Development and Optimization of High-Voltage Power Supply System for Industrial Magnetron

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Abstract—This paper describes the design and analysis of a 42-kW (14 kV, 3 A) high-voltage power supply for a 30-kW industrial magnetron drive. The design is based on a series resonant converter in discontinuous conduction mode (DCM) to take advantage of both the superior arc protection stemming from the current source characteristics and the high power density owing to the use of parasitic elements such as the leakage inductance in the high-voltage transformer. The detailed design procedure for the resonant tank and high-voltage transformer with respect to the input and output specifications is described on the basis of a simplified analysis of the DCM series resonant converter. Special considerations for designing high-power high-voltage power supplies are provided, such as series stacking of diodes for a voltage doubling rectifier and insulation between each winding of the high-voltage transformer. In addition, a comparative study using theoretical equations, simulation, and experimental results was carried out. This study yielded the output voltage and current characteristics at different switching frequencies and verified the advantages of this topology, such as arc protection without an additional protection circuit and high efficiency due to zero-current or zero-voltage switching. Moreover, the parallel operation of two converters with phase shifted gating signal is proposed to reduce the output current ripple and increase power capability for higher-power magnetron drive. Additionally, the design considerations of two auxiliary power supplies (a filament power supply: 15 V, 150 A and a magnet power supply: 50 V, 5 A) are also provided and optimized for effective driving industrial magnetron. Finally, the developed power supply was tested with a 30-kW industrial magnetron, and the results prove the reliability and robustness of the proposed scheme.

Index Terms—High-voltage power supply, industrial magnetron, series resonant converter, transformer design.

I. INTRODUCTION

RECENTLY, research in high-efficiency and eco-friendly microwave technology is increasing due to the continuation of high oil prices and environmental regulations.

The industrial magnetron is a high-efficiency high-power microwave generator with various industrial applications such as in processing foodstuffs, chemicals, textiles, paper, wood, and other materials, as well as in communications equipment and the environment.

Although several studies have been carried out on the development of power supplies for microwave generation, most have focused on consumer-grade magnetrons with capacities on the order of a few kilowatts. A soft-switching inverter-type ac–dc power converter and a one-chip class-E inverter controller achieving a maximum power of 1–1.4 kW has been introduced [1], [2]. In this paper, a 42-kW high-voltage power supply capable of driving a 30-kW 915-MHz industrial magnetron is proposed. Series resonant converters that operate in discontinuous conduction mode (DCM) are adopted for this application due to their specific merits: For high-voltage power supplies, the presence of substantial leakage inductance in the high-voltage transformer which can adversely affect converter operation is inevitable due to the isolation distance between the primary and secondary windings. On the other hand, this parasitic element can be used as a resonant tank element and operate as a resonant inductance in a series resonant converter. Moreover, series resonant converters in the DCM region operate as a current source, which supply constant current regardless of the load condition. This is a significant advantage when driving a magnetron, which has a nonlinear load characteristic similar to that of a Zener diode. Although these kinds of advantages have been previously recognized and basic analyses of topologies incorporating this design have been reported [3]–[19], industrial application studies are required so as to prove the feasibility of this design under a nonlinear load. Based on [20] which provides the equations from the mathematical analysis of the proposed topology and shows the results of simulation and experiment that verify the equations, this paper presents a detailed implementation procedure, including a design of the resonant inverter, together with a description of the high-voltage transformer design with specific leakage inductance and high-voltage rectifier with sensing circuit, in practical aspects.

In addition, reducing the output current ripple observed in [20] when the designed converter operates with magnetron load is considered by means of parallel operation with a six-phase resonant inverter. Such modular structure also facilitates increasing the maximum output power of the designed converter. Moreover, a special control algorithm between a high-voltage power supply and a filament power supply is introduced to prevent the overheating of the filament due to the reflected wave. Furthermore, the optimal operating conditions of the
auxiliary power supplies are investigated for achieving the high oscillation efficiency of industrial magnetron. Finally, the experimental results obtained for a 30-kW industrial magnetron are shown, which prove the feasibility of the proposed topology for use in high-power microwave generation.

II. STRUCTURE AND CHARACTERISTICS OF INDUSTRIAL MAGNETRON

An industrial magnetron generates high-power microwaves by transforming electrical energy in an ultrahigh vacuum at the intersection between a dc electric field and a magnetic field. The device mainly consists of a cathode, an anode, and an antenna, as depicted in Fig. 1. The anode, which encircles the electron-emitting cathode, consists of several vanes made of multiple metals, which constitute the resonant cavity. The microwaves generated in this resonant cavity radiate through the antenna. Depending on the aforementioned mechanism, a continuous microwave output power of an industrial magnetron can reach approximately 100 kW at roughly 80% conversion efficiency.

As depicted in Fig. 2, three kinds of power supplies are necessary for industrial magnetron drive, including the high-voltage power supply to generate the high-power microwave, the filament power supply to heat the cathode for thermoelectron emission, and the magnet power supply for controlling the electron trajectory. The design considerations of each power supplies for effective driving industrial magnetron will be discussed in Section IV.

The load characteristics of an industrial magnetron can be classified into two linear modes on the basis of the value of the cutoff voltage and the voltage applied between the anode and the cathode. When the applied voltage is less than the cutoff voltage, this represents the nonoscillation mode: The magnetron acts as a large resistor that provides rapid voltage increase with increasing current. However, the magnetron can be equalized with a small resistor connected in series, a diode, and a cutoff voltage in the oscillation mode [2]. Due to the piecewise linear relationship between current and voltage in an industrial magnetron, a series resonant converter in DCM is adopted because the output current depends only on the ratio of resonant frequency to switching frequency, not load conditions.

III. DESIGN OF THE SERIES RESONANT CONVERTER FOR HIGH-VOLTAGE POWER SUPPLY

For basic steady-state analysis of a half-bridge series resonant converter in DCM, see [20]. The operating principle and soft-switching mechanism of the proposed converter are explained with respect to the operational mode classified by conducting devices. In addition, the relationships among the converter design parameters such as switching frequency ($f_s$), resonant frequency ($f_o$), quality factor ($Q$), and normalized output plane including normalized output voltage ($M$) and current ($J$) are derived in (1) and (2). Equation (2) represents that the series resonant converter at DCM operation can be interpreted as a current source since the normalized output current is independent of the load resistance.

$$M = \frac{4}{Q\pi} \cdot \frac{f_s}{f_o}$$

$$J = M \cdot Q = \frac{4}{\pi} \cdot \frac{f_s}{f_o}$$

Finally, the design of a 42-kW (14 kV, 3 A) series resonant converter for use with a 30-kW industrial magnetron is presented, as shown in Fig. 3.

The designed power supply consists of an input rectifier and filter inductor ($L_f$), capacitor ($C_f$) parts for dc input voltage to the resonant converter, a three-phase resonant inverter ($s_1 - s_6, C_{r1-1} - C_{r3-2}, L_{r1} - L_{r3}$) with a half-bridge configuration, a high-voltage transformer ($TX1 - TX3$) including a leakage inductance as a resonant inductor, a series-connected high-voltage rectifier section ($D7 - D12, C1 - C6$) in a voltage doubling scheme, and an $RC$ divider circuit ($R1 - R4, C7 - C10$) for high-voltage sensing. The specifications and designed parameters are summarized in Table I.

A. Three-Phase Resonant Inverter

The values of the resonant inductor, capacitor, and transformer turn ratio are the most important parameters in the series resonant converter as they determine the relationship between the output voltage and current and the input. Moreover, they
will influence the stress on the switches and resonant tank [5]. The design procedure starts from the estimation of the maximum allowable switching frequency for insulated gate bipolar transistors (IGBTs). This frequency is based on the calculation of the conduction loss derived from the product of the rms current through the switches ($S_1 - S_6$) and their saturation voltage.

It must be noted that there is no switching loss (or it is negligible) due to the zero current (ZC) turn-on and zero-voltage/ZC turnoff. As provided in Table I, a 1200-V 200-A IGBT module (produced by Infineon Technologies) was used for each leg, and the antiparallel diodes ($D_1 - D_6$) represent the body diodes inside the IGBT structure. The fast reverse recovery characteristic for the antiparallel diodes is not required.
owing to DCM operation. Employing the estimated maximum switching frequency, a detailed calculation procedure for resonant tank parameters is provided in the Appendix.

As depicted in Fig. 3, the designed resonant capacitor \( (C_{r1} - C_{r3}) \) is implemented as the sum of two capacitors \( (C_{r1-1} + C_{r1-2} - C_{r3-1} + C_{r3-2}) \); that is, it is a twin capacitor structure. To allow compact design and cost effectiveness, resonant inductance is implemented using the high-voltage transformer leakage inductance.

The gate drive circuits, which are connected directly to the IGBT modules, receive the frequency-modulated signal at a fixed pulselength of 10 \( \mu \)s. The value of the pulselength should be less than the resonant current period \( (T_o) \) and greater than half of \( T_o \) to allow soft switching in the antiparallel diode conduction region. Fig. 4(a) shows the developed three-phase resonant inverter part including the resonant capacitors, gate drive circuits, and three IGBT modules on the heat sink.

### B. Design of High-Voltage Transformer

The design of a transformer for high-voltage and high-power applications has many constraints, such as the isolation distance between the primary and the secondary winding, the copper and core losses due to high-frequency current and flux, and so on. Furthermore, the leakage inductance of the designed transformer should be a specific value, as it will be used as a resonant inductor without an additional inductor. Taking into consideration the aforementioned constraints, previous research detailed the design of a 14-kW transformer \( (TX1 - TX3) \), including an estimation of leakage inductance, design of a special bobbin for proper insulation and desired leakage inductance, and a loss analysis for both copper and core [20]. In addition, a specially made slot at the front of the bobbin was introduced to prevent breakdown due to surface discharge. The developed high-voltage transformer based on the given design procedure is shown in Fig. 4(b), and the measured leakage inductance is 3.6 \( \mu \)H.

### C. Design of High-Voltage Rectifier and Sensing Part

As depicted in Fig. 3, the voltage doubling scheme was used as a high-voltage rectifier. Three such rectifiers in the high-voltage transformer are connected in series to generate the maximum output voltage of 14 kV. In practice, the diodes \( D7 - D12 \) represent series-stacked diodes, rather than a discrete component. Each diode stack consists of five 1500-V 10-A discrete diodes in series to produce 5-kV rectification. In addition, the capacitors that have a capacitance value greater than the diode junction capacitance are connected in parallel to each diode for voltage sharing. In order to sense voltages as high as 14 kV, the resistor \( (R1 - R3) \) and the capacitor \( (C7 - C9) \) voltage divider circuit is implemented. This circuit will sense the high voltages without noise if one chooses the proper values of resistance and capacitance. The level of the sensing voltage is determined by the ratio of the sensing resistance \( (R4) \) to the total divider resistance. The product of each divider and sensing parameter \( (R1 \cdot C7, R2 \cdot C8, R3 \cdot C9, \) and \( R4 \cdot C10) \) should be the same for noise rejection purposes. Fig. 4(c) shows a picture of the developed high-voltage rectifier and sensing part.

There is also a slot between the diode stacks for the same reason as in the transformer bobbins’ slot. The output filter capacitance value \( (C1 - C6) \) was selected to minimize the ripple in the output; however, too large a value should be avoided so as to prevent influencing the resonant tank parameters. The high-voltage divider resistors and capacitors are located at the right side of the rectifier. The sensing resistor and capacitor are installed inside the controller.

### D. Parallel Operation of Designed Converter for Boosting Output Power and Output Current Ripple Reduction

As explained in Section II, the load characteristics of industrial magnetron at the oscillation mode regard a high-voltage source as a small resistor connected in series. That is, only the increase of the output current is required for a high-power industrial magnetron drive up to 60 kW. Therefore, the parallel operation of the designed converter is considered.

On account of the current source characteristic of the applied topology, the parallel operation can be achieved without problem by using one controller. Moreover, from the previous research [20], a relative high output current ripple was measured when the designed converter operates with magnetron load even if it consists of a three-phase resonant inverter. Based on the aforementioned considerations, the parallel operating scheme is proposed as shown in Fig. 5. Depending on the output of the proportional integral (PI) controller, the six-phase frequency-modulated gating signal for two converters can be made by means of phase shifting circuit, and that provides the reduction of the output current ripple and twice the power rating. In addition, another point worth considering is that two PI controllers for both the output voltage and the output current facilitate the limit of one output while controlling the other. It is very useful to protect the converters from overvoltage when it operates with high-power magnetron. Moreover, it must be noted that the pulselength of each gating signal should be fixed for all switching frequency range in order to achieve the soft switching.

### IV. DESIGN CONSIDERATIONS OF AUXILIARY POWER SUPPLIES

The role of each power supply for driving industrial magnetron was introduced in Section II with brief maximum output specifications. This requires some further explanation about design considerations, including the interlock function and the output current control of each power supply.

The importance of the interlock and protection circuit cannot be overemphasized to protect the industrial magnetron from the malfunction of power supplies. As an example, if the malfunction of the magnet power supply occurs during high-voltage power supply operation, the magnetron will be damaged since the load can be equalized as a short circuit without magnet power supply operation. From the aforementioned reason, the protection schemes, including the high-voltage power supply turnoff interlock against auxiliary power supply malfunction and auxiliary power supply turn-on holding interlock during
high-voltage power supply operation, are suggested for safety operation.

In addition, the filament power supply output current control algorithm also proposed against the overheating of the filament. The temperature of the filament can be increased by not only the filament power supply output current but also the high-voltage power supply output current due to the generation of reflected microwave. Therefore, the automatic control of the filament power supply output current ($I_{\text{filament}}$) with respect to the high-voltage power supply output current ($I_{\text{high\_voltage}}$) scheme is proposed based on (3), where $I_{\text{filament\_set}}$ represents the reference value of the filament output current and $K$ denotes the desired slope of the filament power supply output current decreasing. Moreover, the controllable $K$ parameter provides the usefulness of the developed power supply for a wide range of industrial magnetron. Moreover, the real-time estimation of the filament resistance circuit is used for checking the condition of the filament and determining the high-voltage power supply operation time after preheating. Fig. 6 shows the control block diagram of the filament power supply.

Likewise, the output current of the magnet power supply which can affect the microwave output power and oscillation...
efficiency should be controllable to operate the total system at optimal conditions

\[ I_{\text{filament}} = I_{\text{filament\_set}} - K \cdot I_{\text{high\_voltage}} \]  

(3)

V. EXPERIMENTAL RESULTS

Using the design parameters which were verified by simulation, a power supply was developed that could generate an output current in the range of 0.56–3 A with a 14-kV output voltage. The test for maximum output voltage and current operation was performed with a resistor load; 96% of maximum efficiency was achieved. In addition, the linear relationship between the switching frequency and the output current was measured and compared to theoretical calculations and simulation results [20]. This comparison verified a given design procedure and the aforementioned characteristics of the proposed topology. Furthermore, short circuit testing during operation guaranteed the reliability of the developed converter.

Finally, the developed power supply was tested with a 30-kW industrial magnetron; the results are summarized in Table II with respect to microwave output power. The efficiency of the industrial magnetron alone reaches 80% at a 20-kW output power, whereas the total maximum efficiency was measured as 77% at 30 kW with 105-A 10-V filament power supply and 3.6-A 38-V magnet power supply output conditions. Moreover, the optimal operating point which can achieve the higher oscillation efficiency was investigated with different output conditions of each power supply. The result depicted in Fig. 7 shows the comparative plot of the microwave output power and conversion efficiency depending on the magnet power supply output current. Furthermore, the optimal operating conditions of each power supply were founded as given in Table III.

As shown in Fig. 8, the proposed filament power supply output current control algorithm was also tested with high-voltage power supply. The initial value of the filament power supply output current is 120 A, and it decreases linearly with respect to the microwave output power. Fig. 8 shows the controllable range of filament current based on the value of \( K \), and \( K = 5 \) was finally used for effective microwave generation which represents the 105-A filament current at rated operation.

The waveforms at a microwave output power of 30 kW are shown in Fig. 9, including the resonant current of the high-voltage power supply and the output current of each power supply. In addition, the parallel operation of two high-voltage power supplies by means of the proposed scheme in Fig. 5 was tested with magnetron load. Although the power supply can be operated at an 84-kW output (14 kV, 6 A), the test conditions of parallel operation were 3.8 A and 54 kW with a 43-kW microwave generation due to the constraint of the water cooling system for high-power microwave. From the experimental waveforms shown in Fig. 10, it was observed that the six-phase gating signal helps in the reduction of the output current ripple even if it operates with magnetron load.
VI. CONCLUSION

The analysis, design, and implementation of a series resonant converter in DCM operation have been analyzed for use with an industrial magnetron drive. Using the basic structure and characteristics of an industrial magnetron, a three-phase resonant converter was designed for maximum output voltage and current of 14 kV and 3 A, respectively. The detailed implementation procedure and practical considerations were described, including a three-phase resonant inverter and high-voltage components such as a transformer, a rectifier, and a sensing circuit.

Moreover, the design considerations of auxiliary power supplies were provided, including required interlock schemes and a useful control algorithm for filament current.

Experimental results with a resistor load confirm the linear characteristics of the output current with respect to the switching frequency or frequency ratio and show the advantages of this topology, particularly its current source characteristics, the possibility of effective high-voltage transformer design, and high efficiency.

Finally, the proposed converter was tested with a 30-kW industrial magnetron. The current and voltage characteristics in the oscillating mode were obtained by measuring the current through the anode and voltage between the anode and cathode with increasing microwave output power. In addition, the energy conversion efficiency of the power supply and that of the industrial magnetron were measured separately at each microwave output power. The maximum total efficiency achieved was 77.17%.

Consequently, these experimental results prove the highly efficient and reliable operation of the proposed converter for use with an industrial magnetron drive. Furthermore, the feasibility test results from the parallel operation of the designed converter with a multiphase resonant inverter show the usefulness of the proposed topology owing to the easiness of increasing the output current for a wide range of industrial magnetron and the enhancement in the viewpoint of output current ripple.

APPENDIX

DETAILED DESIGN PROCEDURE OF RESONANT INVERTER

In this section, the simple equations and the generalized step-by-step design procedure of the DCM operation series resonant converter are provided to calculate the resonant tank parameters with respect to given specifications.

1) Determination of resonant frequency \( (f_0) \) based on the allowable maximum switching frequency \( (f_s) \)

\[
f_0 = \gamma \times f_s = 75 \text{ kHz.} \tag{4}
\]

- The constant \( \gamma \) denotes the frequency ratio between the resonant and the switching frequency. The value of \( \gamma \) must be greater than 2 for DCM operation.

2) Calculation of transformer turns ratio \( (n) \)

\[
n = \frac{V_{\text{primary}}}{V_{\text{secondary}}} = \frac{M \cdot V_{\text{in}}}{\alpha \cdot V_o}. \tag{5}
\]

- The higher value of the normalized output voltage \( (M) \) is preferred for less stress of the switch and resonant tank but does not exceed the unit owing to the structure of the proposed topology. Moreover, the value of the constant \( \alpha \) is determined from the rectifier scheme. From the given input \( (V_{\text{in}}) \) and output voltage \( (V_o) \) specifications, the voltage on the transformer primary \( (V_{\text{primary}}) \) and secondary \( (V_{\text{secondary}}) \) can be calculated by (5). Furthermore, it should be noted that the value of the input voltage \( (V_{\text{in}}) \) depends on the configuration of the inverter such as half- or full-bridge circuit.
3) Calculation of characteristic impedance ($Z_0$), resonant inductance ($L_r$), and capacitance ($C_r$):

$$Z_0 = \frac{4V_{in}}{\pi \cdot \gamma \cdot I_o}, \quad (6)$$

$$L_r = \frac{Z_0}{2\pi \cdot f_o}, \quad (7)$$

$$C_r = \frac{L_r}{Z_0}. \quad (8)$$

A simple equation to calculate the characteristic impedance can be derived from the given equation in [20]. Finally, the value of resonant inductance and capacitance can be calculated by (7) and (8).

REFERENCES


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