

PRACTICAL EVALUATIONS OF SINGLE-ENDED LOAD-RESONANT INVERTER USING APPLICATION-SPECIFIC IGBT & DRIVER IC FOR INDUCTION-HEATING APPLIANCE

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ABSTRACT *This paper presents an efficient single-ended type high-frequency induction-heating quasi-resonant inverter circuit using a single advanced 2nd generation IGBT for soft-switching and its specially-designed driver IC, which operates at a zero-voltage soft-switching(ZVS)mode under PFM-based power regulation strategy. The generic voltage-fed and current-fed circuit versions of single-ended resonant inverters for home power electronics appliances are systematically proposed and classified on the basis of the soft-switched PFM mode inverter family. The epoch-making advanced IGBT designed for the application-specific soft-switching and its driver IC, are shown as new induction-heating rice cooker including cooking vessel and evaluated from an experimental point of view. These new technologies are especially developed for quasi-resonant ZVS high-frequency inverter with working coil-linked induction-heating loads.*

This high-efficient high-frequency quasi-resonant inverter system with high-power factor correction and sinewave line current shaping functions is practically demonstrated including a high-frequency IGBT with reduced saturation voltage characteristics, and discussed on the basis of high-power density home-power electronic appliances in the next generation.

1. INTRODUCTION

In recent years, the advanced system technology developments of switched-mode resonant type high-frequency inverter using new power semiconductor devices/modules have attracted special interest in industrial, consumer, medical and space power utilization fields as well as home telecommunication power plants.

The remarkable unique applications of high-frequency inverter and converter circuits with resonant-tank, resonant-pole, resonant DC link and quasi-resonant switch topologies which efficiently operate at a zero-current or a zero voltage soft switching mode, include the static high-power density DC-AC power supplies for induction-heating and melting, high-power ultrasonic generating, discharge-lamp lightening & dimming, microwave oven and CVCF or VVVF power conditioning and processing due to high-frequency AC link and/or resonant DC link. Considering the

consumer power electronic products employing high-frequency resonant inverter, the design important constraints are significantly based upon the requirement such as low cost, lowered acoustic noise, reduced EMI/RFI noises, high-efficiency high-power density and wide power regulation range. Simple inverter topologies must be effectively selected according to the applications in order to meet the inverter requirements mentioned above under a high-frequency switching operation due to load specifications.

In practice, the simple and compact inverter systems should be well shielded to prevent undesirable EMI/RFI noises, which are used for induction-heating cooking appliances such as multi-diverse cooking pan, microwave oven, discharge lamp lightening and TV. In consumer home power electronics, a single-ended quasi-resonant inverter using a single active power semiconductor device is more cost-effective and acceptable which efficiently operates at ZVS principle based upon a resonant switch concept.

This paper describes an advanced quasi-resonant ZVS-PFM inverter using a single specially-designed IGBT and its driver IC in next generation, which is introduced as a high-frequency induction-heating rice cooker/warmer, along with the extended quasi-resonant soft-switching inverter circuit topologies with a single active power switch.

In this paper, this system is experimentally evaluated for the consumer home power electronic apparatus, which includes a unity power-factor correction and sinewave line-current shaping function.

2. POWER CONVERSION SYSTEM

<2-1>TOTAL SYSTEM DESCRIPTION

Figure 1 shows a schematic total power conversion system for induction-heating cooking apparatus, which is mainly composed of a single-phase diode rectifier with a high-pass LC filter, a single-phase single-ended high-frequency resonant inverter operating at ZVS-PFM scheme, working-coil coupled heating load(vessel/pan or utensil) and power regulation control and power device driver IC, including a micro computer-based system controller. In this system, the unity-power factor correction and sinewave-line current shaping operation are simply accomplished without using an additional active-filter type switching converter on the basis of a weak DC-link effect. In other words, this total system can be actually considered as a frequency step-up

cycloconversion system.

This total system is practically applied for the induction-heating cooking vessel/utensil or induction-heating rice cooker/warmer as well as magnetron drive microwave oven in consumer home power electronic systems.

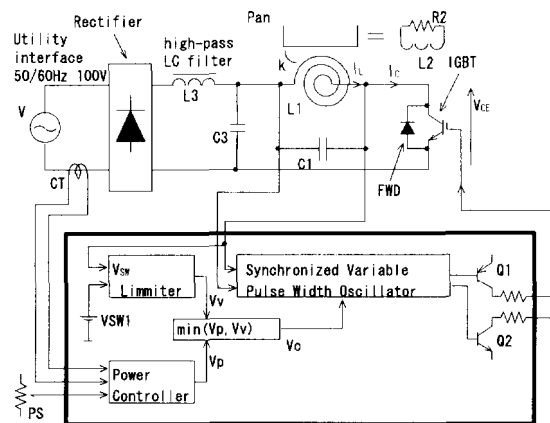


FIG.1. A schematic total power conversion system for induction-heating power supply in home power electronic system

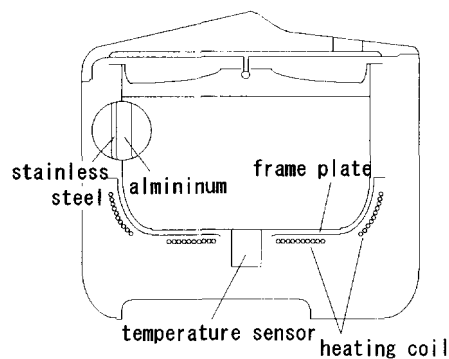


FIG.2. Arrangement of heating-coil for induction-heating rice cooker

<2-2>RICE COOKER IMPLEMENTATION

The induction-heating-coil structure in this system is distributively arranged so as to deliver the high-frequency power into the heating vessel load, which is made of the stainless-steel pan within the aluminum as shown in Figure 2. Note that this structure is different from induction pancake coil structure.

<2-3>INVERTER POWER REGULATION

Figure 3. illustrates the power regulation characteristics of this inverter under the designed circuit parameters; $L1=72H$, $k=0.78$, $L2/R2=9sec$ and $C1=0.27F$ where, T_{on} ; IGBT conduction time, f ; operating frequency as defined in Figure 13. As shown in Figure 3, the output power can be continuously regulated by means of varying a conduction duration time T_{on} . As a result, control frequency varies according to T_{on} and in this case, an operating frequency range is to be relatively-narrow band; $f=20kHz-40kHz$.

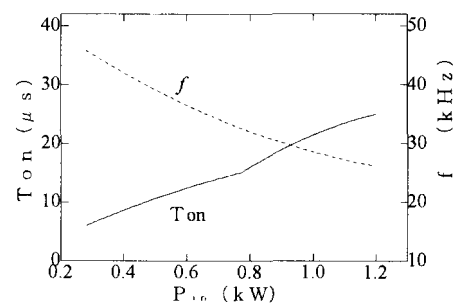


FIG.3. Power regulation characteristics when the operating frequency is controlled

3. EXTENDED INVERTER TOPOLOGIES

The single-ended quasi-resonant inverter circuit topologies using a single power active switch, which operates at ZVS or ZCS can be widely used in order to alleviate the electrical dynamic stresses and switching losses of a power semiconductor switching device and reduce the EMI noise level.

A new family of single-ended ZVS soft-switching inverter circuits employing quasi-resonant switches composed of two or three resonant elements is displayed in Figure 4, which make use of a half-wave resonant mode or a full-wave resonant mode is displayed in Figure 4. The voltage-fed half-wave resonant inverter of these topologies provides a good power regulation in a steady-state because of relatively narrow frequency adjustment. These power inverter topologies can efficiently operate in the frequency range more than 20kHz-40kHz.

These inverter topologies have a significant improvement in performance and high-power density on the basis of introducing a high-frequency low-saturation voltage of IGBT designed for soft-switching.

4. ADVANCED GENERATION IGBT

By using the inverter circuit shown in Figure 1, Figure 5 shows the measured voltage and current waveforms to estimate the conduction loss of IGBT and its turn-off switching losses during its falling time t_f and its tail-current generating time. In addition, its instantaneous conduction loss ($V_{CE}I_C$) during high-conduction time and turn-off switching losses during both falling time and tail current generating time are numerically shown in Figure 5, respectively, along with conduction loss energy and switching loss energy.

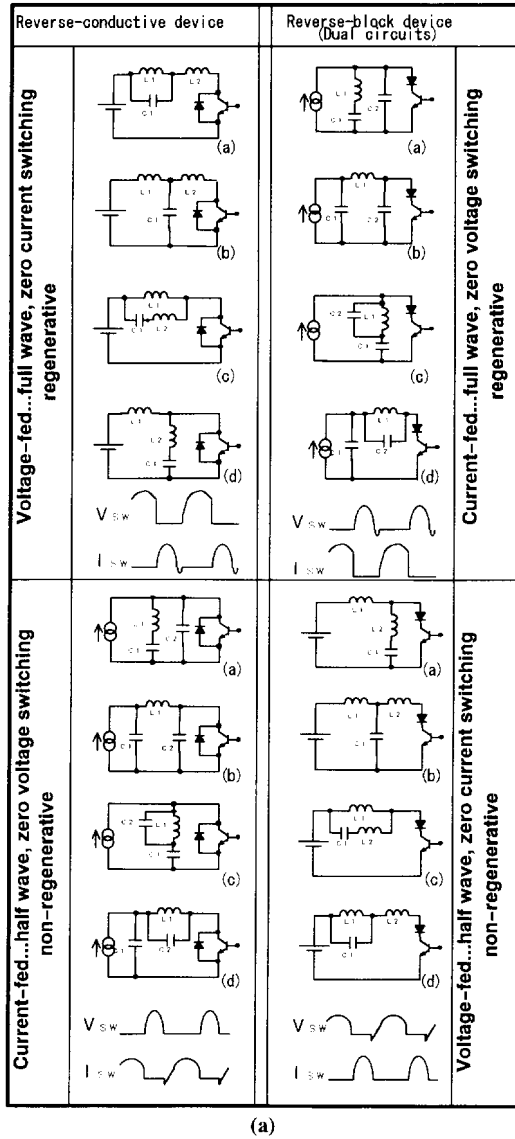
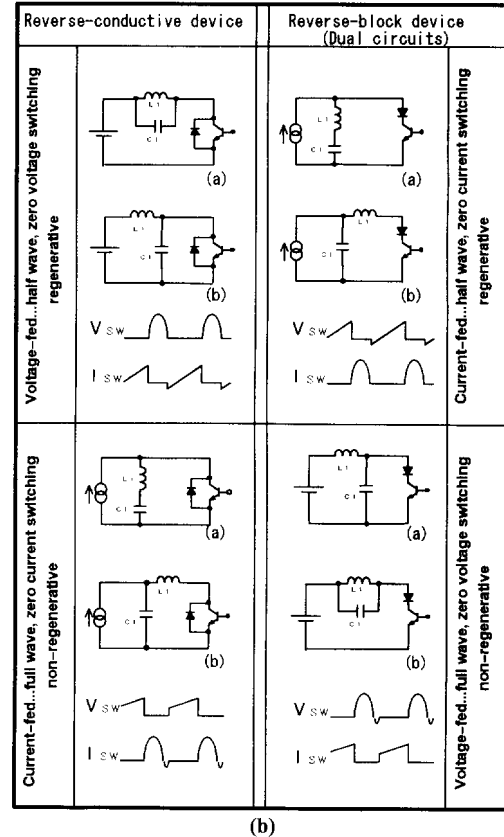


FIG.4. Modified version type single-ended quasi-resonant inverter topologies

Table 1 indicates the maximum power rating of a trially-produced new IGBT with a low voltage drop and a short falling time characteristics. The IGBT appearance developed newly is depicted in Figure 6. In case of the single-ended ZVS inverter incorporating this IGBT, the smaller switching loss due to the tail current occupies as compared with a switching loss during a falling time.

Table 2 indicates the loss analysis of various trially-produced IGBTs which are designed for special-purpose soft-switched mode inverter operating at ZVS and low SOA design, on the basis of elaborate measuring and analysis due to the personal computer system. Figure 7 shows $V_{CE(sat)}$ (saturation-voltage of IGBT) vs. conduction loss characteristics. As can be seen, the conduction loss of a new IGBT family can be sufficiently decreased according to the reduced saturation voltage design.

In addition, its turn-off losses vs. fall time t_f characteristics measured by the quasi-resonant ZVS inverter employing a single trially-developed IGBT are represented in Figure 8. The turn-off switching losses during a falling time and a tail current duration time are analyzed in Figure 8. Of these losses, the switching loss during a falling time is almost kept constant in spite of fast-switching type IGBT design consideration. In experiment, it is taken into account that the switching loss during a falling time



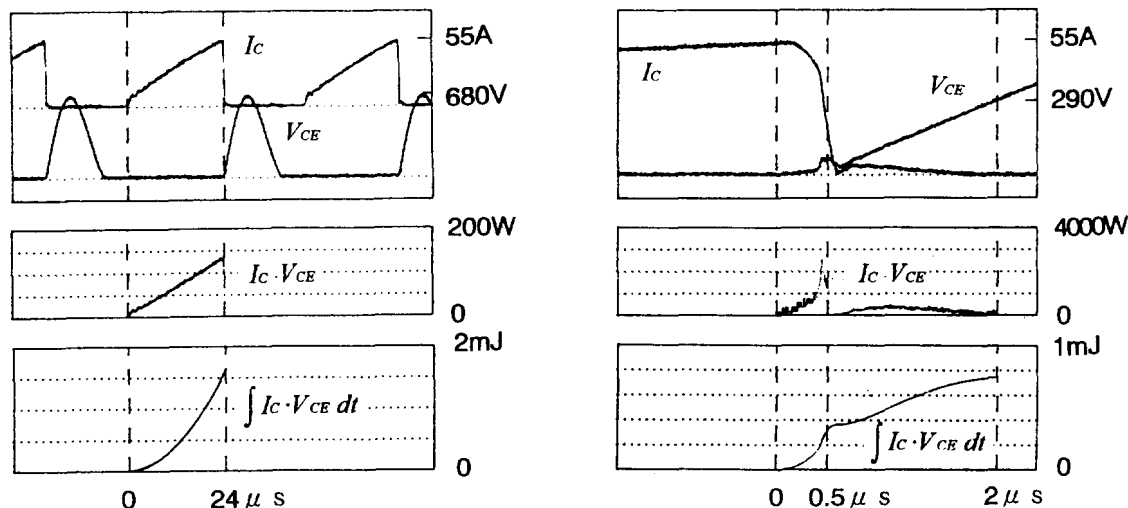


FIG.5. Voltage and current waveform to estimate the conduction loss and switching loss of IGBT used

Table 1 Maximum ratings (Ta=25°C)

CHARACTERISTIC	SYMBOL	RATING	UNIT
Collector-Emitter Voltage	V _{CE}	900	V
Gate-Emitter Voltage	V _{GE}	±25	V
Collector Current (DC)	I _C	65	A
Collector Power Dissipation (Tc=25°C)	P _C	200	W
Junction Temperature	T _j	150	°C
Storage Temperature Range	T _{stg}	-40~150	°C
Screw Torque		0.8	N·m

Table 2 Conduction losses and turn-off losses of various type of IGBTs

NO.	V _{ce(sat)} at I _C =60A (V)	t _f (μs)	total loss (mJ)	turn-off			
				on loss (mJ)	loss fall (mJ)	tail loss	loss
1	3.40	0.18	3.60	3.00	0.60	0.40	0.20
2	3.25	0.21	3.52	2.90	0.62	0.38	0.24
3	2.80	0.24	3.25	2.50	0.75	0.40	0.35
4	2.40	0.30	3.07	2.20	0.87	0.37	0.50
5	2.20	0.35	2.99	2.00	0.99	0.39	0.60
6	2.10	0.47	3.11	1.90	1.21	0.41	0.80

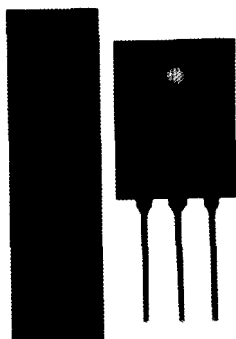


FIG.6. Newly-developed IGBT appearance

occupies a certain constant value, which is proportional to

the energy stored into the parasitic inductances existing in the circuit. In this case, the measured switching loss during the tail current duration time is practically negligibly small for IGBT with fast switching time less than $t_f=0.1s$ as compared with the switching loss during a turn-off falling time.

The IGBT switching loss designed for short falling time is almost equal to the turn-off switching losses in case of IGBT designed for a relatively-large falling time. In practice, the total turn-off loss energy would not effectively be reduced

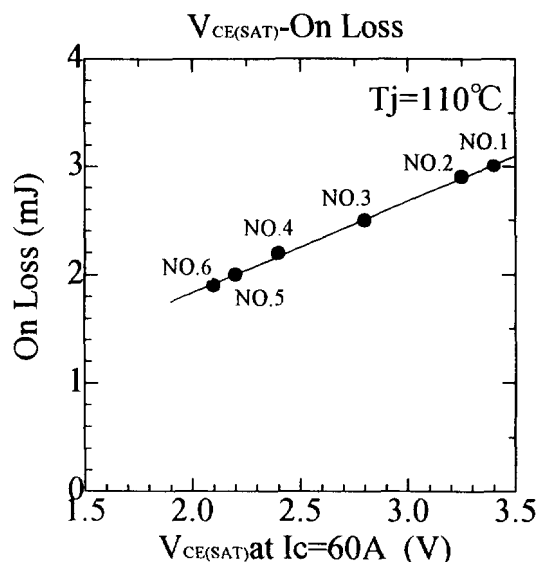


FIG.7. Conduction losses vs $V_{CE(sat)}$ characteristics of various type of IGBTs

even if various new IGBTs with $t_f<0.1s$ were produced trially.

Figure 9 gives t_f vs. $V_{CE(sat)}$ characteristics for various IGBTs in the 1st, 2nd, advanced 2nd generations. Broken lines in Figure 9 denote the regions which achieve an indicated total-loss. As can be seen, the newly- developed next generation IGBT realize much lower loss(3mJ) as compared with conventional 1st,2nd IGBTs. In particular, sample IGBT named NO.5 accomplishes the optimum design.

Total losses vs the temperature characteristics of the advanced-2nd generation IGBT are illustrated in Figure 10. This shows a conduction loss of IGBT and its switching loss when the junction temperatures are changed. According to

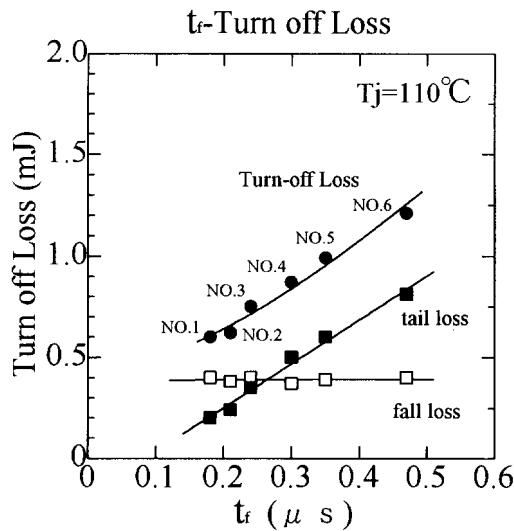


FIG.8. Turn-off losses vs falling switching time characteristics of various type of IGBTs

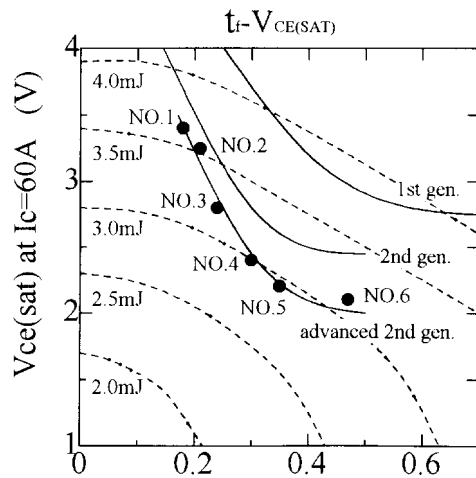


FIG.9. t_f - $V_{CE(sat)}$ characteristics in 1st, 2nd and advanced 2nd generation

the temperature rise, it is noted that the total losses of this IGBT is to increases with a relatively-small temperature gradient less than 0.6% /deg.

Allowable current waveforms of the trially-produced IGBT incorporated into the testing circuit similar to the single-ended ZVS inverter shown in Figure 1 are experimentally shown in Figure 11. The turn-off operation in resonant-load is shown in Figure 11(a), and the shoot through operation under the capacitive-load is shown in Figure 11(b). Taking into account these testing data, this new IGBT produced here can turn-off as large current as 4 times of the rating current and more it can shoot through as large current as 8 times of the rating current at $T_j=150$.

The IC(AN6721) structure without isolation link for

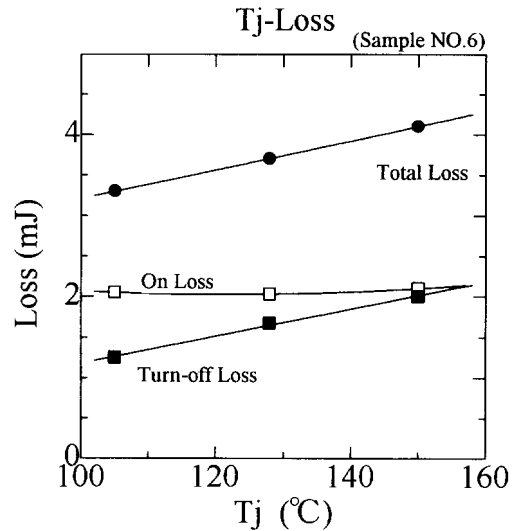
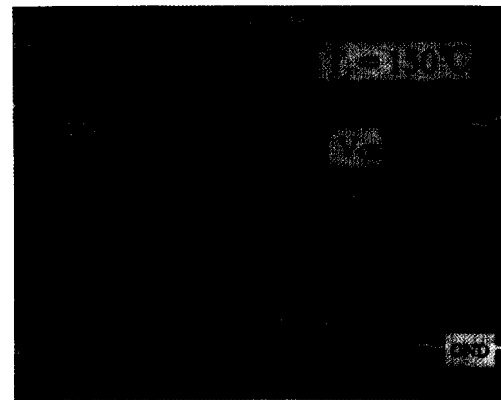
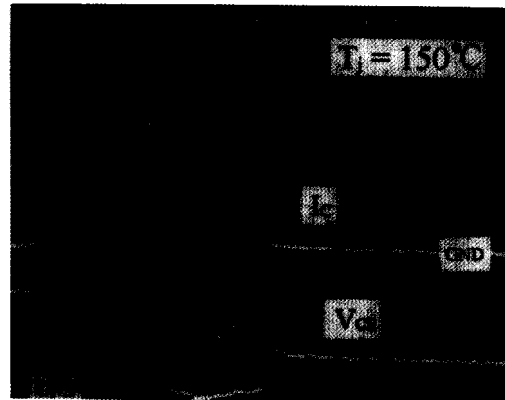


FIG.10. Conduction losses and switching losses when junction temperatures are changed



I_c :50A/div V_{CE} :200V/div t :200ns/div

(a)resonant-load turn-off(250A)



I_c :200A/div V_{CE} :100V/div t :2 μ s/div

(b)capacitive-load short(450A)

FIG.11. High current operation of newly-developed IGBT

IGBT drive is provided in Figure 12, which is acceptably designed for a high-density arrangement.

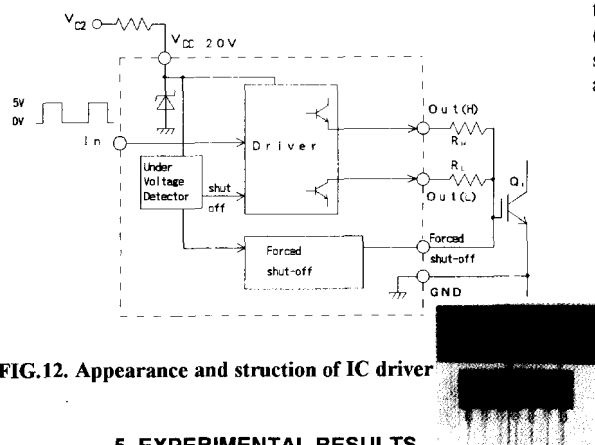


FIG.12. Appearance and struction of IC driver

5. EXPERIMENTAL RESULTS

The steady-state voltage and current waveforms when the quasi-resonant ZVS inverter operates under the condition of the full-power setting are observed as shown in Figure 13.

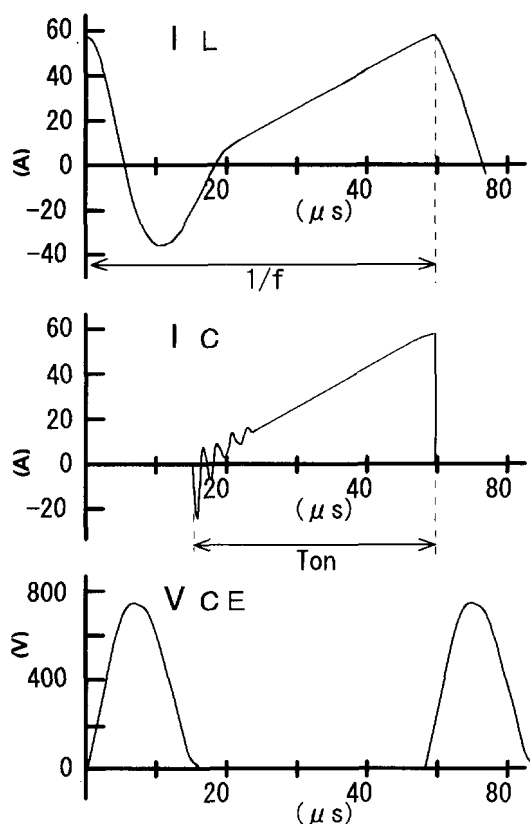
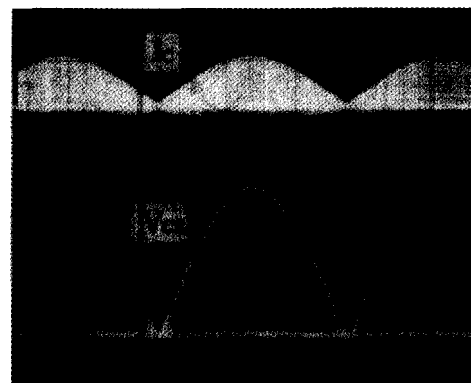


FIG.13. Voltage and current wave form under ZVS condition

Figure 14 indicates the observed voltage and current waveforms in utility interface side of the inverter systems. In this system, the input power factor becomes almost unity (0.99). The line current is effectively shaped to be a sinewave with a high-power factor without a complicated active switched-mode rectifier.



Ic:50A/div Vce:200V/div t:2ms/div

FIG.14. Sinewave line current shaping and unity power-factor correction

6. CONCLUSIONS

The single-ended high-frequency inverter utilizing zero-voltage soft-switching and a working coil-coupled resonance has been presented introducing a single advanced-2nd generation IGBT and its driver IC, and evaluated for induction-heating rice cooker/warmer as well as induction-heating cooking vessel/utensil.

This quasi-resonant inverter systems efficiently operates at a relatively-narrow frequency range and under the principle of ZVS due to resonant switch concept in order to alleviate switching stresses switching losses and EMI noise. In particular, the switching characteristics of specially-designed IGBT for soft-switched power conversion has been illustrated as compared with the conventional other IGBTs from an experimental point of view.

In addition, it has been substantially proved that the newly-developed voltage-sourced type IGBT inverter system which has just put into a commercialized practice as induction-heating appliance includes a significant improvement in performance and power density.

Furthermore, a generic family of single-ended quasi-resonant inverter topologies employing resonant switch concept which operate at ZVS or ZCS mode under PFM scheme has been systematically demonstrated and classified on the basis of a dual circuit topological theory and resonant switch structures. Some of them are able to be effectively applied for induction-heating cooking power supply used in home power electronic appliances introducing more improved MOS-gate new power semiconductor switching devices/modules in next generation.

In the future, the novel soft-switching single-ended load resonant inverter topologies which operate under the PFM mode should be applied the other consumer power electronic appliance such as microwave oven, and DC-DC power conversion supplies and so on, including the improved technology of single-ended resonant inverter operating at constant frequency PWM strategy.

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