A Magnetron Power Supply with Transition-Mode ZVS Inverter

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***Abstract*—This paper designs a transition-mode zero-voltage-switching inverter for cooker magnetrons. The inverter drives a leakage transformer to generate high voltage and stabilize current. While switch is ON, pulsating input voltage magnetizes the transformer. And, while switch is OFF, the transformer resonates with a parallel capacitor. For achieving zero-voltage switching, a transition-mode driver L6561 is utilized to detect the ending of resonance and drives an insulated–gate-bipolar transistor. The ON time of transistor is controlled to regulate the magnetron power and is set to be inversely proportional to the input voltage. To demonstrate the analyses and designs of this paper, a 1kW ZVS inverter is implemented.**

I. INTRODUCTION

Cooker magnetrons have been utilized in the applications of cooking and heating for a long time. A cooker magnetron principally consists of one cathode filament, even-number anode cavities, two ring magnets and one output antenna, as shown in Fig.1. Generally, anode is grounded to the oven chassis. To start up a magnetron, power supply must preheat the cathode filament with large current and supply the cathode with negative high potential. While temperature and potential both reach critical values, cathode filament start to emit thermal electrons and anode attracts the electrons. While electrons are moving to anode, the magnetic fluxes of two ring magnets deflect the direction of electrons and make the electron currents rotate around the even-number anode cavities. Due to the rotation, alternating currents around the resonant cavities and electric fields between two neighbor anode vanes generate oscillating magnetic and electric fields in the resonant cavities. With the aid of output antenna, radiated 2450MHz microwaves are finally guided to a metal chamber for cooking or heating.

The V-I curve shown in Fig.2 conceptually illustrates the nonlinear V-I characteristic and the equivalent circuit of a cooker magnetron. For simplicity, the V-I curve is divided into two regions and respectively designated as non-oscillation and oscillation regions. In the non-oscillation region, the anode-cathode current I_{AK} is very small and is roughly proportional to the anode-cathode voltage V_{AK}. Therefore, a cooker magnetron operated in non-oscillation region can be regarded as a linear resistor of having high resistance. However, while the operating point of magnetrons enters the oscillation region, the variation on the voltage V_{AK} is very small and therefore the equivalent circuit can be viewed as a voltage source series connected with an ideal diode and a low-resistance resistor. Accordingly, the V-I characteristic of a cooker magnetron is similar to a Zener diode has. Anode current determines magnetron power. In order to steadily work, the magnetron currents must be stabilized. Improper driving currents always shorten the magnetron lifetime. While power control is applied to the magnetron, the filament temperature should be kept in a range to avoid generating spurious noise.

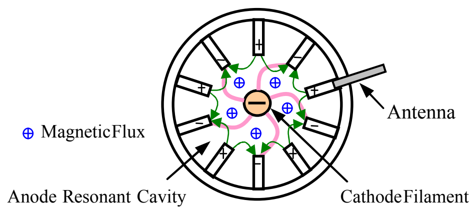

Figure 1. The structure and operation of a cooker magnetron.

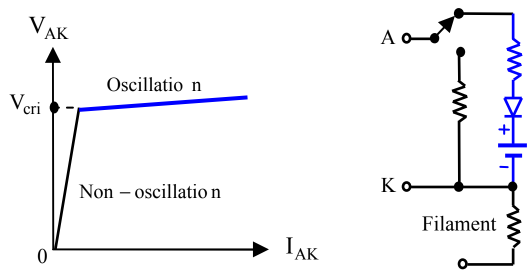

Figure 2. The simplified V-I characteritic curve and equivalent circuit of a cooker magnetron.

In the past, magnetron power supplies usually employ line frequency leakage transformers to generate the required high voltage and limited current. And, the magnetron power is regulated with intermittent ON-OFF operation. Nowadays, due to the considerations of performance, cost, volume and weight, especially in consumer applications, bulky and weighty line-frequency leakage transformer is gradually replaced with slim and compact high-frequency inverter and transformer [1]. Moreover, ancillary circuits can be added in the inverter [2]. At present, many candidate circuits can be selected for magnetron drive [1-13]. However, for AC110V microwave ovens, due to simplicity and low cost, the voltage-fed quasi-E resonant inverters were widely used [1]. Specific integrated circuits (ICs) were developed for specific products of microwave ovens [6]. In this paper, a widely used transition-mode power factor correction IC, L6561, is used to substitute the specific ICs. And, a general-purpose digital signal controller, disPIC30F4011, is employed to calculate and control the magnetron power.

II. TRANZITION MODE ZVS INVERTER

Up to the present, the transition-mode ZVS inverter is one of the simplest switching circuits for cooker magnetrons. It is usually adopted in the application of household microwave ovens, because of low parts count. Fig. 3 illustrates the main circuit of the ZVS inverter. In the power circuit, a full-bridge diode rectifier is used to rectify the line-frequency 60Hz AC source and a non-smoothing LC filter is employed to filter out the high-frequency switching current. Therefore, the following transition-mode ZVS inverter is fed with 120 Hz pulsating DC voltage.

The ZVS inverter consists of an insulated–gate-bipolar-transistor (IGBT) Q, a leakage transformer T_r and a resonant capacitor C_r. The transistor Q switches the transformer T_r to generate start-up voltage for magnetron. While Q is ON, T_r is magnetized with voltage V_d. While Q is OFF, T_r resonates with the capacitor C_r. Due to high-frequency operation, the required inductance and resonant capacitance are both greatly decreased.

For generating the required operation voltage, transformer T_r boosts its primary voltage with a large turns-ratio $n_2/n_1 >> 1$. Inherently, the large turns-ratio windings and the required insulation both increase the leakage inductance of T_r. Fortunately, the resultant leakage inductance can be utilized to stabilize the magnetron currents. However, too large leakage inductance deteriorates the circuit efficiency of the inverter. Therefore, in this paper, the coupling coefficient of the leakage transformer T_r is set around 0.75.

In the secondary of T_r, a full-wave voltage doubler is used to provide a negative high potential for the cathode. It doubles the secondary voltage of T_r with diode and capacitor D_1C_1 and D_2C_2. And, the positive is connected to the chassis of oven machine. In the tertiary of T_r, a low-voltage winding is used to heat the cathode filament and the filament current is stabilized with leakage inductance.

The used driver for the transistor Q is a transition-mode IC, L6561. It detects the ending of resonance and turns on the transistor Q again. The ON time of Q, and hence the magnetron power, is controlled with a digital signal controller (DSC). On the basis of better flexibility and immunity, a 16-bit DSC, dsPIC30F4011, is adopted in this paper. It regulates the ON time of Q to control the magnetron power according to the measured input current and voltage.

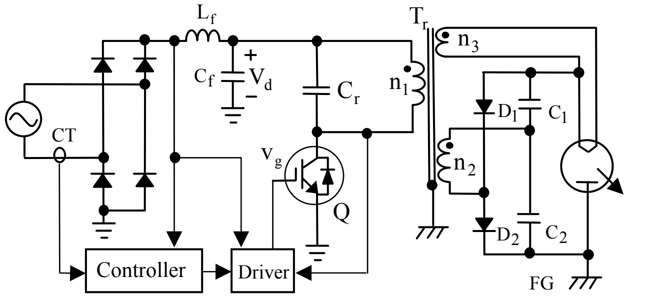

Figure 3. The magnetron power supply with a transition mode ZVS inverter.

III. CIRCUIT ANALYSIS

The cooker magnetron is a non-linear load. Its operating point enters the oscillation region while the anode-cathode voltage V_{AK} is greater than a critical value V_{cri}. As shown in Fig. 2, its equivalent circuit alternates with operation regions. While the ZVS inverter is fed with a pulsating DC voltage source, the operation regions alternate with the pulsating voltage V_d. As the pulsating input voltage rises to a critical point where the magnetron voltage equals to the critical value V_{cri}, the magnetron operating point enters the oscillation region. As the pulsating voltage falls from the critical point, the magnetron operating point comes back to the non-oscillation region. That is, the operating point, and hence the equivalent circuit, alternates with the pulsating DC voltage.

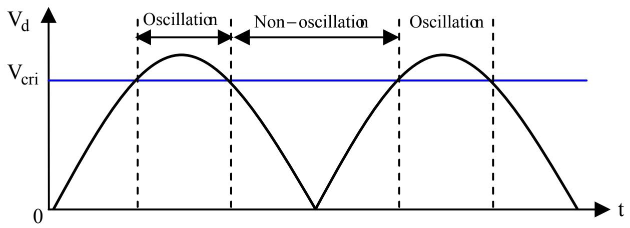

Figure 4. The alternation of operation regions in a line-frequency cycle.

During the start-up stage, the magnetron operating point is in the non-oscillation region. And, before the circuit operation, the initial capacitor voltage of the voltage doubler is zero and the cathode filament is cold. Namely, the secondary of transformer is equivalently short-circuited in the first switching cycle. Accordingly, the first resonant cycle of the ZVS resonant inverter is shorter than the second and the following resonant cycle. While filament temperature and cathode potential both reach their critical values, the operating point enters the oscillation region and the cooker magnetron starts to work.

In the secondary of T_r, the voltage doubler and magnetron can be roughly integrated as a resistive load because the capacitance of C_1 and C_2 are small and the secondary leakage inductance limits the current of magnetron. While all circuit parameters are transferred to the primary of the transformer [13], the transition-mode ZVS inverter can be redrawn as a simplified circuit shown in Fig. 5, where the pulsating DC input voltage V_d is regarded as a constant in a switching cycle. Fig. 6 conceptually illustrates the principal switching voltage and current waveforms of the inverter. Here, a complete switching cycle is divided into four stages.

Stage-1 ($t_0 \sim t_1$): This stage starts at time t_0 and ends at time t_1. If the energy stored in the transformer is large enough, the resonant current i_{Ls} can naturally flow through the reverse diode of Q. Therefore, Q can be turned on with zero voltage condition. As the resonant current returns to zero, this stage ends.

Stage-2 ($t_1 \sim t_2$): In this stage, the voltage source V_d magnetizes the leakage transformer and the current of transformer keeps rising till Q is turned off at time t_2.

Stage-3 ($t_2 \sim t_3$): This stage starts at time t_2 and ends at t_3. At t_2, Q is cut off and the transformer current starts to discharge the parallel capacitor C_r. At time t_3, transformer current drops to zero and capacitor voltage reaches negative maximum.

Stage-4 ($t_3 \sim t_4$): At time t_3, the reverse capacitor voltage drives the transformer. At time t_4, the capacitor voltage is greater than the input DC voltage V_d and the reverse diode of Q conducts naturally.

In stage-1 and stage-2, Q is ON. Transformer is connected to the DC voltage source. The primary current and voltage of transformer can be respectively approximated as

$$i_{Ls}(t) = i_{Ls}(t_0) + \frac{V_d}{L_r}(t - t_0)\,, \tag{1}$$

$$v_{Cr}(t) = V_d \tag{2}$$

In stage-3 and stage-4, Q is OFF. The transformer resonates with the parallel capacitor. The transformer primary current and voltage can be respectively written as

$$i_{Ls}(t) = i_{Ls}(t_2)\cos\omega(t - t_2) + \frac{V_d}{Z_0}\sin\omega(t - t_2)\,, \tag{3}$$

$$v_{Cr}(t) = V_d - V_d(1 - \cos\omega(t - t_2)) + Z_0 i_{Ls}(t_2)\sin\omega(t - t_2)\,, \tag{4}$$

, where Z_0 is characteristic impedance $Z_0 = \sqrt{\frac{L_r}{C_r}}$.

The OFF time is not a constant, but depends on the DC input voltage and the ON time of switch. According to the status of the magnetron, operating in non-oscillation region or oscillation region, as shown in Fig.4, the inductance L_r can be approximated as $L_s + L_p$ and L_s respectively. The series inductance L_s stabilizes current and the parallel inductance L_p dominates voltage.

As shown in Fig. 6, the ON time of Q determines the peak magnetizing current and the energy stored in the transformer. As the stored energy is large enough to naturally conduct the reverse diode, then switch Q can be turned on at zero voltage condition. However, the more ON time normally results in the more voltage stress on the switch Q and the more current on the magnetron. Possessing high voltage stress is the key feature of the transition-mode ZVS inverter.

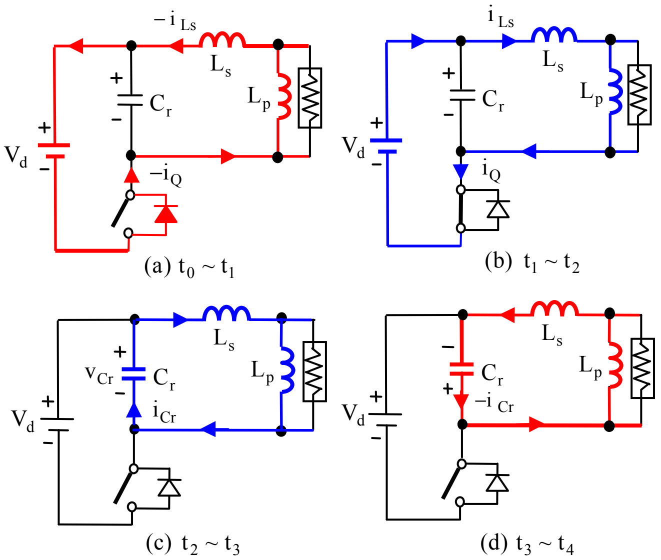

Figure 5. Four-stages circuit operation of the transition-mode ZVS inverter.

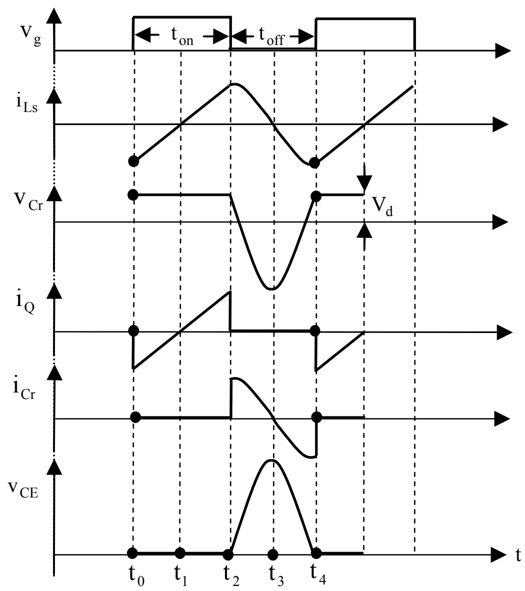

Figure 6. Switching waveforms of the transition-mode ZVS inverter..

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The magnetron current should be stabilized in a range and cannot exceed the rating. As shown in Fig. 4, the waveform of input voltage is a rectified sine wave and hence the magnetron only operates in the region that around the maximum point of input voltage. Namely, adjustable range of power is therefore limited. In this paper, in order to extend the power range and improve the input power factor, the ON time of the switch Q is set to be inversely proportional to the rectified input voltage. A control signal v_{con} inversely proportional to the input voltage V_d, as shown in Fig. 7, is added to the ON time control circuit. The ON time is controlled with a 16-bit digital signal controller, dsPIC30F4011. A longer ON time makes a larger magnetron current and power. While Q is off, the operation status of magnetron determines the resonant period or OFF time. Therefore, a transition-mode IC, L6561 is used to detect the ending of resonance. As the collector-emitter voltage of transistor Q falls to zero, the L6561 driver turns on the transistor again.

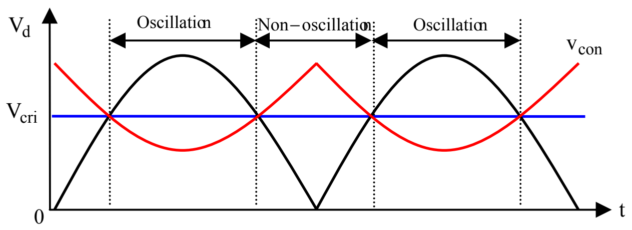

Figure 7. The ON-time control signal in a cycle of line-frequency.

IV. SIMULATION AND EXPERIMENT

In this work, the used cooker magnetron is the Panasonic 2M244-M23. Its oscillation frequency is about 2460MHz, maximum power is 1010W, anode-cathode voltage is 4.35kV, anode-cathode current is 320mA, cathode filament voltage and current are 3.15V and 10A respectively. Based on the specifications of the magnetron, principal inverter parameters are designed as follows. $L_s = 10\mu H$, $L_p = 32\mu H$, $n_2 / n_1 = 15$, $C_r = 0.32\mu F$, $C_1 = C_2 = 8.5nF$. Here, the used IGBT switch is GT60N321 and the high-voltage diodes are UX-C2B.

Due to the nonlinear V-I characteristic of magnetron, the required OFF time of transistor varies with the operation status of magnetron. Therefore, transition-mode switching operation is required and the widely used driver IC L6561 is utilized. Two simulation results shown in Fig. 8 are obtained with the same ON time but different input voltage. Two different resonant time illustrate the required OFF time of transistor varies with the operation status of magnetron, where the higher resonant voltage waveform corresponds to a higher input voltage.

The transformer current and capacitor voltage waveforms shown in Fig. 9 and Fig. 10 are respectively obtained with SPICE circuit simulation and MATLAB mathematical simulation. Here, the mathematical simulation uses the equations expressed in (1)-(4). The similarity of two simulation results confirms the simplified equations and the circuit operation analyzed in Section III.

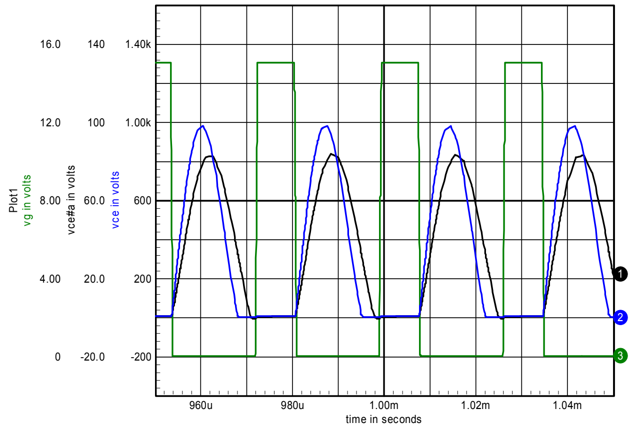

Figure 8. The resonant period varies with the operation status of magnetron.

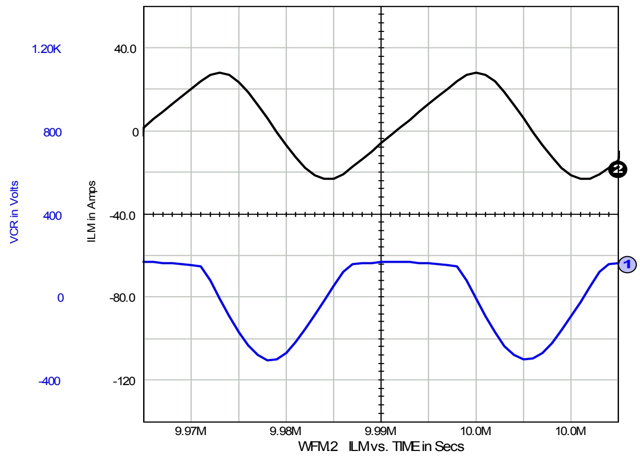

Figure 9. The transformer current and capacitor voltage waveforms obtained with SPICE circuit simulation.

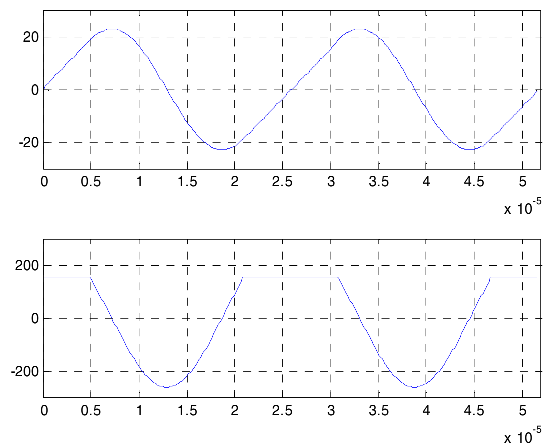

Figure 10. The transformer current and capacitor voltage waveforms obtained with MATLAB mathematical simulation.

Fig. 11 shows the start-up scenario of the magnetron with the waveforms of magnetron voltage and input current. It demonstrates the start-up process and verifies the magnetron power. Fig. 12 displays the anode-cathode voltage and current waveforms in a cycle of line-frequency 60Hz. It illustrates the operation status of magnetron is alternated with the pulsating input voltage. In Fig. 12, the cooker magnetron enters the oscillation region at high input voltage and comes back to the non-oscillation region at low input voltage.

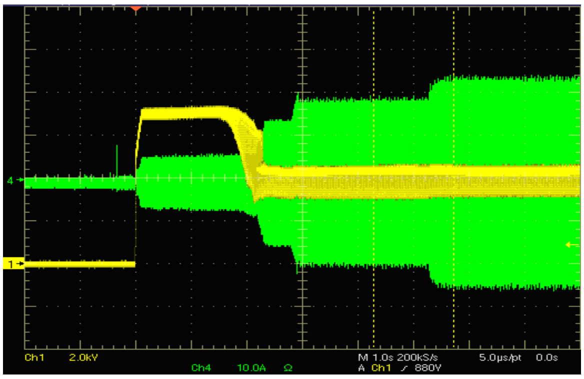

Figure 11. The start-up scenario of magnetron, where time scale is 1s/div, anode-cathode voltage is 2kV/div and input current is 10A/div.

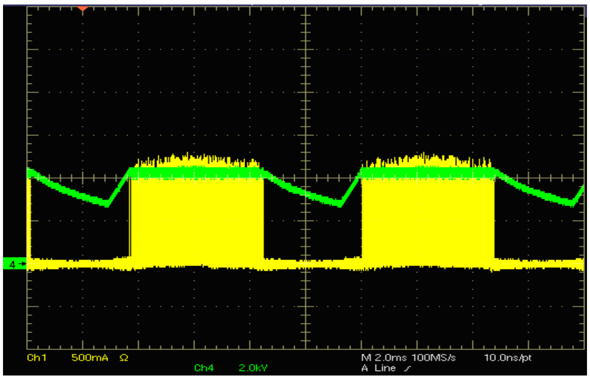

Figure 12. The anode voltage and current waveforms in a cycle of line frequency 60 Hz, where time scale is 2ms/div, anode urrent is 500mA/div and anode-cathode voltage is 2kV/div.

V. CONCLUSION

This paper analyzes the principle of a transition-mode ZVS inverter for cooker magnetrons and implements a 1kW power supply for AC110V microwave ovens. Due to the nonlinear V-I characteristic of magnetrons, transition-mode resonant operation is adopted to overcome the uncertain variations of resonant period. In order to extend the adjustable range of magnetron power and improve input power factor, the ON time of transistor is regulated with the input voltage that rectified form line-frequency 60Hz. The use of 16-bit digital signal controller enhances the programming flexibility and eases the magnetron power control.

ACKNOWLEDGMENT

This work is partly supported by the NSC of Taiwan. Contract number is NSC 99-2622-E-131-007-CC3.

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