PRACTICAL SOFT-SWITCHING HIGH-VOLTAGE DC-DC CONVERTER FOR MAGNETRON POWER SUPPLIES

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Abstract

A new soft-switching, high-voltage dc-dc converter for magnetron power supply application is presented in this paper. The proposed dc power supply consists of three main circuits: front-end flyback converter, high-frequency transformer, and high-voltage diode rectifier circuit. The front-end flyback dc-dc converter employs a soft-switching technique to minimize switching losses. Two high-frequency transformers with five secondary windings were developed to obtain a high voltage. Experimental results are provided to verify the superiority of the proposed converter under 200W and 4kV magnetron operations. The developed magnetron power supply, based on the proposed soft-switching converter topology, achieved an overall efficiency of 85%.

Introduction

The magnetron is a high-powered vacuum tube that generates microwaves. Typical applications of such microwaves include heating and drying in industry and home [1]. Heating and drying with microwaves provide fast, efficient and accurate control of power over the conventional thermal-based system. A high-voltage power supply, which can supply several kV, is required to operate a magnetron.

High-voltage dc-dc converters are widely used for magnetron power supplies. As these converters are very expensive, they are usually limited to applications that are the most demanding. One current challenge is to develop a low-cost dc-dc converter to drive magnetron lamps. Since these dc-dc converters transfer low-voltage power to high–voltage power, traditional converters have to utilize low-frequency ac transformers and rectifiers, resulting in low performance.

Recently, the development of a new class of low on-resistance power metal-oxide semiconductor field-effect-transistor (MOSFET) switching devices and high-frequency core materials has led to more compact dc-dc converters. They operate at higher frequencies and power densities than the traditional dc-dc converters [1], [2]. In order to improve efficiency, some converters have been using a soft-switching technique to reduce switching loss and stress on the switch [3], [4]. However, for safety, these high-voltage converters require high-voltage insulation and the high-voltage transformers are usually mounted on a board. Therefore, they tend to be large and bulky converters, resulting in a lower efficiency of 75% with 4kV for a magnetron power supply.

This study focused on the development of a cost-effective, soft-switching, high-power density dc-dc converter for a magnetron power supply that can achieve a reduced size and weight, improved efficiency, accurate voltage regulation, and effective power delivery to the output dc. The major accomplishments of this work were

- The development of a cost-effective, high-voltage dc-dc converter using quasi-resonant flyback soft-switching dc-dc converter topology. The converter reduces the turn-on loss of the power MOSFET switching devices. The main switching device is efficiently powered at high voltages and low currents with low power consumption.
- The development of a current-mode pulse-width modulation (PWM) controller using a commercially available off-the-shelf (COTS) switch-mode power supply (SMPS) control integrated circuit (IC) TEA1533 from NXP Semiconductors [5]. The controller regulates a constant output voltage to maintain the magnetron lamp current. Using the COTS SMPS control IC reduces the system cost, while providing several advantages such as precise current regulation, resistance to breakdown, and extremely efficient soft-switching operation at the high power levels.
- The development of sensory and control logic to enable anode current control in the magnetron. This practical design and implementation of the high-voltage converter created a compact power stage in addition to safe voltage insulation and accurate current and voltage control.
- Improvement of the overall efficiency of the 200W and 4kV magnetron power supply to 85% by reducing the turn-on switching loss of the main device, using a new high-voltage transformer design and its compact power packaging.

Proposed DC-DC Converter

The simplified block diagram of the overall configuration of the proposed dc power supply to drive the magnetron is shown in Figure 1. The power supply, which provides 4kV and 40mA of output power, consists of an EMI filter, continuous-mode power factor correction (CMPFC) [10] - [13], quasi-resonant flyback dc-dc converter, and two

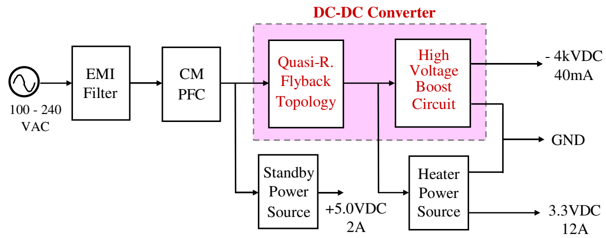


Figure 1. Overall block diagram of the proposed magnetron power supply

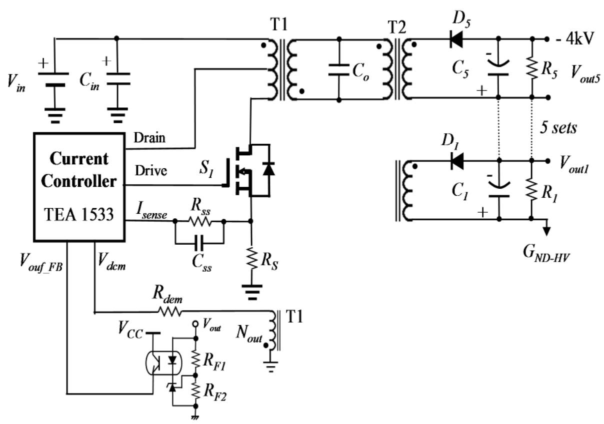


Figure 2. Proposed high-voltage dc-dc converter topology and its controller

outputs for the standby and heater power. The input to the power supply has a universal operating range of 100V to 240V. Figure 2 shows the proposed soft-switching dc-dc converter topology for the magnetron lamp drive. The converter consists of two power stages: low- and high-voltage.

The low-voltage stage contains quasi-resonant flyback topology with only one MOSFET switch and a flyback transformer. It is possible to allow the operation of the converter with critical conduction mode control, so that the converter achieves soft switching for the main switch, S_1, by using the leakage inductance in the transformer. The high-voltage stage is connected to the isolated two-stage windings of the transformer for high-voltage insulation.

An output filter bank is composed of five series-connected capacitors, C_1 through C_5, with the rectifying diode connected to each side of the load. At this stage, the high-voltage ac produced by the transformer is rectified and converted back to high-voltage dc. The output is then filtered by a capacitor bank to produce a low-ripple dc.

The switching sequence of the converter, based on the switch-voltage and current waveforms, is shown in Figure 3. The converter has four operational modes to achieve the desired output voltage waveforms at steady-state operation. The TEA1533 SMPS control IC was selected to achieve the zero-voltage switching (ZVS) operation [5]. The converter was operated under ZVS in valley switching technology. In order to achieve the soft-switching operation, a time delay is

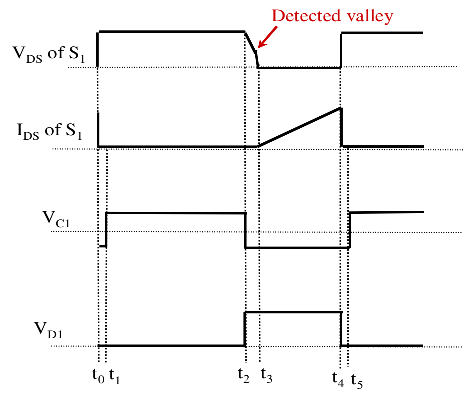


Figure 3. Voltage and current waveforms of the main switch

inserted between the turn-off of the freewheeling diode and turn-on of the main MOSFET switch, S_1. At the valley voltage region, an L-C resonance is formed by the leakage inductance on the primary winding of the transformer and the device capacitance across S_1.

For effective ZVS operation, it is necessary that the converter controller accurately detect the voltage drop and turn on the main switch at valley points. In the converter, the two high-frequency transformers have one winding with a turns ratio of 1:1 and five windings connected in series with a turns ratio of 1:9 in order to meet the high-voltage safety requirement. Since this converter has quasi-resonant flyback topology, the switching frequency was varied up to 250kHz, depending on the load condition. In this converter, a frequency of 50kHz was selected for full load. The configuration of the implemented high-voltage transformer is shown in Figure 4.

Design of current Controller and System Operation

The current controller block-diagram with secondary voltage sensing is shown in Figure 2. The current controller was operated with a TEA1533 device that consists of an input filter, a transformer with a third winding, and an output stage with a feedback circuit [5]-[9]. The TEA1533 current controller regulates the output voltage. The turn-on time of the main switch, S_1, is controlled by the internally-inverted

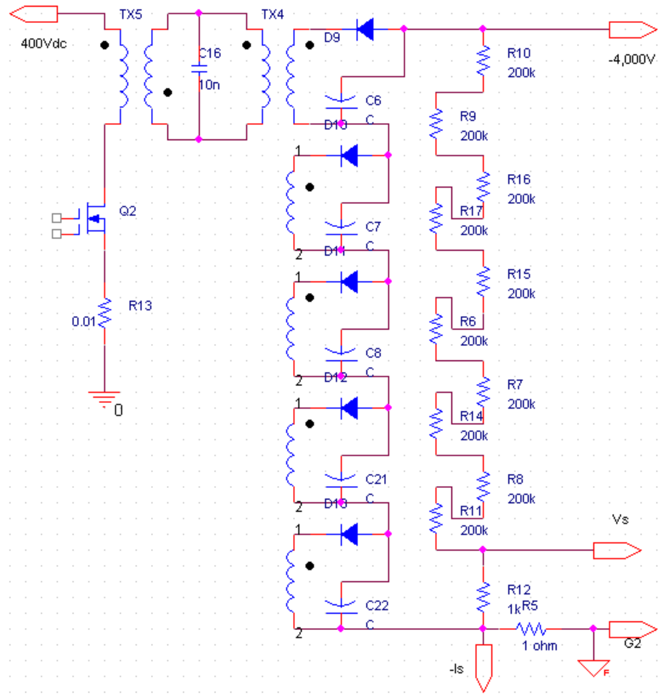


Figure 4. Overall configuration of the implemented high-voltage transformer

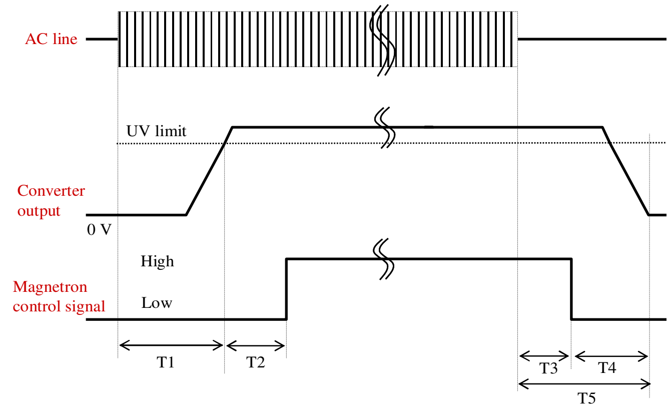


Figure 5. Magnetron control voltage pattern.

Table 1. Output current and voltage requirements to the magnetron power supply

Output Current [mA]	Output Voltage [kV]
0	0
10	3.82
20	3.87
30	3.93
40	4.0

control voltage, which is compared with the primary-current command. Also, the primary current was sensed across an external resistor, R_s. The sense resistor converts the primary current into a voltage at the I_{sense} pin. The value of the sense resistor was determined by the maximum primary peak current.

The operational requirement of the dc power supply to drive a magnetron lamp is shown in Figure 5. The sequence of operation for the proposed power supply is as follows: During T1, the power supply must provide the control signal to activate the magnetron lamp when the converter is turned on and its output voltage reaches 4kV. When the magnetron lamp is turned off, the power converter should be turned off with a time delay. Even though an ac line is removed, the converter must have the capability to turn the magnetron lamp off safely.

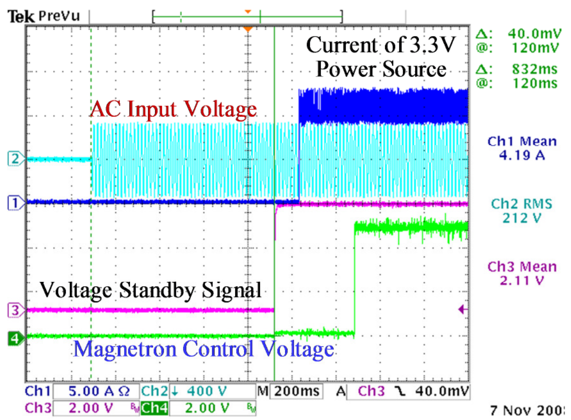
For the high-voltage operation of the magnetron lamp, the controller of the converter should be designed with at least a 200ms time delay at startup. After period T2, the fast response of the controller is required for impedance matching between the front-side quasi-flyback converter and the transformer secondary output. In addition, the response bandwidth of the converter for the change of input control voltage should be designed within approximately 20ms for a T5 period. The fall time for the constant anode current should not be greater than 2ms. Thus, the controller can actively regulate the output current for controlling the magnetron lamp. Table I describes the output-current and voltage requirements for the magnetron power supply.

Experimental Results

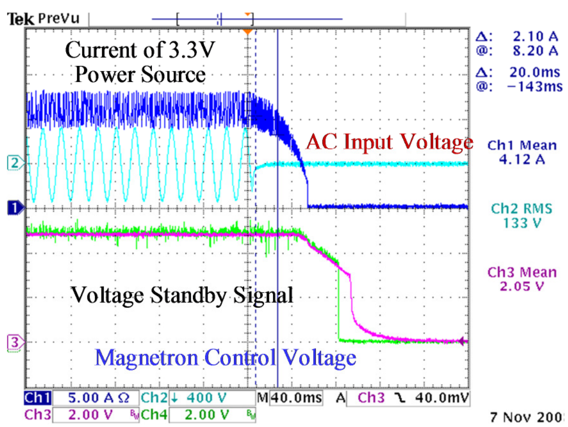
In order to validate the proposed converter operation, various experiments were conducted. The parameters of the output filter capacitors, C_1 through C_5 , and a resonant capacitor, C_o , were selected as 0.1µF/1kV and 6.8nF/1kV, respectively. A total of five 0.1µF capacitors are connected to five transformer secondary taps. For the high-voltage balance, two 1.2MΩ, 0.5W resistors were also connected in series across each tap.

The experimental waveforms during the magnetron lamp operation are shown in Figure 6(a). The time delay for start-up was measured to 200ms, which matches the design target. Figure 6(b) shows the voltage and current waveforms during ac power line turn off. Figure 5 shows that the waveforms satisfy the design specification.

The experimental waveforms of the input current and input voltage of the converter are shown in Figure 7. It can be clearly seen that the voltage and current are synchronized in-phase under near unity power factor (PF). The PF was measured at 0.98 under 230V ac input and full load, including a cooling fan. Note that the current spike near the zero crossing originates from the cooling fan to manage the thermal issues. The measured current and voltage of the primary winding of the transformer are shown in Figure 8. It should be noted that the current was well-regulated, and the active switch



(a) Current and voltage waveforms at starts up



(b) Current and voltage waveforms at turns off

Figure 6. Timing and sequence of operation of the converter

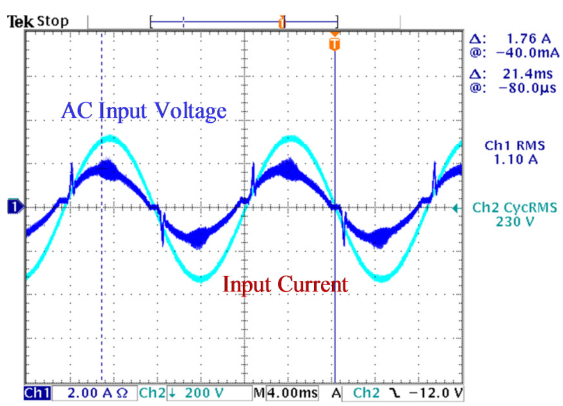


Figure 7. Input voltage and current waveforms at 230Vac under full load (PF = 0.98)

turned on at the lower valley voltage, as explained in Figure 3 [9]. Figure 9 shows the results of the conductive EMI/EMC test for the developed power supply. It is clear that the proposed soft-switching power supply met the minimum 4dB margin for the conductive EMI level at 230V ac. The layout of the major components, which are required for 8kV high-voltage insulation, is shown in Figure 10. The integrated prototype power supply is shown in Figure 11.

The power in the major circuitry was measured with 230V ac nominal input voltage under full-load conditions. The measurement shows that the proposed dc-dc converter achieved 85% conversion efficiency.

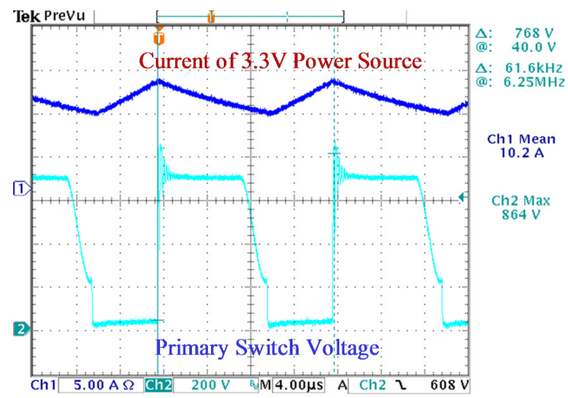


Figure 8. Output current and voltage waveforms of the transformer primary winding

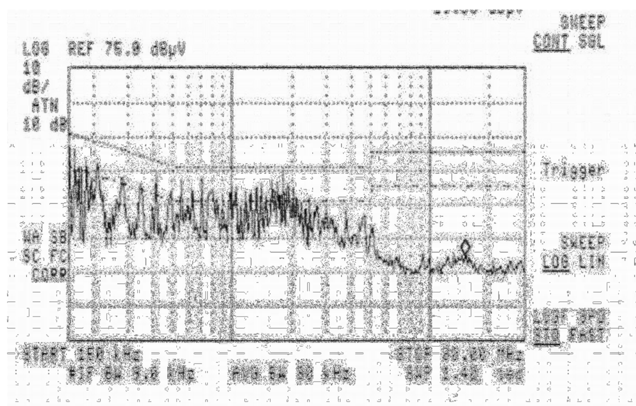


Figure 9. Measured conductive EMI/EMC for the developed power supply

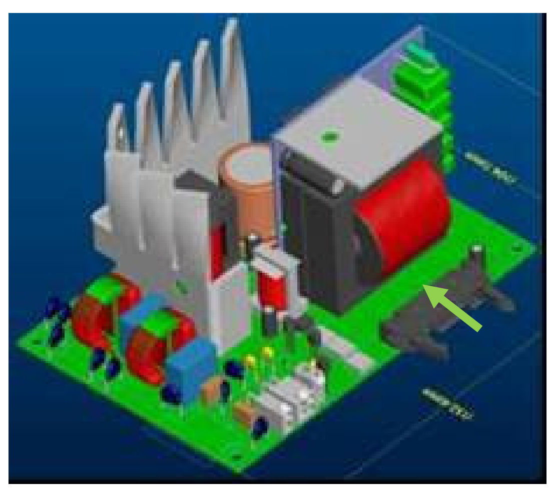


Figure 10. Component layout of the proposed power supply

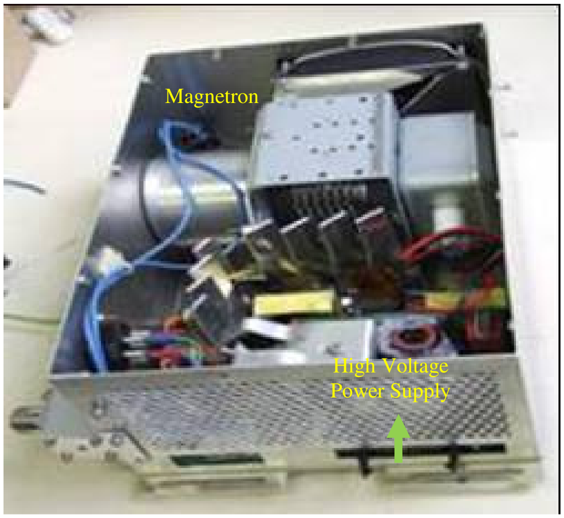


Figure 11. Integrated high voltage power supply and a magnetron

The measurement details are as follow:

- Total input power: 235W,
- High-voltage output power: 160W (4.0kV, 40mA),
- Magnetron filament power: 35W (3.4V, 10.3A),
- Cooling fan power: 4.6W,
- Standby power: 1.0W (5V, 0.2A).

Conclusion

A cost-effective soft-switching high-voltage dc-dc converter for a magnetron power supply is presented in this paper. The proposed dc-dc converter employs a quasi-resonant flyback soft-switching topology to reduce the turn-on loss of the power-MOSFET switching device. The main switching device efficiently powers at high voltages and low currents with low-power consumption. Using the COTS SMPS control IC reduced the system costs, while providing several advantages such as precise current regulation, resistance to breakdown, and extremely efficient soft-switching operation at high power levels.

The various practical design criteria, including a new high-voltage transformer, main switching device, and current controller were supported by experimental results. The quasi-resonant flyback converter achieved an overall efficiency for the 200W and 4kV magnetron power supply of 85% by the reducing the turn-on switching losses of the main switching device without any additional auxiliary circuitry.

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