Pulse Width and Pulse Frequency Modulation Pattern Controlled ZVS Inverter Type AC-DC Power Converter with Lowered Utility AC Grid Side Harmonic Current Components for Magnetron Drive

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Abstract- The grid voltage of commercial utility power source in Japan and USA is 100rms, but in China and European countries, it is 200rms. In recent years, in Japan 200Vrms out putted single phase three wire system begins to be used for high power applications. In 100Vrms utility AC power applications and systems, an active voltage clamped quasi-resonant inverter circuit topology using IGBTs has been effectively used so far for the consumer microwave oven. In this paper, presented is a half bridge type voltage-clamped high-frequency inverter type AC-DC converter using which is designed for consumer mag netron drive used as the consumer microwave oven in 200V utility AC power system. This zero voltage soft switching inverter can use the same power rated switching semiconductor devices and three-winding high frequency transformer as those of the active voltage clamped quasi-resonant inverter using the IGBTs that has already been used for 100V utility AC power source. The operating performances of the voltage source single ended push pull type inverter are evaluated and discussed for consumer microwave oven. The harmonic line current components in the utility AC power side of the Ac-DC power converter operating at ZVS-PWM strategy reduced and improved on the basis of sine wave like pulse frequency modulation and sine wave like pulse width modulation for the utility AC voltage source.

Index Terms; **Zero Voltage Soft Switching Inverter, High Voltage Transformer, Voltage Doubler, Non smoothing LC Filter, New Pulse Pattern Modulation**

1. INTRODUCTION

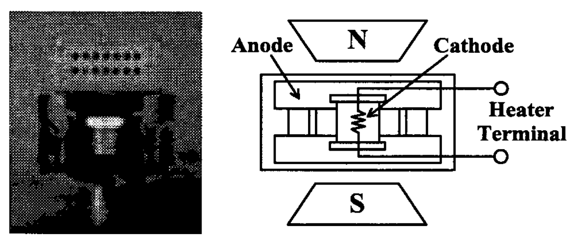
Overseas prospect of the microwave oven that is mounted on the inverter is desired. 200VAC system is used in the commercial power supply of Europe and China. Therefore, the specification of power semiconductor switching devices and three winding transformer becomes to differ in an active clamped quasi-resonant inverter which has already been used in 100VAC power source of Japan and North America. The standardization of the main component that constitutes the inverter is desired in order to carry out the rationalization in the manufacturing.

In this paper, a half bridge type quasi-resonant ZVS-PWM high frequency inverter circuit topology for the magnetron drive which carries out the zero voltage soft switching on the basis of the quasi resonance is presented. The operating analysis and characteristic evaluations of switching power converter circuit for microwave oven in 200VAC power supply such as Europe and China are discussed on the basis of simulation and experimental results.

Proposed is a new modulation pattern selection method of the partially-modulated operating frequency and its duty factor in order to improve harmonic current components under a condition of the peak limitation of the magnetron anode current.

2. v-i CHARACTERISTICS AND ELECTRICAL EQUIVALENT CIRCUIT MODEL OF MAGNETRON

Fig.1 shows the structure of the magnetron. The internal construction (see Fig.1(b) and Fig.2) obtains cylindric cathode and an anode on the concentric circle, and permanent magnet axially gives the magnetic field as depicted Fig.2. Fig.3 represents the voltage vs. current characteristics model of the magnetron. Concerning to the magnetron v-i characteristics, magnetron has non-linear v-i characteristics, what is called, piecewise linear characteristics which includes high resistance area in non-oscillating range for magnetron and low resistance area in oscillating range for magnetron. When the voltage between anode and cathode exceeds about 3.6[kV] (cut-off voltage), the magnetron anode current begins to flow from anode to cathode. On the other hand, when the voltage between anode and cathode is lower than a cut-off voltage,



(a) Structure (b) Internal Construction

Fig.1. Magnetron

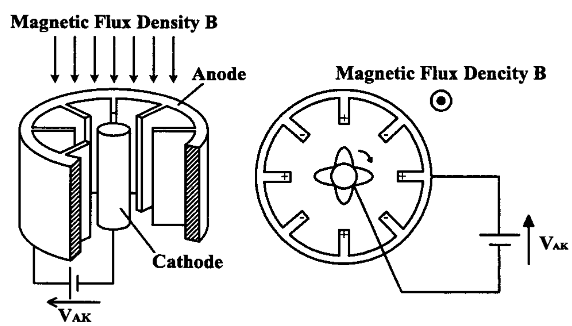


Fig.2 Operation Principle

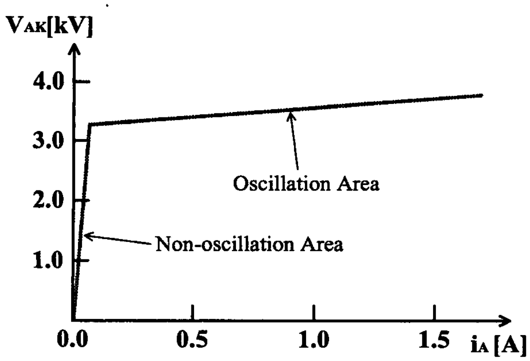


Fig.3 Voltage vs. Current Characteristics Model of Magnetron

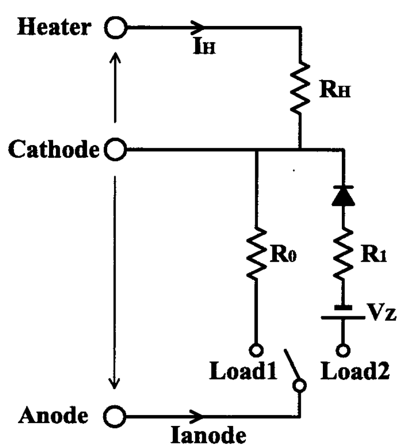


Fig.4 Electrical Equivalent Circuit Modeling of Magnetron

the anode current does not mostly flow. The electrical equivalent circuit model of the magnetron which has these characteristics can simply represent by using pure resistance, id eal diode, ideal battery (cut-off voltage Vz) as shown in Fig.4. As illustrated in Fig.4, load type (Load1 or Load2) is selected whether the voltage between anode and cathode is higher than 3.6[kV] or not.

3. CONVERTER SYSTEM TOPOLOGY

3.1. Main Circuit Description

Fig.5 shows a schematic total configuration system as the high-frequency transformer linked AC-DC converter incorporating a half bridge type quasi-resonant ZVS-PWM inverter (Voltage source push pull type inverter) using IGBTs. This power converter is designed for the magnetron drive in consumer power applications. This power supply system for microwave oven is mainly composed of a single-phase full-bridge diode rectifier D1 with a non-smoothing filter (Ld, Cd), a half bridge single ended push pull type quasi-resonant ZVS-PWM high frequency inverter with a lossless capacitor C1, a three-winding high-frequency transformer with loose couplings, a full wave voltage doubler type rectifier (D2, D3, C2, C3), and magnetron which generates a microwave power. In the inverter circuit of this AC-DC power converter, two reverse conducting type active power switches; IGBTs, main switching block Qm (SWm in parallel with Dm) and subsidiary switching block Qs (SWs and Ds), capacitor C1 for voltage quasi-resonance, capacitor Cs, are incorporated respectively. This circuit purposes in 200V utility AC system are to use the three winding high frequency transformer and active power switching devices which has used in an active voltage clamped quasi-resonant high frequency inverter in 100V utility AC system. Therefore, it is required that the operating frequency and the input power in the 200V utility AC system is similar to those in the 100V utility AC system. Then, the capacitor Cs is connected in series with the transformer primary winding, since the current i1 which flows into the inductor L1 in the 200V utility AC system would become to equalize a current value in the 100V utility AC system.

3.2. Gate Pulse Control Implementation

Fig.6 gives the timing asymmetrical PWM sequences. These gate pulse voltages are respectively supplied to the power semiconductor switching blocks; main switching block Qm(SWm/Dm) and subsidiary switching block Qs(SWs/Ds). In this Fig.6, duty factor (duty cycle) control scheme is implemented for the continuous power regulation

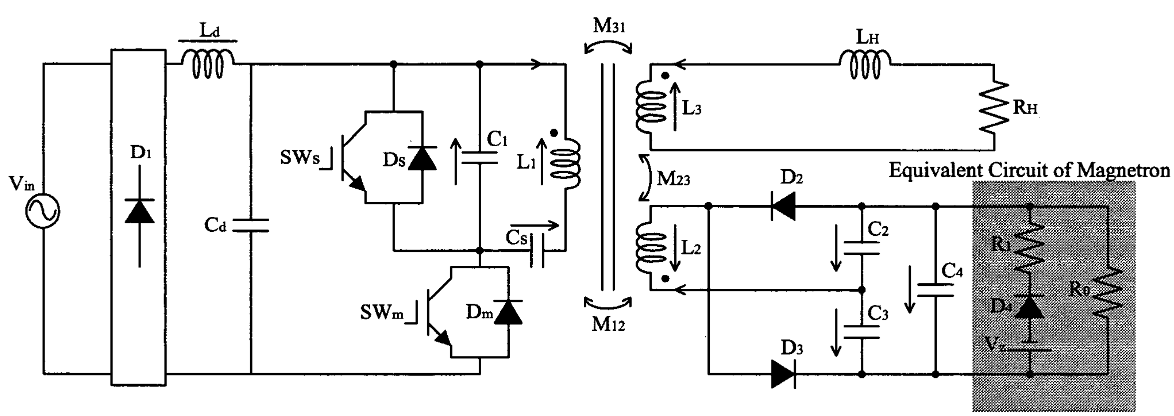


Fig.5 A Single-Ended Push-Pull (SEPP) ZVS-PWM High frequency Inverter-Fed AC-DC Converter

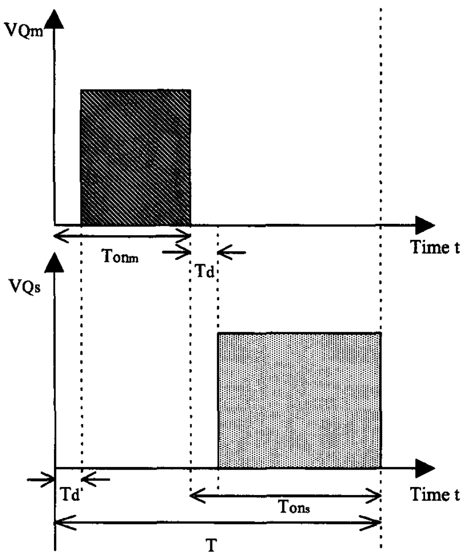


Fig.6 Gate Voltage Pulse Signal Time Sequence of Active Power Switches SWm and SWs

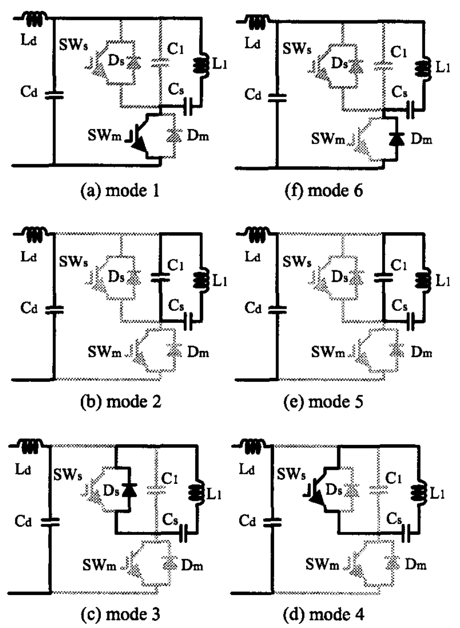


Fig.7 Operating Modes and Equivalent Circuit

of this a half bridge type single ended push pull quasi-resonant ZVS-PWM high frequency inverter using IGBTs. Duty factor (Duty cycle) is defined as the conduction time Tonm including a dead time Td of the main active power switch SWm during one period T. The variable range of this duty factor is theoretically from 0 to 1. The output power of this inverter is controlled continuously by varying this duty factor (the ON time of the gate voltage pulse signal for driving main active power switch SWm as a control variable).

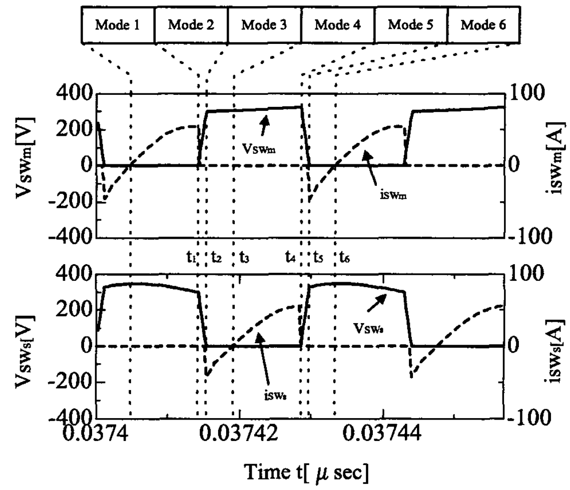


Fig.8 Operating Waveforms of Active Power Switch SWm and SWs under Soft Switching

3.3. Circuit Operation

The equivalent circuits of the inverter section in each mode are depicted in Fig.7. The steady-state operating principle of a half bridge type quasi-resonant ZVS-PWM high frequency inverter is described for the operation modes corresponding to mode 1 to mode 6 during one-cycle on the basis of its relevant operating voltage and current waveforms illustrated in Fig.8.

4. POWER REGULATION CHARACTERISTICS

Frequency characteristics of this power converter (see Fig.5) are shown in Fig.9. When the inverter operating frequency increases in the condition of a constant duty factor, the input power decreases. Because one period time T shortens in accordance with the increase of the inverter operating frequency. The ON time of the main active power switch SWm shortens and the input energy can not be supplied to the inductor L1.

The asymmetrical PWM-based power characteristics of this power converter in the condition of a constant operating frequency are shown in Fig.10. As shown in this figure, a soft switching operating area of this power converter circuit becomes from 0.26 to 0.50 on the duty factor as a control variable.

5. PARTIALLY-DISTRIBUTED MODULATION AND PERFORMANCE EVALUATIONS

5.1 Modulation Control Strategy for utility AC voltage

When the magnetron oscillates, the equivalent resistance R1 decreases. But before the magnetron oscillates, the load of this power converter is a condition only of the high resistance Ro. Therefore, much input energy is not consumed, and it is regenerated in the capacitor Cd of a non-smoothing LC filter circuit. The Capacitor Cd is charged by this regeneration, and the voltage across the

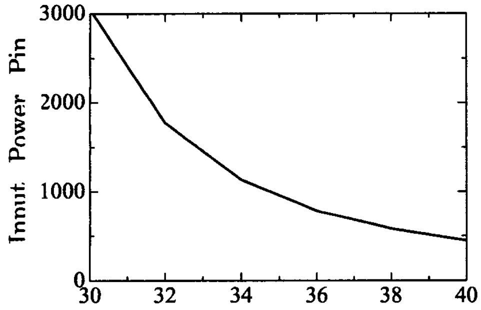


Fig.9 Frequency

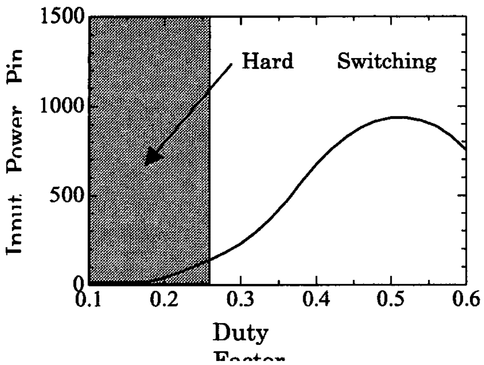


Fig.10 PWM Power Characteristics

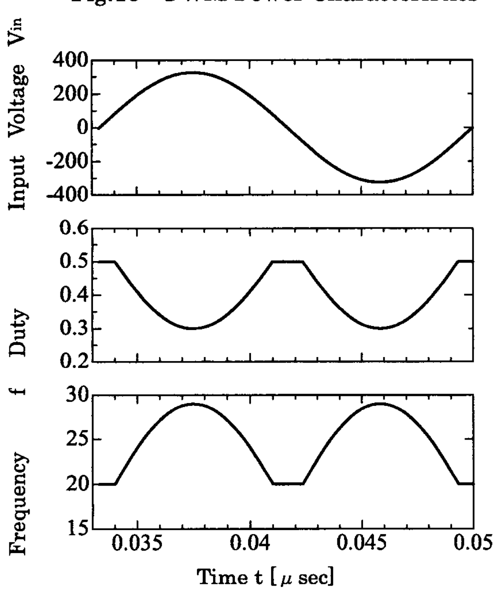
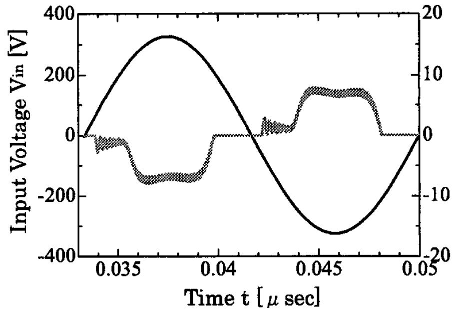
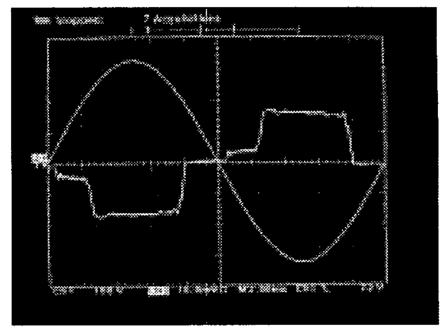


Fig.11 Partial Modulated PFM and PWM Control Scheme

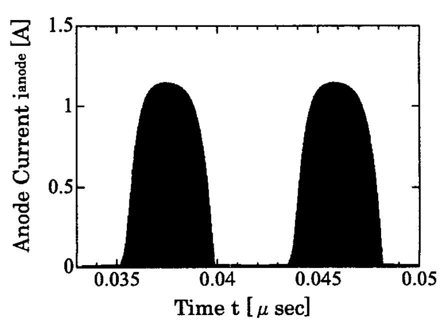


(a) Simulation



100[V/div] 5[A/div] 2[msec/div]

(b) Experimental



(c) Anode Current

Fig.12 Voltage and Current Waveforms in Utility AC Side

and Anode Current Waveform in Partial

capacitor Cd rises toward the commercial power supply voltage. Then a single-phase full-bridge diode rectifier D1 is biased reversely, it is shut off. The commercial power supply line current is cut off. By this operation, the input current waveform is almost similar to the magnetron anode current waveform. In other wards, when the voltage between anode and cathode exceeds a magnetron cut-off voltage 3.6[kV], the input current begins to flow. The idle period which the input line current is not flowing exists, and its harmonic current components become a significant problem. In order to reduce harmonic current components, it is necessary to shorten this idle period as much as possible.

Fig.11 demonstrates a modulation pattern selection method of the partially-modulated inverter operating frequency and its duty factor-based asymmetrical pulse width modulation in order to improve line current harmonic distortion and power factor in the utility AC power side. In the low voltage potion of the utility AC power side, the ON

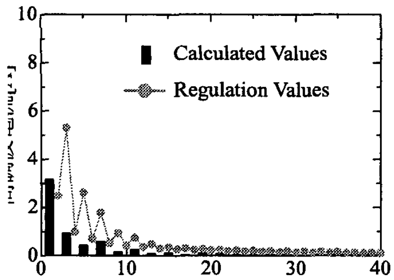


Fig.13 FFT Spectrum of Input Current in Utility AC Side

time of the gate voltage pulse signal for driving the main active power switch SWm is lengthened in order to supply energy to the inductor L1 as much as possible. As a result, it is possible to shorten the idle period.

In the peak voltage potion of the utility AC power side, it is necessary to shorten the ON time of the main active power switch SWm in order to avoid the excessive energy supply to the magnetron. In the condition of a constant frequency, the ON time of the subsidiary active power switch SWs is lengthened and the shortage of the resonance energy for achieving ZVS commutation is generated. Then, in the resonance period for ZVS, the voltage Vc1 across the capacitor C1 can not exceed the voltage Vcd across the capacitor Cd. As a result, the voltage across the main active power switch SWm can not reach the zero. (This inverter operates at a hard switching commutation.)

Therefore, in order to ensure the energy for achieving ZVS, it is necessary to shorten the ON time of the subsidiary active power switch SWs. After all, it is required that the inverter frequency is increased in order to shorten both the ON time of the main active power switch SWm and the subsidiary active power switch SWs. But, the inverter frequency must be set to higher value than 20kHz in order to avoid audible acoustic noises.

5.2 The current harmonic components level in utility AC power side

Fig.12 shows the simulation and observed waveforms of the AC-DC converter system for the consumer microwave oven that operates in partial pulse modulation control scheme for the utility AC voltage with 60Hz. It is evaluated under the condition of the utility AC side input power 1.2[kW] for the consumer microwave oven. Fig.13 indicates the FFT spectrum of the input line current of the AC-DC power converter system.

As shown in this figure, it is proven that current harmonic components of the input current in utility-grid AC power source side are effectively suppressed within the specified guide line values of harmonic current components.

6. CONCLUSION

In this paper, a zero voltage soft switching inverter circuit configuration of a half bridge type quasi-resonant ZVS-PWM high frequency inverter type AC-DC converter with three winding coupled transformer link has been presented for the magnetron drive in consumer power electronics. And the steady-state operation of this AC-DC power converter was analyzed on the basis of simulation and verified in experiment. By using the single-ended push-pull (SEPP) soft switching inverter treated here in the commercial power supply for 200V utility AC system, it was possible to standardize a three winding high frequency transformer and power semiconductor switching devices of an active voltage clamped quasi-resonant inverter which has used in commercial power supply for 100V utility AC power system.

Furthermore, it was confirmed that by the pulse modulation of inverter operating frequency and duty factor in the form of the sinusoid for the utility 60Hz AC voltage, harmonic current components in the input busline could be sufficiently suppressed and the anode current of magnetron could be almost kept within an allowable current value 1.2[A]. It was proved that the proposed AC-DC converter switching power supply system using the single ended push pull soft switching inverter with asymmetrical PWM strategy for magnetron drive has excellent characteristics.

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