FFT analysis of utility AC power source side current (experimental)

frequency power frequency converter in Fig.2 are shown in Fig.3. The asymmetrical PWM strategy as control variable is defined as the equation (2). That is, the duration proportion of on time T_{on1} of the main power switch for a high frequency power frequency converter period T is defined as Duty Factor or Duty Cycle d_{PWM} in the alternate asymmetrical PWM control scheme exchanged synchronizingly by the positive or negative polarity of the utility AC voltage. It is noted that the duration time of T_{on1} contains a dead time T_d. In addition, the gate pulse trains of the main and auxiliary power switches must be reversed in accordance with positive ore negative utility AC voltage to supply the desired high frequency AC power for IH-DPH load, because each role of $Q_1(SW_1)$ and $Q_2(SW_2)$ is reversed in accordance with either positive or negative voltage of the utility frequency AC power source. By introducing this pulse modulation control strategy, the high frequency power frequency converter enables to supply of the desired high frequency output AC power for the IH-DPH load.

$$d_{PWM} = \frac{T_{on1}}{T} \quad \text{.............(2)}$$

In addition to this asymmetrical PWM control strategy, the commercial utility frequency AC-PDM (Pulse Density Modulation) ZVS control scheme or commercial utility AC voltage cycle control scheme is also introduced herein. By introducing the commercial utility frequency AC-ZVS-PDM control strategy, the output HFAC effective power by changing the discrete cycle numbers of commercial utility frequency AC voltage pulse trains in its some intervals T_{PDM} to the IH-DPH load can be regulated on the basis of PDM principle in Fig.4. New concepts of the commercial utility frequency AC-ZVS-PDM control strategy are conceptually shown in Fig.4. The ZVS-based commercial utility frequency AC-PDM time ratio as a control variable d_{PDM} is defined as the equation (3). In the high frequency power frequency converter, the quantity in a period of utility AC power source under in 1/10 periods of utility AC voltage can be ajustted discretely.

$$d_{PDM} = \frac{T_{on}}{T_{on} + T_{off}} \quad \text{.............(3)}$$

The high frequency power frequency converter circuit topology depicted in Fig.2 can adjust high-frequency AC output power on the basis of load power dependent dual-mode control scheme of asymmetrical PWM and commercial frequency AC-PDM under a condition of zero voltage soft switching commutation and constant frequency. 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-ZVS-PDM control and the asymmetrical PWM control in case of high power setting ranges. The changing point of asymmetrical PWM and commercial frequency AC PDM

changed by in this high frequency power frequency converter is set to $d_{PWM} = 0.3$. The changing point of pulse modulation scheme is determined by time ratio which depends on IH-DPH load power and switching frequency. In all the high frequency AC power regulation ranges, this high frequency power frequency converter operate in overwide soft switching commutation range by changing the control scheme changing point of pulse modulation, even if the IH-DPH load might be replaced by the different IH-DPH load.

4.Simulation and Experimental Results

The results in simulation and experiment of the high frequency power frequency converter using IGBT module are described as follows. The design specifications and circuit parameters for experimental setup of high frequency power frequency converter are listed in Table 1.

Figure 5 shows input voltage and current survey waveforms of the power frequency converter. When duty factor $d_{PWM} = 0.5$, 0.3, 0.1, the input current form is sine wave. Although, input current wave form is not sine wave when $d_{PWM} = 0.1$. Fast Fourier Transform-based harmonic analysis results of the commercial AC current are illustrated
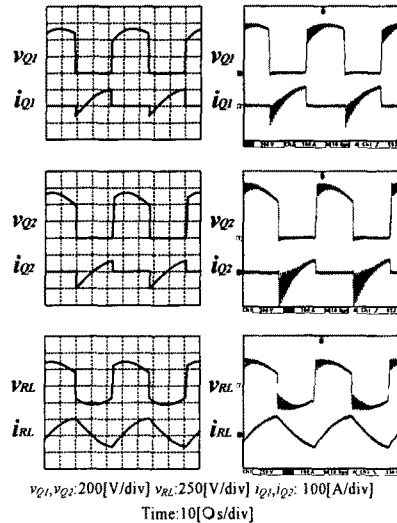

v_{Q1}, v_{Q2}:200[V/div] v_{RL}:250[V/div] i_{Q1}, i_{Q2}: 100[A/div]
Time:10[Qs/div]

Fig. 7. Soft switching voltage and current waveforms in case of d_{PWM}=0.5 in asymmetrical ZVS-PWM scheme.

(Left traces:Simulation, Right traces:Expeliment)

in Fig.6. The IH application cooking equipment is concerned with class A with home electric appliances, of general-purpose harmonic suppression countermeasure guideline. Commercial current spectrum calculated from each harmonic current specified value and observed waveform under class A is shown in Fig.6.

The relevant simulation and measured operating waveforms near the peak value of utility sinewave AC voltage $v_{AC}(t)$ as the high frequency power frequency converter set up in

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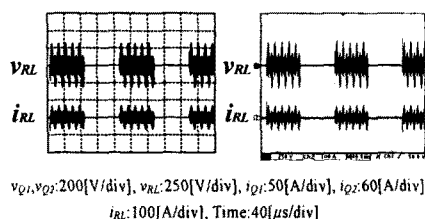i_{RL}:100[A/div], Time:40[μs/div]

Fig. 8. Soft switching voltage and current waveforms in case of utility AC frequency-based utility AC-ZVS-PDM control scheme in asymmetrical ZVS-PWM scheme. (d_{PWM} =0.3, d_{PDM} =0.5).

(Left traces:Simulation, Right traces:Experiment)

case of d_{PWM} =0.5 are shown in Fig.7. The typical voltage and current operation waveforms of simulation and measured ones have a good agreement within the slight error. Therefore, it is noted that the proposed pulse modulation control scheme is more effective for the high frequency power frequency converter.

The simulation and measured operating voltage and current waveforms in case of the utility frequency AC-ZVS-PDM control strategy for the asymmetrical ZVS-PWM control strategy are shown in Fig.8. This figure represents the operating voltage and current waveforms in case of d_{PWM} =0.3 and d_{PDM} =0.5. The operation waveforms of simulation and measured ones are comparatively illustrated herein. The utility frequency AC and high-frequency AC voltages are synchronized with each other. As a result, the utility frequency AC-ZVS-PDM control can operate accurately and efficiently.

Figure 9 illustrates the power conversion efficiency characteristics of the high frequency power frequency converter (see Fig.2). In Fig.9, the actual efficiency of the high frequency power frequency converter using asymmetrical ZVS-PWM control might be reduced in the low power setting ranges, because the high frequency power frequency converter becomes hard switching operation mode in low power setting ranges. The high conversion efficiency over 90% can be almost maintained, when the utility frequency AC-ZVS-PDM is used for low power setting ranges, since high frequency power frequency converter can operate under a condition of the soft switching commutation in all the high frequency power regulation ranges. Therefore, the selective dual mode pulse modulation control scheme using asymmetrical ZVS-PWM and utility frequency AC-ZVS-PDM is more effective, which is put into practical use for the high-efficient high frequency power control implementation.

5.Conclusions

In this paper, high frequency zero voltage soft switching pulse modulated power frequency converter based on LFAC to HFAC power converter with non electrolytic capacitor DC voltage smoothing filter link was newly proposed, which can achieve compactness in a volumetric physical size and weight, low cost, high reliability, high efficiency, low noise and long life. And then, the soft
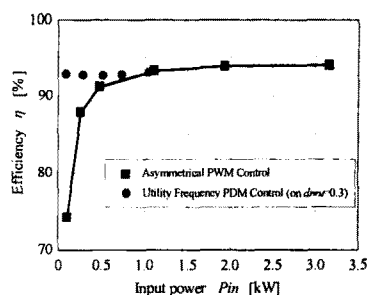

Fig. 9. Actual power conversion efficiency vs. input power characteristics in dual mode control and non dual mode control schemes.

switching circuit operation principle and features of the soft switching high frequency power frequency converter were actually clarified for unique consumer induction heating applications based on new type DPH using spiral plate with copper end ring as IH heat exchanger. Its high efficiency power conversion could be achieved from an experimental point of view by using LFAC to HFAC power converter using the dual mode pulse modulation time-sharing control implementation due to asymmetrical ZVS-PWM and commercial utility frequency AC-ZVS-PDM over the wide power regulation setting areas ranging from a low power to a high power setting.

In the future, the optimum circuit design method of the input filter part of the high frequency soft switching power frequency converter treated here should be investigated, and the power loss analysis of high frequency soft switching power frequency converter using measured v-i characteristics of soft switching pulse modulated power semiconductor switching devices (IGBTs; CSTBTs) represented by piece wise linear characteristics should be analyzed as well as improved. The actual efficiency and conventional efficiency characteristics have to be compared and studied in experiment. Finally, the LFAC to HFAC power conversion circuit using bidirectional power switches due to reverse blocking IGBT defined as high frequency power frequency converter.

References

(1) Hideaki Tanaka, Mitsuru Kaneda, Srawouth Chandhaket, Mamun Aubdallha AL, and Mutsuo 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), pp.306-311, Mexico(2000)