New Circuit Topology of Single-Ended Soft-Switching PWM High Frequency Inverter and Its Performance Evaluations

Y. Deguchi, S. Moisseev, M. Nakaoka
The Graduate School of Electrical and Electronics Engineering,
Yamaguchi University, Yamaguchi, Japan

I. Hirota, H. Yamashita, H. Omori, H. Terai
Home Appliance and Housing Electronics Research
Laboratory,Matsushita Electric Industrial Co. Ltd. Osaka, Japan

***Abstract*:** This paper presents a simple and cost effective circuit topology of single-ended type high frequency quasi-resonant PWM inverter using IGBTs, which can operate under wide soft switching operation range based on ZCS for main power switch as compared with a conventional active voltage-clamped ZVS-PWM high frequency quasi-resonant inverter developed previously. In principle, this new circuit topology can efficiently operate under a constant frequency PWM control-based power regulation scheme. In particular, it is noted that the zero current soft switching (ZCS) commutation can achieve for the main active power switch. On the other hand, the zero voltage soft switching (ZVS) commutation can also achieve for the auxiliary active power switch. The operating principle of this high-frequency Inverter treated here and its power regulation characteristics are illustrated on the basis of the simulation and feasible experimental results.

***Keywords*:** New Quasi-Resonant PWM Inverter, High Frequency Inverter, Soft-Switching, ZCS Arm and ZVS Arm, Induction Heated Cooker, Consumer Power Electronics

I . INTRODUCTION

The state of the art soft switching high frequency power electronics technology has attracted special interest in the household consumer power applications as well as the business consumer power applications from a viewpoint of energy saving. A variety of efficient power conversion processing circuit has been introduced by the authors for the consumer power electronic applications. In particular, the simplest low cost single-ended voltage resonant ZVS-PFM high frequency inverter using a single active power switch which is used for the induction heating (IH) food cooking and processing appliances is developed because of the simplification of the power circuit topology and control circuit, system compactness, low cost and high efficiency as well as a low noise due to soft-switching. At present, this inverter is conveniently used for the consumer power electronic appliances such as high voltage DC-DC converter for microwave oven and induction heated food cooker and rice cooker. However, there is a significant problem to be solved for this type of inverter which includes generation of the beat interference-based acoustic noise due to the frequency difference of multiplex inverter operation, when the inverter power has to be regulated in the IH multi-burner equipment by its PFM control strategy. The advanced research and development of high frequency inverter on the basis of the ZVS-PFM inverter should be pushed from a practical point of view. The voltage-clamped ZVS-PWM high frequency inverter with the additional voltage-clamped active capacitor switch in series with the capacitor as well as half bridge voltage-clamped SEPP ZVS-PWM high frequency inverter is developed. Further, technological development of the inverter developed previously should be made from viewpoints of low cost, high-efficiency, compactness and constant frequency PWM for the power regulation of this inverter.

This paper presents a new circuit topology which can achieve the wide soft switching range in spite of simpler circuit topology and lower cost as compared with an active voltage-clamped soft switching PWM inverter developed previously. The high frequency inverter topology of a previously developed voltage-clamped ZVS-PWM high frequency inverter operating at a constant frequency variable power scheme under a principle of ZVS is compared with the new soft switching PWM resonant inverter operating under two ZVS and ZCS arms commutation modes. The operation principle on the basis of the simulation and experimental results, together with the comparative operating performances

II . NEW SOFT SWICHING PWM HIGH FREQUENCY INVERTER

<A> *System topology and circuit description*

The simple and low cost soft-switching PWM inverter circuit topology proposed newly is shown in Fig.1 as the total system, which is based on a constant frequency variable power regulation function scheme. This inverter circuit operates the soft switching, which has advantages of low cost, miniaturization in physical size, constant frequency power regulation and wide soft switching range. This high frequency inverter system for induction heated cooker and steamer is composed of a single phase diode bridge rectifier with non-smoothing filter inductor Lf, to block higher harmonic current components, and capacitors Cf1, Cf2 to bypass higher harmonics current components in the inverter input side, high frequency inverter with reverse-conducting type power semiconductor switching devices (IGBTs) as the switching blocks Q1, Q2, induction heating load including non-magnetic conductive stainless steel plate coupled with a planer type working coil. This inverter is designed so as to deliver from the full-wave rectification of the utility single-phase 60Hz 100V power supply. The load circuit of this inverter consists of the working coil composed of Litz wire and heated metal plate (pan or vessel) represented by the transformer equivalent circuit model of the induction heating load (Load time constant τ =L2/R2 [R2: Equivalent effective resistance due to a skin effect of the heated body itself], Electromagnetic coupling coefficient $k = M/\sqrt{L1 \cdot L2}$ and self-inductance L1 of the working coil) with loosely coupled mutual inductance M. This is more remarkable for the home and business consumer applications such as induction heating cooker, induction heating rice cooker, induction heating waste disposer, induction heating

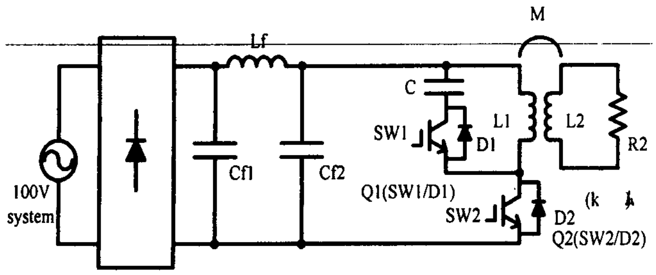


Fig. 1 A proposed PWM high frequency inverter

superheated steamer and induction heating dryer and the forth, which are profitably used for the consumer high power applications.

The equivalent inductance derived from the working coil side of this IH load is required for achieving ZCS of the low side switch which is the inductor for the resonance. Then, a circuit topology has a configuration of the high side switch in series with the series resonant capacitor for the quasi-resonance requirement.

<B> *Steady state operation principle*

In this inverter circuit, the mode transition and equivalent circuit (see Fig.2) and timing pulse sequences under the gate pulse signal (see Fig.3) of the high frequency quasi-resonant inverter are shown assuming that the input DC power source voltage V_d specified as the peak value of AC power source.

(i) MODE1

SW1 is ON state, and the discharging state of the resonant capacitor C is defined as MODE1. Then, reverse conducting diode D2of Q2 turns on naturally, when the voltage across the capacitor C exceeds the DC source voltage V_d and this mode moves to MODE2.

(ii) MODE2

This mode becomes the power regeneration. The gate signal of the switching SW2 is provided during this period. When the load current commutates, SW2 turns on naturally and this mode moves to MODE3 (SW2 ZVS & ZCS).

(iii) MODE3

In this period, the energy is injected into the IH load from the DC power source V_d. This mode is an operating period due to Duty Factor as a power control variable defined in Fig.3. SW2 is turned off in the accordance with Duty Factor.

(iv) MODE4

By the discharge of the resonant capacitor C with the voltage as DC power source voltage V_d charged during MODE1 period, SW2 turns off with ZVS. On the other hand, SW1 operates with the ZCS turn-off commutation, when the load current commutates. This mode moves to the next mode.

(v) MODE5

During this mode, this mode becomes a state that all the currents do not flow, because the gate signals of both the active power switches have been made to be off. SW1 is turned on during the operation period.

The resonant capacitor C charged negatively begins to discharge, when SW1 is turned on. It becomes MODE1 periodically. The current flowing into the active power switch SW1 tends to the increase by the initial current stored by the equivalent load inductor. The active power switch SW1 turns on with the ZCS. The circuit operation mentioned above is repeated cyclically in a periodic steady state. Timing sequences of the gate pulse signals delivered to the power semiconductor switching devices (IGBTs SW1, SW2) of the high frequency inverter circuit is shown in the Fig.3. The switch SW1 is turned on during the period determined by switching frequency, and the switch SW1 is turned off during the period from MODE2 to MODE4. SW2 is turned on during the diode D2 conduction period, and adjusts the power by determining the timing of the turn-off. Duty Factor as a control variable is defined as a time ratio from the turn-on of SW1

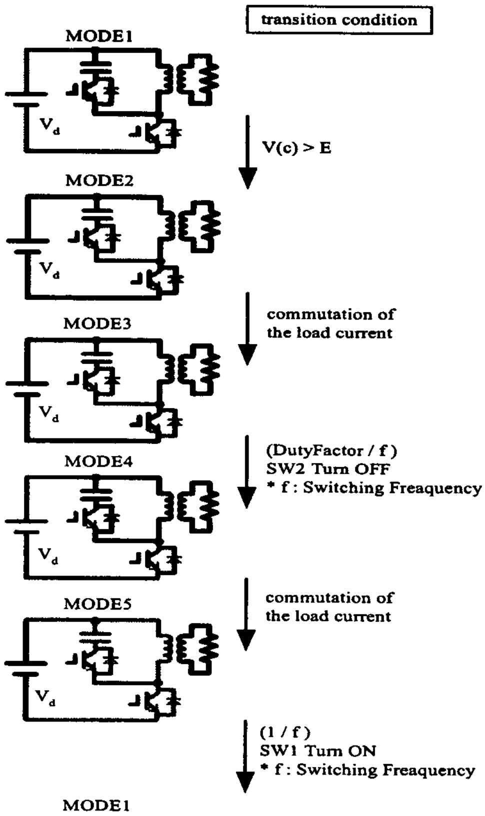


Fig. 2 Mode transition and equivalent circuit

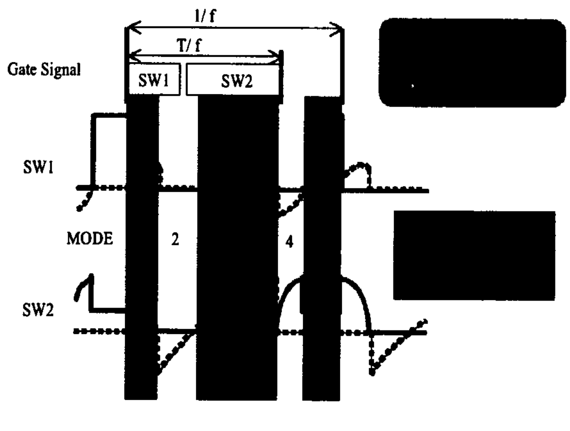


Fig. 3 Basic action waveform in the switch division

to the turn-off of SW2 for this operation period. The Duty Factor becomes 0.3 as the smallest value on SW1, so that Duty Factor may be made to change by adjusting pulse width of the gate signal of the switch SW2 under the constant pulse width.

The power regulation of this inverter is able to continuously regulate the input power of the high frequency inverter treated here in accordance with Duty Factor under a fixed operating frequency.

<C> *Experimental results and discussions*

On the high frequency inverter circuit proposed here, the experiment as set up is built and tested under the design specifications of this high frequency inverter and its circuit parameters indicated in Table 1. In the feasible experiment set up the non-smoothing filter in DC side of this high frequency inverter is used in order to cut the high-frequency current components of the high-frequency inverter and to improve the current distortion due to harmonic current components in the utility power AC side and utility power factor correction characteristics. Accordingly, the output voltage of non- smoothing filter becomes a full-wave rectified sinewave different from that in case of using the smoothing filter.

Table 1 Design specifications and circuit parameters

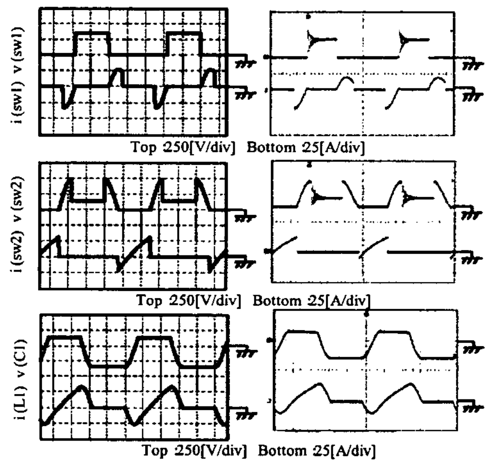
	symbol	parameter
Source voltage (rms)	E	100.0 [V]
Switching frequency	F	20.0 [kHz]
Resonance capacitor	C1	0.3 [μ F]
Working coil	L1	65.4 [μ H]
Load time constantng	τ	12.54 [μ sec]
Electromagnetic coupling coefficient	k	0.64

The power semiconductor switching devices used in the experimental circuit set up are the IGBTs (FUJI ELECTRIC 2MBI50N-120H 1200V-50A), and the iron vessel (k=0.64, τ =12.54[μ sec]) is used for the induction heated load in the consumer power applications. When the inverter design is carried out in order to provide the rating power 1200 [W]. Observed waveforms and simulating waveforms are respectively shown in Fig.4. In the power rating, there is no blocking period in MODE 5 as shown in Fig.2. Therefore, the proposed inverter circuit is similar to the operating waveforms for the ZVS high frequency inverter circuit (circuit topology without SW1 of the proposed circuit in Fig.5). Measured waveforms are shown in Fig.6. Besides, the Duty Factor vs. input power characteristics for this high frequency inverter is illustrated in Fig.7.

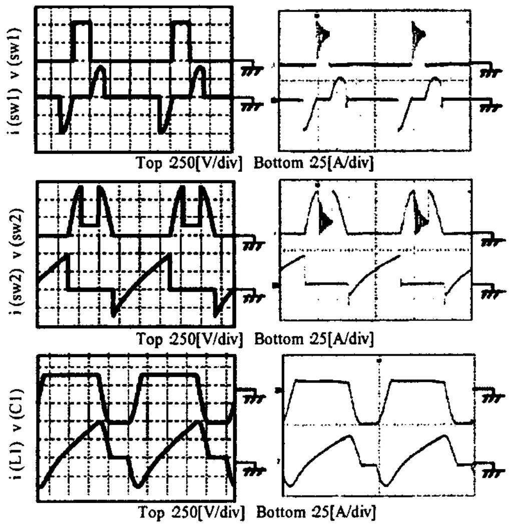
III. POWER REGULATION CHARACTERISTICS AND DISCUSSIONS

The voltage regulation vs. Duty Factor characteristics under the soft switching region, the peak voltages and currents of the power semiconductor switching device which is assumed as the input side of the proposed high frequency inverter circuit in DC power source are respectively depicted in Fig. 9(a). The power continuously is changed under the soft switching operation by the varying Duty Factor. The circuit design specifications of this inverter are below: L1=65.4[μ H], C1=0.3[μ F], switching frequency: 20[kHz], DC power source voltage: 141.2[V], induction heated load parameter: electromagnetic coupling coefficient k=0.8, load time constant τ =9.0[μ sec]. As well as the experimental circuit parameters, then, the load parameters have been made to be a general value in making to be the enameled pot.

The circuit component for the voltage-clamped ZVS-PWM high frequency inverter circuit shown in comparison with the proposed high frequency inverter circuit in Fig.8 and the power regulation characteristic for Duty Factor shown in Fig.9 (b). The circuit design specifications of this inverter are as follows; circuit constant: L1=65.4[μ H], C1=3.0[μ F], C2=0.3[μ F], switching frequency: 20[kHz], DC power source voltage: 141.2[V], the induction heated load parameters; electromagnetic coupling coefficient k=0.8, load time



(a) In case of Duty Factor=0.5 (Input voltage: 251.2[W])



(b) In case of Duty Factor=0.7 (Input voltage: 628.4 [W])

Fig.4 Operation waveform under the conditions constant τ =9.0[μ

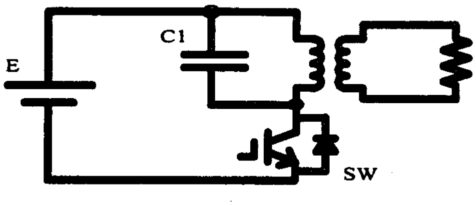


Fig.5 The single-ended ZVS circuit

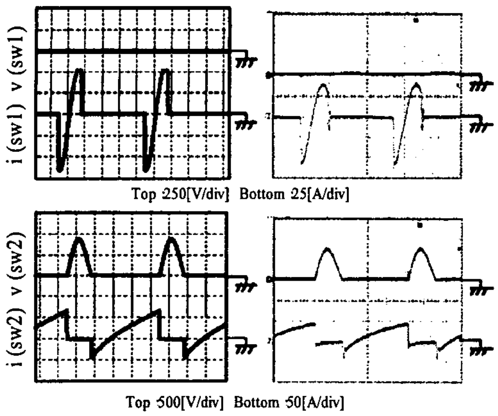


Fig.6 Voltage and current waveforms for switching

(Input voltage: 1200 [W])

sec].

The voltage-clamped high frequency inverter circuit developed previously is composed of the additionally connected capacitor C2 to the high frequency inverter circuit proposed newly. In the proposed inverter circuit, there is no voltage-clamped function, since the resonant components of L and C has respectively which are incorporated into the proposed inverter, and the voltage across the switching power device of the proposed inverter becomes high as well as the conventional single-ended ZVS inverter circuit. However, the inverter configurations are simple and can achieve PWM operation under the constant frequency. In Fig. 9, the lowest power for the rated power 5[kW] under this soft switching region is 548[W] for the proposed inverter, and the lowest power also is 965[W] for the voltage-clamped inverter circuit, because it is proven to be wide on the soft switching region of the proposed high frequency inverter.

Ⅳ. CONCLUSIONS

In this paper, the circuit topology of the new soft switching high frequency quasi-resonant inverter with a constant frequency variable power regulation function was proposed for consumer power applications such as IH cooker. It was clarified that the operation principle of this resonant high frequency inverter and its soft switching PWM-based power regulation characteristics in the steady operation were evaluated on the basis of the simulation and the experimental results. Though the circuit topology that was added to the inductor for the resonance current storage as a technique for the purpose of extending the soft switching region for the high frequency inverter of the conventional voltage-clamped PWM inverter circuit

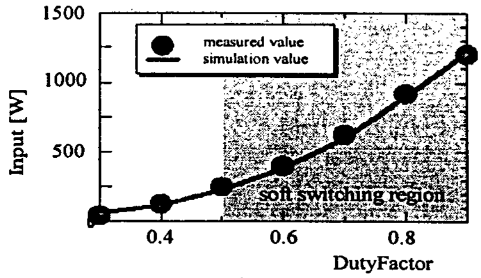


Fig.7 Duty Factor vs. Input power regulation characteristics

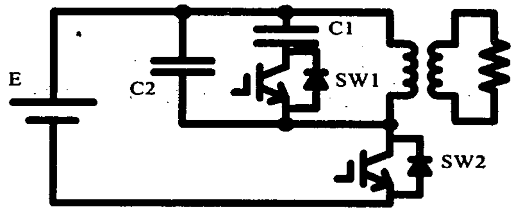
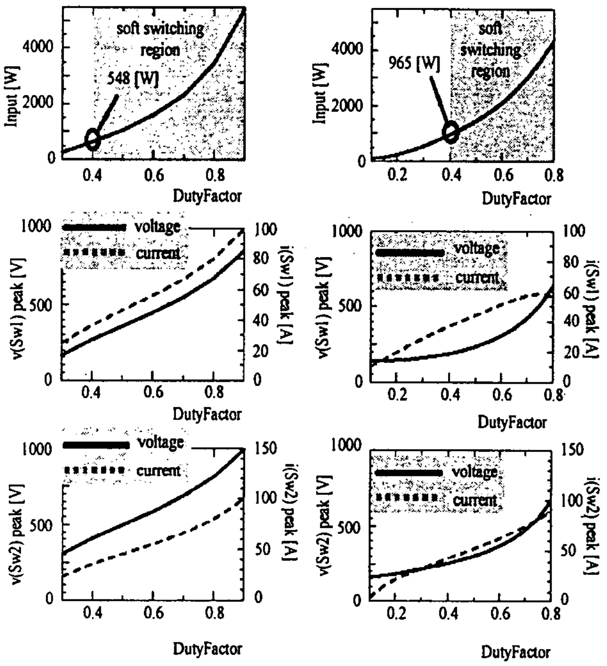


Fig.8 Active voltage-clamped ZVS-PWM inverter circuit



(a) Proposed inverter (b) Voltage-clamped inverter

Fig.9 Comparative inverter characteristics between proposed and previously developed inverters

system was discussed and evaluated from an experimental point of view. Finally, it was confirmed that the proposed simple inverter circuit treated here has less circuit components as compared with the voltage-clamped inverter circuit in addition to wide soft switching region.

REFERENCE

S.Hishikawa, M.Nakaoka, I.Hirota, H.Omori, H.Terai "High frequency eddy current-based fluid heater using soft-switching inverter" IEICE-Japan Technical Research Report on Energy Electronics, Vol.100 No.628, EE2000-64, pp.19-24 (2001-2)