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High-Frequency Resonant Matrix Converter using IGBT-Based Bidirectional Switches for Induction Heating

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ABSTRACT
This paper deals with a novel type soft switching utility frequency AC- high frequency AC converter using asymmetrical PWM bidirectional active switches which can be defined as high frequency resonant matrix converter.This power frequency changer can directly convert utility frequency AC power to high frequency AC power ranging more than 20kHz up to 100kHz. Only one active edge resonant capacitor-assisted soft switching high frequency load resonant cyclo-converter is based on asymmetrical duty cycle PWM strategy. This high frequency cyclo-converter uses bidirectional IGBTs composed of anti-parallel one-chip reverse blocking IGBTs. This high frequency cycloconverter has some remarkable features as electrolytic capacitorless DC busline link, unity power factor correction and sinewave line current shaping, simple configuration with minimum circuit components and low cost, high efficiency and downsizing. This series load resonant cycloconverter incorporating bidirectional active power switches is developed and implemented for high efficiency consumer induction heated food cooking appliances. Its operating principle is described by using equivalent circuits. Its operating performances as soft switching operating ranges and high frequency effective power regulation characteristics are discussed on the basis of simulation and experimental results.

Index terms - Bidirectional switches, Direct power frequency conversion, High frequency PWM cycloconverter, Soft switching commutation, Induction heating, One-chip reverse blocking IGBTs.

I. INTRODUCTION

In recent years, the high frequency soft switching power conversion circuits (high frequency inverters, highfrequency switching DC-DC converters) technologies contribute for effective home and industrial power applications. The performance enhancement, energy saving and downsizing for the domestic electric power appliances have been proceeded with great advances of power semiconductor devices and passive circuit components. The high frequency inverter circuits have has been actively promoted so far that research and development on high frequency power conversion technologies for the high frequency induction heating.Electromagnetic induction heating applied technologies in home and business usages have been spotlighted in attractive induction heating appliances as metal working process, heat treatment, dissolution process, induction heating soldering with the self temperature function magnetic alloy heating element, induction fusion of polyethylene pipe, IH rice cooker, IH boiler, IH hot-water supplier, IH flyer and superheated vapor steamer by the state-of-the art IH fluid heating techniques. The developments on the modern electric kitchen systems with advantages as simple, reliability, safety, maintenance free, efficiency improvement of the food cooking and processing work, and reduction in total running cost have attracted special interest in modern society. From these viewpoints, the development of high frequency power supply appliances for kitchen equipments and facilities are required more and more. The development of the new high frequency induction heating cooker, boiler and super heated steamer, that is high-performance, high power density and high-efficiency compared with the conventional gas cooking equipment are much more attractive for home and business uses. By such technological background, high-frequency soft switching power supply for the electromagnetic induction heating has been developed as well as these control schemes.

This paper proposes high frequency PWM cycloconverter defined as the UFAC to HFAC direct power frequency changer using bidirectional power semiconductor switching devices based on one chip reverse blocking IGBT anti-parallel connection. The operation principle of the soft switching high frequency cyclo-converter treated here is described by using switching equivalent circuits. Furthermore, its circuit performance characteristics on the basis of simulation are illustrated herein.

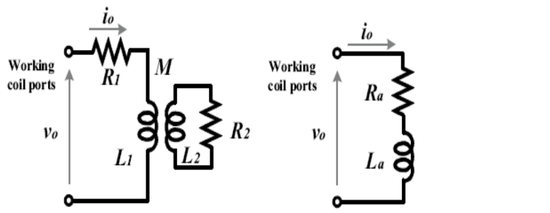
II. EQUIVALENT MODELLING OF INDUCTION HEATING LOAD

The equivalent circuit modeling of the electromagnetic induction heating load discussed below is shown in Fig.1(a) and (b). Figure 1 is an approximate linear equivalent model of the induction heated load circuit represented by equivalent effective inductance L_a in series with equivalent effective resistance R_a in reffered the input side of working coil terminals of the generic induction heater. R_a and L_a of the IH load are respectively determined by the self-inductance L_1 and internal resistance R_1 of the working 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 actually considered that these circuit parameters in spite of output power regulation delivered to the high frequency IH load is approximately kept constant, when high frequency AC power is regulated for a constant frequency PWM. The high frequency dependent resistance R_2 recognized and estimated by the skin effect resistance is kept constant under a principle of a fixed frequency asymmetrical PWM scheme.

. The measurement methods of circuit parameters R_a and L_a in the regulated IH load are as follows. High frequency AC voltage is provided to the IH load via ceramic spacerand working coil excited by high frequency inverter, high frequency cyclo-converter as well as high frequency linear power amplifier. The effective AC value V_{rms} of HFAC voltage and effective value I_{rms} of HFAC current with electrical angular frequency (ω=2πf),power factor $\cos\theta$($\cos\theta$: difference angle between output voltage and output current) are directly measured for high frequency IH load with working coil driven by HFAC power supply. Equation (1) is simply obtained on the basis of the sinewave AC circuit theory.

$$\begin{cases} \frac{Vrms}{Irms} = Z = \sqrt{Ra^2 + \omega La^2} \\ \cos\theta = \frac{Ra}{\sqrt{Ra^2+\omega La^2}} \quad \ldots\ldots\ldots\ldots\ldots (1) \\ \sin\theta = \frac{\omega La}{\sqrt{Ra^2+\omega La^2}} \end{cases}$$

The impedance Z_{rms} of the high frequency induction heating load for the angular frequency ω of output voltage and output current from high frequency linear power amplifier or high frequency inverter is calculated using the equation (1). By using measured fundamental power factor, the equivalent circuit parameters R_a and L_a of the high frequency IH load with pan, kettle and utensil or vessel placed exactly on pancake type working coil are estimated. In the case of considering internal resistance R_a of the planar working coil itself, the equivalent effective resistance value becomes $R_a + R_1$. The circuit parameters coupling coefficient k between L_1 and $L_2$and time constant τ expressed in Fig.1(a) are represented as follows by using R_a and L_a.



$\mathbf{K}=\frac{M}{\sqrt{L1L2}}$; *Ra : equivalent effective resistance*

$\tau = \frac{L2}{R2}$ *La*.: equivalent effective inductance

(a) Transformer type *equivalent circuit model* **(b) *R_a- L_a Series* equivalent circuit model**

Fig.1 Equivalent circuit modeling of electromagnetic induction eddy current based joule's heating load

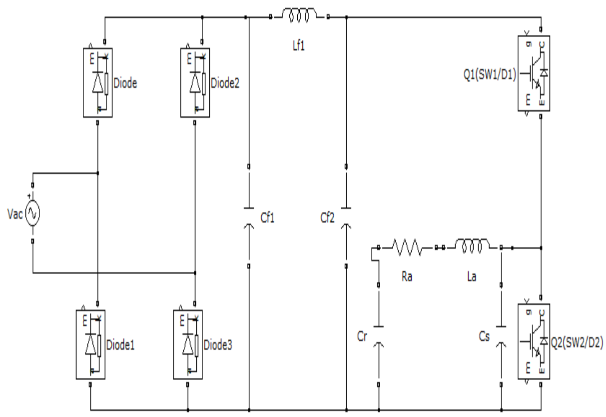
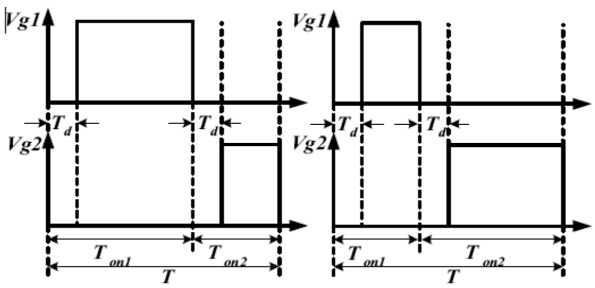


Fig.2 Asymmetrical PWM soft switching high frequency inverter

III. ASYMMETRICAL PWM SOFT SWITCHING HIGH FREQUENCY INVERTER

A. Circuit Description

Figure 2 illustrates the circuit topology of the voltage source type SEPP (single-ended push-pull) soft switching PWM high frequency inverter composed of two stage power conversion (UFAC-DC-HFAC) processing circuits.



(a) High power input **(b) Low power input**

Fig.3 Gate voltage pulse signal sequences of asymmetrical PWM

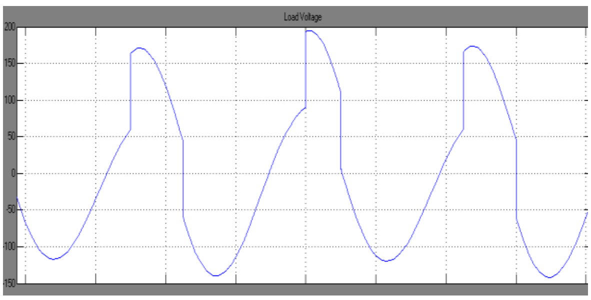
This high frequency inverter stage is composed of IH load represented by equivalent *Ra-La* series inductive load and switching power devices; $Q_1(SW_1/D_1)$ and $Q_2(SW_2/D_2)$ of the 2in1 IGBT module, series load compensated resonant capacitor C_r, lossless snubber capacitor C_s, smoothing filter L_{f1}, C_{f2}, C_{f3} and diode bridge rectifier. By repeating PWM of the switching power devices $Q_1(SW_1/D_1)$ and $Q_2(SW_2/D_2)$, this high frequency inverter can deliver high frequency AC power to the IH load via ceramic spacer and working coil.

B. Constant Frequency Asymmetrical PWM Control

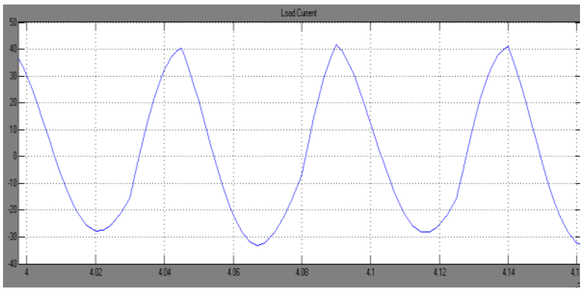
The gate pulse signal timing sequences for constant frequency asymmetrical PWM control are depicted in Fig.3. The asymmetrical PWM as a control variable in output power regulation of this high frequency inverter is defined as eq.(2).

$$D = \frac{Ton1}{T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

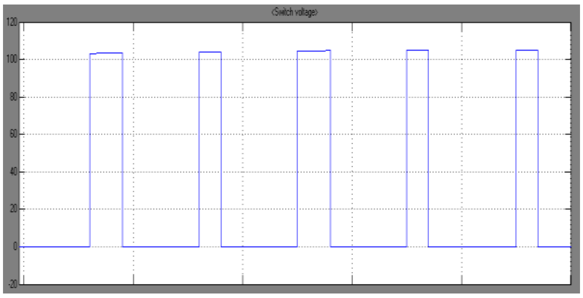
The duration proportion of on time T_{on1} of the power switches for a high frequency inverter period T is named as a duty factor or a duty cycle D in the asymmetrical PWM control scheme. In this case, the duration time of T_{on1} contains a dead time T_d. By introducing this time ratio control strategy, due to the soft switching PWM controlled high frequency inverter enables to supply the desired high frequency output AC regulation power for the IH load.



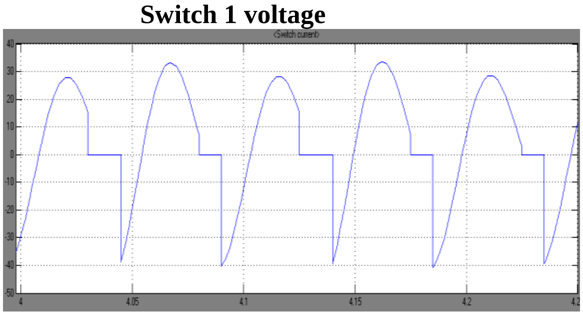
Load voltage



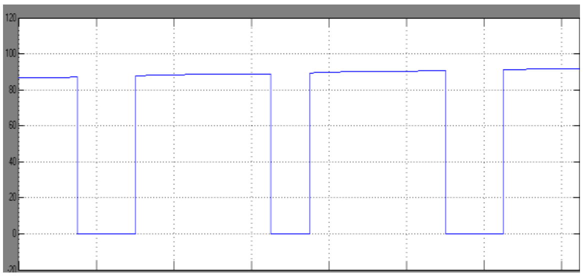
Load current



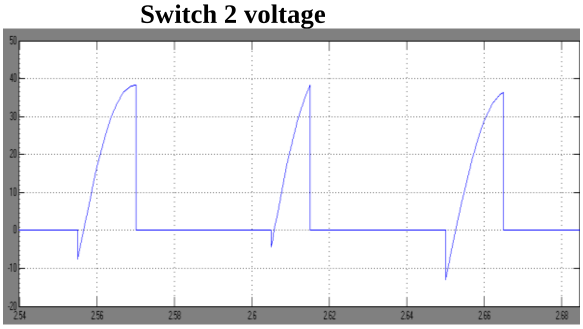
Switch 1 voltage



Switch 1 current



Switch 2 voltage



Switch 2 current

Fig. 4 simulation results

C. Simulation Results

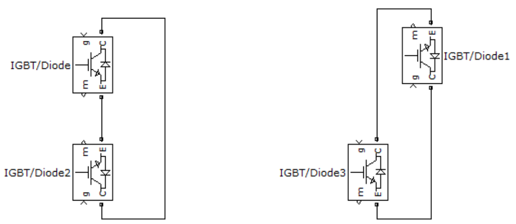
Figure 4 shows simulation waveforms of asymmetrical PWM controlled voltage source SEPP soft switching high frequency inverter for IH applications. As can be seen, the measured voltage and current waveforms have good agreements with the simulation waveforms.

IV. ANTIPARALLEL ONE CHIP REVERSE BLOCKING IGBT BASED BIDIRECTIONAL SWITCH

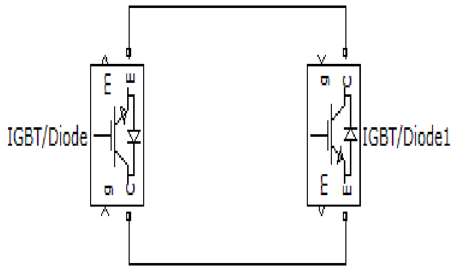
A new structure type IGBT has been recently developed by IXYS Corporation (IXRH40N120), providing reverse blocking capability for one chip IGBTs. This unique feature is needed a variety of applications, such as current source resonant inverters, a voltage source edge-resonant inverters, and high frequency resonant matrix converters. The rated data of the reverse blocking IGBT developed newly is listed in Table I.

The bidirectional switches which make use of anti parallel reverse blocking IGBTs are applied to voltage source high frequency inverter such as half bridge, single ended topologies. By substituting the switch parts of the high frequency inverter in Fig.2 with the bidirectional switches, and then, diode bridge rectifier of commercial AC input side can be eliminated for high frequency AC output. In short, one stage power conversion can be achieved for the high frequency cyclo-converter or high frequency resonant matrix converter.

Figure 5 shows bidirectional switches using conventional IGBTs with reverse conducting diode and anti-parallel reverse blocking IGBTs for high frequency cyclo-converter. The following features can be expected by using the reverse blocking IGBT: cost reduction, downsizing, reduction in ON-state voltage, high reliability, electrolytic capacitor DC filterless.



(a) 2 IGBTs & 2 Diodes(4 devices)



(b) 2 Reverse blocking IGBTs(2 devices)

Fig.5 Bidirectional power semiconductor switches

TABLE 1
REVERSE BLOCKING IGBT IXRH40N120

Item	**Symbol**	**Value**
Collector-Emitter voltage	V_{CES}	$\pm 1200V$
Collector current	I_{C25}	55A
Collector-Emitter saturation voltage	$V_{CE(Sat)}$	2.3V

V. SOFT SWITCHING PWM HIGH FREQUENCY CYCLOCONVERTER WITH BIDIRECTIONAL SWITCHES

A. Circuit Description

Figure 6 illustrates the circuit structure of the soft switching PWM high frequency cyclo-converter using the bidirectional switches shown in Fig.5. A novel circuit topology of high frequency cyclo-converter with PWM scheme, so called, high frequency matrix converter introduces the anti-parallel one chip reverse blocking IGBT type bidirectional switches into two switch high frequency inverter. The conventional two stage power converter including rectification converter and high frequency inverter are converted utility frequency AC power into regulated high frequency AC power. However, this high frequency cyclo-converter circuit topology can realize the commercial frequency AC to high frequency AC conversion directly without the rectification DC link stage due to the electrolytic capacitor filler. Accordingly , this high frequency resonant cyclo-converter (Matrix converter) can achieve cost reduction, because the high frequency cyclo-converter does not substantially require the diode bridge rectifier with electrolytic DC capacitor filter link.

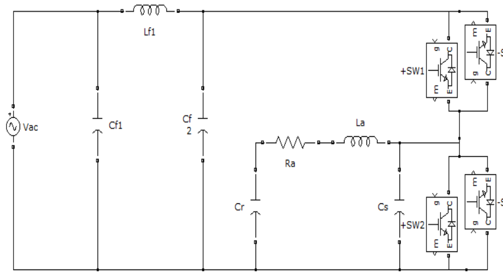
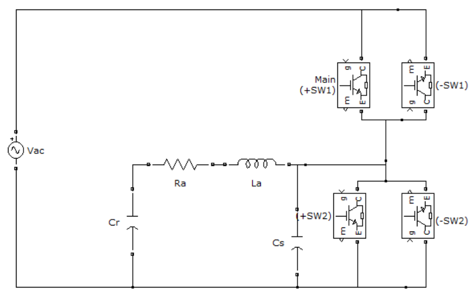


Fig.6 Soft switching high frequency cyclo-converter

(a) $V_{AC} > 0$



(b) $V_{AC} < 0$

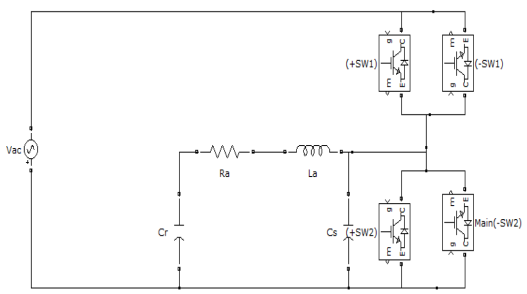


Fig.7 Gate voltage pulse signal sequences

This voltage-fed ZVS-PWM high frequency cycloconverter with bidirectional switches, which can operate soft commutation scheme is composed of low pass filter L_{f1}, C_{f1}, C_{f2}, high frequency IH load, bidirectional switches Q_1(+SW_1/–SW_1) and Q_2(+SW_2/–SW_2), lossless snubber capacitor C_s, series load resonant tuned capacitor *Cr* and single phase 100V_{rms} input commercial AC power grid.

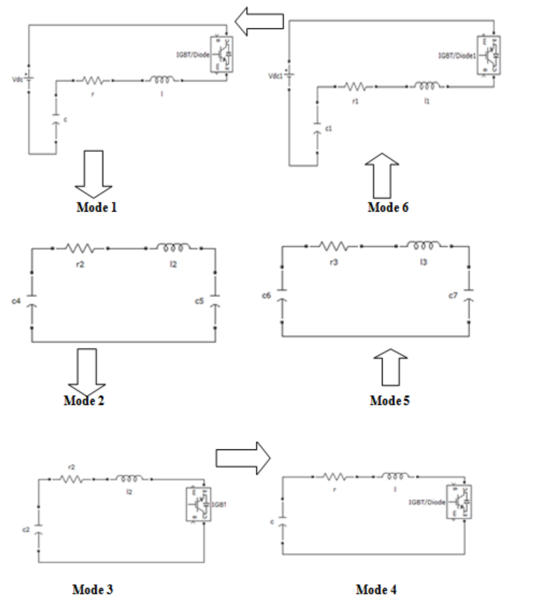
TABLE 2
DESIGN SPECIFICATIONS AND CIRCUIT PARAMETERS

Item	Symbol	Value
Utility ac voltage (rms)	V_{AC}	100V AC
Switching frequency	f	21kHz
Series resonant capacitor	C_r	2.5μF
Lossless snubbing capacitor	C_s	0.20μF
Effective resistance component of IH load	R_a	0.910
Effective inductance component of IH load	L_a	30.8μH
Dead time	T_d	3.0μsec

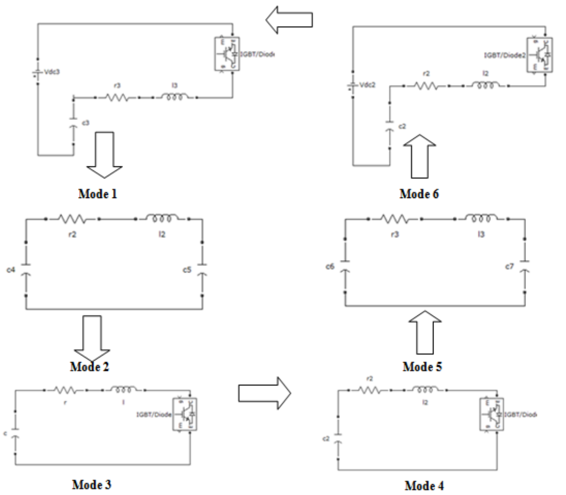
B. Control Scheme

The voltage-source type soft switching PWM high frequency cyclo-converter has to input the control signal pulses synchronized with 50Hz/60Hz frequency of the utility AC power supply into the switches Q_1 and Q_2, because high frequency AC power converter from commercial AC power directly. Figure 7 shows the gate drive signals delivered to the switches.When instantaneous voltage of 60Hz frequency is during the positive half wave period, the asymmetrical PWM signal trains are provided in order to regulate the high frequency output AC power by the switches +SW_1 and +SW_2. During this case, the switches – SW_1 and –SW_2 are on-state continuously. On the other hand, during negative half wave of utility AC input voltage, the switches +SW_1 and +SW_2 are on-state continuously. By using this control scheme, the HFAC output power of the high frequency cyclo-converter can be smoothly regulated by asymmetrical PWM control scheme described in chapter III.

C. Switching Mode Transition Operation



(a) $V_{AC} > 0$



(b)$V_{AC} < 0$

Fig.8 Switching mode transitions and equivalent circuits in the case of positive and negative half wave of input voltage

Mode transitions in the steady state operation of this soft switching PWM voltage-type high frequency cyclo converter using bidirectional PWM is illustrated in Fig.8. The operation of positive and negative half wave of the input utility frequency AC voltage is basically identical by changing the direction of the circuit components. Therefore, the operating switching mode transitions and switching mode equivalent circuit for the positive half wave of utility frequency AC voltage are described below.

[Mode 1] This mode is a power supplying mode which supplies the high frequency AC power provided to the IH load through the switch +SW1 from the utility frequency AC power supply voltage V_{AC}. This mode ends when the switch $+SW_1$ is turned off after the duration period T_{on1} relating to duty factor defined as eq.(2).

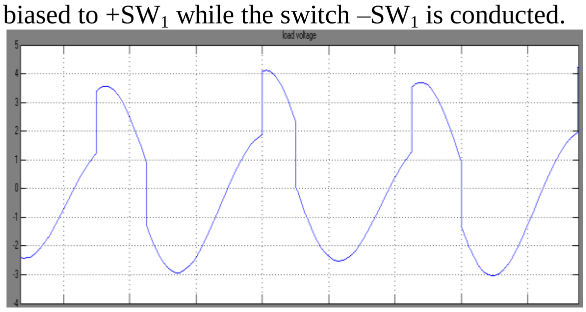
[Mode 2] When the switch $+SW_1$ is turned off, the load current commutated to lossless snubber capacitor C_s, and the capacitor *Cs* starts to discharge. The voltage across the switching power device $Q_1(+SW_1/-SW_1)$ also rises slowly because the snubber lossless capacitor *Cs* discharges slowly with the aid of resonant phenomena during this interval. Therefore, the switch $+SW_1$ can be turned off with ZVS commutation. This mode ends when lossless snubbing capacitor *Cs* completes discharging.

[Mode 3] This mode is resonant mode by $-SW_2$ of Q_2,high frequency IH load and power factor compensation capacitor C_r. The current through $-SW_2$ decreases in the load resonance and $+SW_2$ can achieve the natural commutation when on signal is delivered into the switch $+SW_2$ while $-SW_2$ is conducting. As a result, $+SW_2$ can be turned on with ZVS&ZCS.

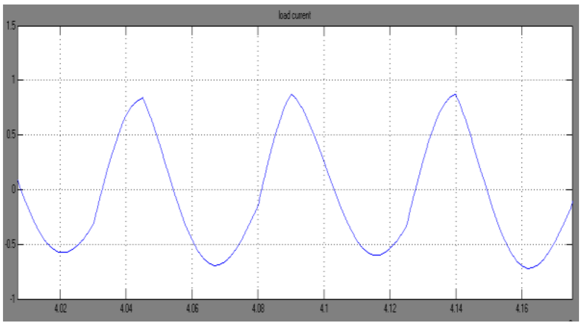
[Mode 4] This mode is a resonant mode by $+SW_2$, IH load and power factor compensation capacitor C_r. This mode ends when $+SW_2$ is turned off with ZVS.

[Mode 5] In this mode, the load current flows through the loop with C_s and the series resonant capacitor C_r when $+SW_2$ is turned off with ZVS. The voltage across $Q_2(+SW_2/–SW_2)$ also rises slowly, because C_r is charged slowly with the aid of resonance. Therefore, $+SW_2$ can realize ZVS turn-off commutation. Mode 5 ends when the voltage V_{cs} reaches to utility AC voltage V_{AC}.

[Mode 6] In this mode, $–SW_1$ is turned-on with ZVS&ZCS. The current through$–SW_1$ decreases by the series load resonance. This mode ends when $+SW_1$ commutates naturally. Therefore, the switch $+SW_1$ can achieve ZVS&ZCS when the gate signal is biased to $+SW_1$ while the switch $–SW_1$ is conducted.



Load voltage



Load current

Fig.9 Simulation Results

D. Simulation Results

The circuit parameters and design specifications for simulation is listed in Table II. This resonant high frequency cyclo-converter is operated with 6 sub operating modes. This operating mode is basically the same as conventional high frequency inverter. Fig.9 show's simulation load voltage and load current waveforms of $Q_1(+SW_1/–SW_1)$ and $Q_2(+SW_2/–SW_2)$ for a constant frequency asymmetrical PWM control strategy in the case of duty factor *D*=0.5. The measurement points of these operating waveforms are positive and negative peak points of the utility AC input voltage, respectively. As can be seen, the measured voltage and current waveforms have good agreements with the simulated ones. From these figures, the resonant high frequency cyclo-converter can achieve ZVS&ZCS at turn-on and ZVS at turn-off transition for all the active switches Q_1 and Q_2 without rectifier circuits. Therefore, the resonant high frequency cyclo-converter is able to realize UFAC to HFAC direct power frequency conversion processing under soft switching commutation without two power conversion processing stages

VI. CONCLUSIONS

This paper proposed the novel prototype of one stage voltage-type multi-resonant SEPP-ZVS PWM high frequency AC power conversion circuit operated as the resonant high frequency PWM cyclo-converter (resonant high frequency matrix converter) using the anti parallel one chip reverse blocking IGBT type bidirectional switches for consumer induction heating appliances. The soft switching PWM resonant high frequency cyclo converter discussed in operation principle and power regulation characteristics on the basis of simulation.

In the future, the actual efficiency and conventional efficiency characteristics should be evaluated for resonant high frequency cyclo-converter using bidirectional switches. The optimum circuit design method of the utility AC input filter part of the resonant high frequency soft switching cyclo-converter treated here should be investigated from a practical point of view

REFERENCES

[1] A.Lindemann: “A New IGBT with Reverse Blocking Capability” *Proceedings of EPE Conference*, Graz, 2001.

[2] T.Minato and H.Takahashi: “New Power-Element Technology” *Mitsubishi Electric ADVANCE*, March 2004, pp.24-27.

[3] Hisayuki Sugimura, Tarek Ahmed, Mohamed Orabi, Hyun-Woo Lee, Mutsuo Nakaoka, “Commercial Utility Frequency AC to High Frequency AC Soft Switching Power Conversion Circuit with Non Smoothing DC Link for IH Dual Packs Heater”, Proceedings of The 30th Annual Conference of the IEEE Industrial Electronics Society, (IECON), November, 2004, Pusan, Korea, pp.1155-1160.

[4] Hisayuki Sugimura, Hyun-Woo Lee, Kenji Yasui, Toshiaki Iwai, Hideki Omori, Nabil A.Ahmed, Sung Jun Kim and Mutsuo Nakaoka, “Commercial Utility AC Frequency to High Frequency AC Cycloinverter with Non Electrolytic Capacitor DC Link”, *Proceedings* of International Power Electronics Conference (IPEC), April, 2005, Niigata, JAPAN, No.S38-2

[5] N.Nguyen-Quang, D.A.Stone, C.M.Bingham, M.P.Foster, “Single phase matrix converter for radio frequency induction heating”,Proceedings of International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), May,2006, pp.614 - 618.