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# Single Phase Utility Frequency AC-High Frequency AC Matrix Converter Using One-Chip Reverse Blocking IGBTs based Bidirectional Switches

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***Abstract-*** **This paper presents a novel type soft switching PWM power frequency AC-AC converter using bidirectional active switches or single phase utility frequency AC-high frequency AC matrix converter. This converter can directly convert utility frequency AC (UFAC, 50Hz/60Hz) power to high frequency AC (HFAC) power ranging more than 20kHz up to 100kHz. A novel soft switching PWM prototype of high frequency multi-resonant PWM controlled UFAC-HFAC matrix converter using antiparallel one-chip reverse blocking IGBTs manufactured by IXYS corp. is based on the soft switching resonance with asymmetrical duty cycle PWM strategy. This single phase UFAC-HFAC matrix converter has some remarkable features as electrolytic capacitor DC busline linkless topology, unity power factor correction and sinewave line current shaping, simple configuration with minimum circuit components, high efficiency and downsizing. This series load resonant UFAC-HFAC matrix converter, incorporating bidirectional active power switches is developed and implemented for high efficiency consumer induction heated food cooking appliances in home uses and business-uses. Its operating performances as soft switching operating ranges and high frequency effective power regulation characteristics are illustrated and discussed on the basis of simulation and experimental results.**

**Keywords- Bidirectional switches, Direct power frequency conversion, UFAC-HFAC matrix converter, Electrolytic DC capacitor filterless topology, Soft switching commutation, Electromagnetic eddy current-based induction heating (IH)**

## I. Introduction

In recent years, the high frequency soft switching power conversion circuits (high frequency inverter, high-frequency switching DC-DC converters) and systems technologies have attracted special interest for home power utilizations and industrial power applications. The performance enhancement, energy saving and downsizing and so forth for the consumer power appliances have been proceeded with great advances of power semiconductor switching devices and switching made power converter circuit topologies. In multi-diverse technological innovations, it is actively promoted that research and development on applied high frequency power conversion technologies for the high frequency electromagnetic induction heating (IH) applications. Electromagnetic induction heating appliances have been spotlighted in attractive utilization fields as metal working process, heat treatment, dissolution process, high frequency IH soldering with the self temperature function using magnetic alloy heating element, electromagnetic induction fusion of polyethylene pipe, fixing heat roller, IH rice cooker, IH boiler, IH hot-water producer, IH flyer and superheated vapor steamer in the novel IH pipeline. Recently, the developments the electric power processing kitchen systems with advantages such as simplification, reliability, safety, maintenance free, cleanliness, efficiency improvement of the food cooking and processing work, flexible kitchen style design and reduction in total running cost have attracted special interest in modern society. From these viewpoints, a variety of research and developments of high frequency power supply systems for kitchen equipments and facilities are required from now on. The development of the new high frequency electromagnetic induction cooker, steamer and roller that is more high-performance and high-efficient as compared with the conventional gas cooking equipments are more and more attractive for business use. Under such a technology background, research and developments of high-frequency soft switching power supply circuits and this associated control schemes are indispensable for consumer IH products.

This paper proposes single phase UFAC-HFAC matrix converter defined as the commercial frequency AC to high frequency AC direct power frequency converter using bidirec-

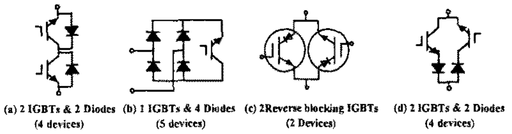

(a) 2 IGBTs & 2 Diodes (4 devices) (b) 1 IGBTs & 4 Diodes (5 devices) (c) 2Reverse blocking IGBTs (2 Devices) (d) 2 IGBTs & 2 Diodes (4 devices)

Fig.1 Bidirectional switches

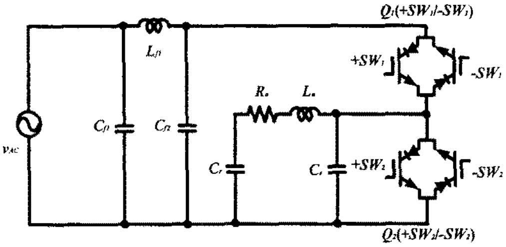


Fig.2 Soft switching high frequency cyclo-converter

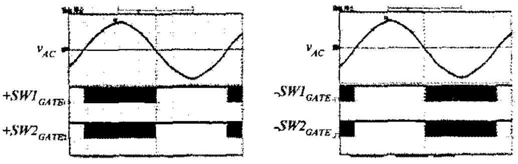


Fig.3 Gate voltage pulse signal sequences

tional power semiconductor switching devices based on one chip reverse blocking IGBT anti-parallel connection. The operation principle and operating analysis of the single phase UFAC-HFAC matrix converter are described, and the performance evaluations are carried out on the basis of simulation and experimental results.

## II. Antiparallel One Chip Reverse Blocking IGBT based Bidirectional Switch

A new structure type IGBT has been recently developed by IXYS, providing IGBT with reverse blocking capability. This power device is needed for various IH applications, using current source resonant inverters, a certain quasi-resonant circuits, AC voltage regulator and matrix converters. In this paper, bidirectional switches which makes use of antiparallelly connected reverse blocking IGBTs are applied to the voltage source type single-ended push-pull (SEPP) high frequency inverter circuit topology. By replacing the switch parts of the high frequency inverter with the bidirectional switches and then, diode bridge rectifier of commercial AC input side can be eliminated for obtaining high frequency AC output. In short, one stage UFAC-HFAC power conversion becomes possible for the single phase high frequency resonant matrix converter. The bidirectional switches using conventional IGBTs with reverse conducting diode and antiparallel reverse blocking IGBTs are shown in Fig.1. 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.

Table 1 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 snubber capacitor | $C_s$ | 0.20μF |
| Effective resistance component of IH load | $R_a$ | 0.910Ω |
| Effective inductance component of IH load | $L_a$ | 30.8μH |
| Dead time | $T_d$ | 3.0μsec |

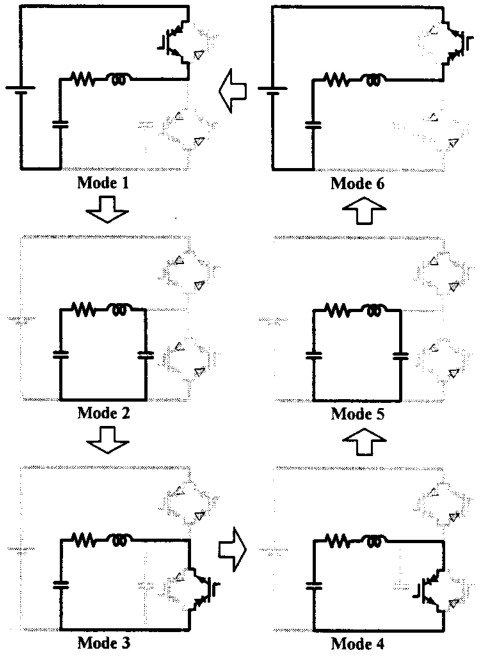


Fig.4 Switching mode transitions and equivalent circuits

## III. Soft Switching PWM Controlled High Frequency Cyclo-Converter with Bidirectional Switches

### *A. Circuit Description*

The circuit structure of the single phase UFAC-HFAC matrix converter using the bidirectional switches is shown in Fig.2. A novel circuit topology of the UFAC-HFAC matrix converter with PWM scheme introduces the antiparallel one chip reverse blocking IGBT type bidirectional switches into two switch parts of the conventional high frequency inverter. This circuit topology realizes the commercial frequency AC to high frequency AC conversion directly without the rectification DC link stage due to the electrolytic capacitor bank. This single phase UFAC-HFAC matrix converter operating at soft commutation is composed of low pass filter Lfl, Cfl, Cf2, IH load, bidirectional switches $Q_1(+SW_1/-SW_1)$ and $Q_2(+SW_2/-SW_2)$, lossless snubbing capacitor $C_s$, series resonant tuned capacitor $C_r$ and single phase $100V_{rms}$ input commercial AC power grid. Two stage power converter using conventional rectification converter and high frequency inverter are converted utility frequency AC into regulated high frequency AC. Accordingly, this single phase UFAC-HFAC matrix converter does not require the diode bridge rectifier and bulky electrolytic DC capacitor filter.

### *B. Control Scheme*

The gate pulse signal timing sequences for constant frequency asymmetrical PWM control scheme are depicted in Fig.3. The asymmetrical PWM as a control variable in high frequency AC power regulation of this high frequency inverter is defined as (1). The duration proportion of conduction time $T_{on1}$ of the main switch for a high frequency inverter period $T$ is defined as Duty Factor $D$ in the alternate 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, the single phase UFAC-HFAC matrix converter enables to supply of the desired high frequency output AC power for the IH loads.

$$D=\frac{T_{on1}}{T} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

The single phase UFAC-HFAC matrix converter must input the control signal pulses synchronized with 50Hz/60Hz frequency of commercial power supply into the switches $Q_1$ and $Q_2$, because high frequency AC power supply generates from commercial AC power directly. The gate pulse signals given to each switch is shown Fig.3. The gate signal is inputted in order to control the output HFAC power by switches $+SW_1$ and $+SW_2$, when instantaneous voltage value of the 60Hz frequency (UFAC) is during the positive half wave period. The other switches $-SW_1$ and $-SW_2$ become conduction-state during this period. During a positive half wave period of utility frequency AC voltage, the switches $-SW_1$ and $-SW_2$ similarly can behave the same operation of the reverse conducting diode of SEPP-ZVS high frequency inverter. Conversely, during a negative half wave period, the switches $+SW_1$ and $+SW_2$ of the single phase UFAC-HFAC matrix converter can operate as well as that of reverse conducting diode of the SEPP-ZVS inverter.

### C. *Switching Mode Transition Operagion*

Mode transitions in the steady state operation of this single phase UFAC-HFAC matrix converter using bidirectional PWM scheme is shown in Fig.4. The operation of positive and negative half wave of the input UFAC voltage is basically identical by changing the direction of the circuit elements. The operating mode transitions and switching mode equivalent circuit for the positive half wave of utility AC voltage are described below.

<Mode 1> Mode 1 is a power supplying mode which supplies HFAC power to the IH load through $+SW_1$ from UFAC power supply voltage $v_{AC}$. By turning off $+SW_1$ after the period $T_{on1}$ due to Duty Factor defined in (1), the circuit operation shifts to Mode 2.

<Mode 2> The load current flows to the loop with lossless snubbing capacitor $C_s$ and the capacitor $C_s$ starts to discharge when $+SW_1$ is turned off. The voltage across $Q_1(+SW_1/-SW_1)$ also rises slowly, because the snubbing capacitor $C_s$ discharges slowly with the aid of resonance phenomena during this period. Therefore, the switch $+SW_1$ realizes ZVS turn-off commutation. By turning on the antiparallel reverse blocking IGBT $-SW_1$, this mode transition shifts to Mode 3 when lossless snubbing capacitor $C_s$ finishes discharging.

<Mode 3> Mode 3 is a resonance period by reverse blocking IGBT $-SW_2$ of $Q_2(+SW_2/-SW_2)$, IH load and series power factor compensation capacitor $C_r$. The voltage across $+SW_2$ decreases in load resonance including $-SW_2$, when on signal is inputted into the gate of $+SW_2$ during the conduction period of $-SW_2$. The natural commutation of $+SW_2$ is completed by the current decrease of $-SW_2$ in the load resonance, when on signal is inputted into the gate of $+SW_2$ during the conduction period of $-SW_2$. The current through $-SW_2$ decreases in the load resonance and $+SW_2$ can realize the natural commutation when on signal is delivered into the gate of $+SW_2$ while $-SW_2$ is conducted. At this time, $Q_2(+SW_2/-SW_2)$ can realize the ZVS&ZCS turn-on, and the operation mode shifts to Mode 4.

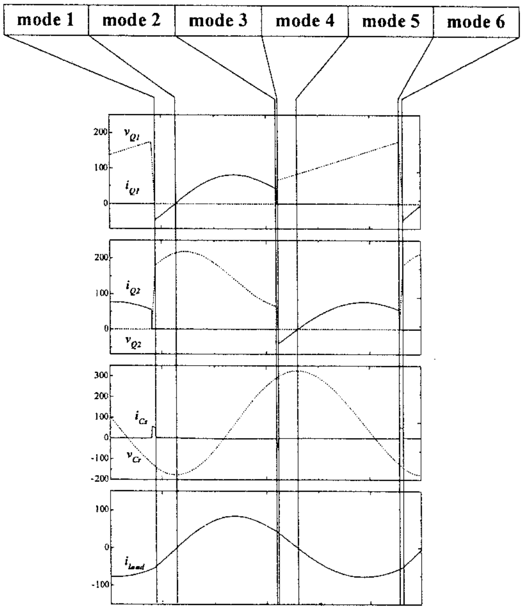
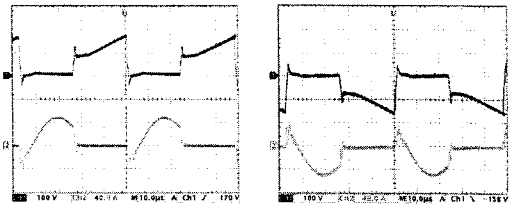


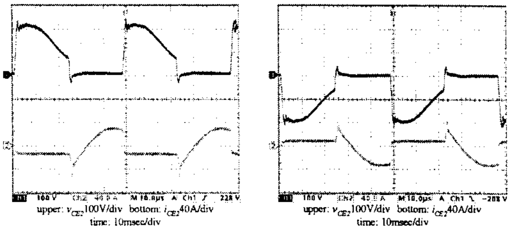
Fig.5 Steady state operation waveforms in case of $D$=0.5


upper: $v_{CE1}$100V/div bottom: $i_{CE1}$40A/div
time: 10msec/div

upper: $v_{CE1}$100V/div bottom: $i_{CE1}$40A/div
time: 10msec/div

**(a)Switch $Q_1(+SW_1/-SW_1)$**
**(in case of positive peak)**

**(b)Switch $Q_1(+SW_1/-SW_1)$**
**(in case of negativepeak)**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upper: $v_{CE2}$100V/div bottom: $i_{CE2}$40A/div
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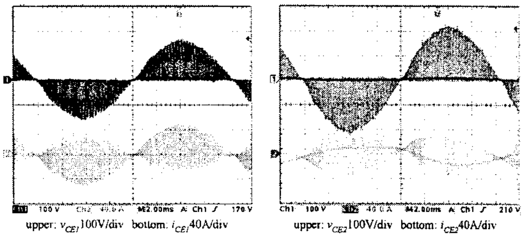
**(c)Switch $Q_2(+SW_2/-SW_2)$**
**(in case of positive peak)**

**(d)Switch $Q_2(+SW_2/-SW_2)$**
**(in case of negative peak)**

Fig.6 Experimental voltage and current waveforms in case of $D$=0.5


upper: $v_{CE1}$100V/div bottom: $i_{CE1}$40A/div
time: 10msec/div

upper: $v_{CE2}$100V/div bottom: $i_{CE2}$40A/div
time: 10msec/div

**(a)Switch $Q_1(+SW_1/-SW_1)$**

**(b)Switch $Q_2(+SW_2/-SW_2)$**

Fig.7 Experimental voltage and current waveforms in case of $D$=0.5 (utility frequency: 60Hz)

<Mode 4> Mode 4 is a resonant period by $+SW_2$ and IH load and power factor compensation capacitor $C_r$. By turning off $+SW_2$ after the period $T_{on2}$ progress duty factor determined, mode transition shifts to Mode 5.

<Mode 5> The load current flows through the loop with lossless snubbing capacitor $C_s$ and the capacitor $C_r$ can be charged when $+SW_2$ is turned off. The voltage across $Q_2(+SW_2/-SW_2)$ also increases slowly because the capacitor $C_r$ is charged slowly with the aid of a resonant phenomena. Therefore, the switch $+SW_2$ can realize ZVS turn-off. The reverse blocking IGBT $-SW_1$ of $Q_1(+SW_1/-SW_1)$ turns on. The circuit operation shifts to Mode 6 when lossless snubbing capacitor $C_s$ finishes charging up to a source voltage $v_{AC}$.

<Mode 6> Mode 6 is a resonant period of $-SW_1$, source voltage $v_{AC}$, IH load and power factor compensation capacitor $C_s$. In addition, Mode 6 is the power regeneration mode. The current through $-SW_1$ decreases during the load resonance period and the natural commutation can be achieved to $+SW_1$ when the on signal is supplied into the gate of $+SW_1$ while $-SW_1$ is conducted.

## IV. Experimental Results and Discussions

### A. *Simulation and experimental waveforms*

The designing circuit parameters for simulations and experiment is listed Table 1. Simulation waveforms of this single phase UFAC-HFAC matrix converter are shown in Fig.5. Experimental voltage and current waveforms of $Q_1(+SW_1/-SW_1)$ and $Q_2(+SW_2/-SW_2)$ for the constant frequency asymmetrical PWM control strategy is shown in Fig.6. In this figure, the voltage and current waveforms are identical, when the input voltage is positive or negative. In addition, it was able to be confirmed that the soft switching commutation for all the new switching power devices was possible in this single phase matrix converter which does not require a rectifier circuit. This single phase UFAC-HFAC matrix converter becomes the switching mode equivalent circuit in which each circuit from the viewpoint of the input UFAC side for positive or negative half wave UFAC voltage are fundamentally identical. Simulated waveforms have good agreement with experimental results.

The voltage and current waveforms of $Q_1(+SW_1/-SW_1)$, $Q_2(+SW_2/-SW_2)$ and IH load from the viewpoint of the period of input UFAC 60Hz applied to the high frequency cycloconverter in case of a duty factor $D$=0.5 are represented in Fig.7. In this figure, it was able to be confirmed that it is perfectly synchronized with operating frequency of the single phase UFAC-HFAC matrix converter for the inversion of positive or negative in UFAC input voltage source period. In addition, it was also able to be confirmed that the bidirectional power semiconductor devices are accurately switched for the inversion of positive or negative in every 60Hz period. Therefore, the single phase UFAC-HFAC matrix converter was able to realize the UFAC to HFAC direct power conversion under soft switching commutation without two stage power conversion processing.

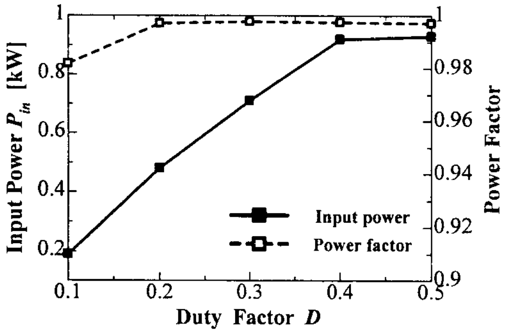


Fig.8 Input power and Power factor characteristics

### B. *Input Power Regulation and Input Power Factor Correction Characteristics*

Input power regulation and power factor correction characteristics in the experiment circuit of single phase UFAC-HFAC matrix converter proposed here are shown in Fig.8. Rated input power 940W is able to realize in case of $D$=0.5. The power factor in utility AC side can operate the single phase UFAC-HFAC matrix converter over 0.98 in all power regulation ranges. The feasible experiment that power frequency conversion proposed was kept to be the high power factor.

## V. Conclusions

In this paper, one stage voltage-type SEPP-ZVS high frequency AC power conversion circuit defined as the single phase UFAC-HFAC matrix converter using the antiparallel reverse blocking IGBT type bidirectional switches was proposed for consumer induction heater. The evaluations and examinations of single phase UFAC-HFAC matrix converter were carried out and verified on the basis of simulation and experiment on operation principle and control characteristics of the single phase UFAC-HFAC matrix converter. The practical effectiveness of single phase UFAC-HFAC matrix converter operating under a soft switching PWM was proved in experiment.

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