Design of High Performance Magnetron Power Supply on the Basis of PWM Power Control

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Abstract: This paper proposed a kind of high-performance magnetron power supply circuit, the output power of which could be regulated precisely and stably. Based upon the LLC resonant converter with multiplier, efficient power conversion and stable loop control were realized when the switch frequency was near to the resonant frequency. The driving pulses of the switches were controlled by a low-frequency PWM signal, thus realizing the intermittent operation mode. Therefore, the output voltage was in the form of pulsation, which met the requirement of the magnetron. Furthermore, the mean output power of the microwave could be regulated through the PWM duty ratio. An experimental prototype of 1000 W magnetron power supply was completed. As shown in the experiment, the soft switch of this circuit possessed excellent performance. The converting efficiency was higher than 93%; moreover, its output power could be easily adjusted.

1. Introduction

The magnetron is a kind of high-power and efficient vacuum electronic component. It is able to produce microwaves of certain frequencies by self-oscillation, amplify the microwaves to a certain power level then output it. Magnetron has seen wide adoption diverse fields. In operation, it needs dual power supply circuits: a filament power supply \(V_F\) and an anode power supply \(V_A\). The filament power supply heats the cathode to produce electrons, and normally the voltage is 3.3V/10A. The anode power supply is fitted between the anode and the cathode of the magnetron to produce a high-voltage electric field, so as to control the anode electric current.

The magnetron is a type of non-linear load. Its volt-ampere characteristic curve was shown in Figure 1. If the anode voltage is lower than the cutoff voltage (commonly 3.8KV more or less), the anode current is so little that a majority of cathode electrons cannot reach the anode to formulate current. It is known as the non-oscillation area. However, when the anode voltage is close to the cutoff voltage, the anode current will spiral up into the oscillation area. Simultaneously the microwave is produced by the magnetron. In the oscillation area, the current has immense slope of change versus the voltage, so the requirements on accuracy and stability on the anode voltage are very strict. In Figure 1, the shadow area represented the actual operation area of magnetron.
According to the load characteristics of the magnetron, the non-linear circuit model of magnetron can be set up, as shown in Figure 2, where $C_m$ is the parasitic capacitance between the anode and the cathode of magnetron, $R_{no}$ is the equivalent resistance in the non-oscillation area, $R_o$ is the equivalent resistance in the oscillation area, $VT$ is the voltage-regulator tube which breakdown voltage equals to the cutoff voltage of the magnetron. In non-oscillation area, as $VT$ is not conductive, its equivalent load resistance $R_{no}$ is relatively larger. The load current changes little with the voltage. In oscillation area, $VT$ is conductive and its equivalent load is relatively smaller, so the load current changes greatly with the voltage.

In magnetron, it happened that the dispatched electrons bombard back to the cathode and thus boost the temperature of cathode. Provided the anode was supplied by DC voltage, the cathode would be bombarded by high-energy electrons and ions continuously, so that the current value would spiral up. Therefore, to ensure the magnetron in normal operation for long term, it needed to operate between the oscillation area and the non-oscillation area alternatively. The anode voltage required certain pulsation. Its minimum voltage was supposed to be lower than cutoff voltage. Furthermore, in that the anode of magnetron was connected to the ground, its actual voltage of cathode was pulsating negative high voltage.

The traditional magnetron power supply is a kind of linear circuit. It boosts voltage by leakage flux transformer. Then the voltage is rectified by the circuit that comprises diodes and capacitors to produce anode high voltage. Such circuit is large in size and low in efficiency. Its voltage is non-adjustable and worse than that, the power factor is relatively lower. Therefore, as of now, it has been weeded out and replaced by the switch mode power supply that possesses tiny size and high efficiency.

The efficiency was apparently improved in the magnetron by using the switch mode power supply in zero voltage switch (ZVS). In addition, the size became smaller, so it promoted the application of magnetron in various fields. Reference [1] presented a magnetron power supply based on series resonant converter. Reference [2] proposed a type of magnetron power supply based on full-bridge phase-shifting converter. Reference [3] raised another type of magnetron power supply that possessed half-bridge phase-shifting converter.

In recent years, LLC resonant converter has been widely used in magnetron power supply [4-7]. Introduced in Reference [4], the power frequency voltage passed through the rectifier then directly converted itself by means of LLC resonant converter. Switch frequency was regulated by input voltage, accordingly changing the gain value of LLC resonant converter. In this way, it realized the basically stable pulsing DC output and satisfied the requirements on magnetron power supply. Introduced in Reference [5], high voltage was produced by LLC resonant converter; then high voltage pulse modulation was realized via two switches.

A number of references had studied the magnetron in terms of its power efficiency, stability, power density and else [8-18]. In order to realize pulsing voltage for the magnetron, the rectifying filter circuits were selected with relatively less capacitance. In the oscillation area, the pulsing voltages were realized by the voltage sag of the energy-storage capacitors. In some references the sine power frequency signals were directly input without power frequency rectification filter, thus realizing the voltage pulsation. These methods may cause unstable output voltage and fluctuating load currents.
In practical application, the microwave power of magnetron was subject to be controlled and regulated. Theoretically, the anode voltage could be used to control the cathode current of magnetron, thus fulfilling the adjustment of microwave power. Nevertheless, Figure 1 indicated that, if the anode voltage exceeded the cutoff voltage, even tiny voltage fluctuation would lead to dramatic changes on current. Therefore, it imposed relatively higher requirements on the accuracy of anode power supply and the control loop. It was not only difficult to fulfill accurate control, but power supply expenditure increased and the design became more difficult. Otherwise, none of abovementioned references had provided appropriate solutions to the magnetron power control issues.

Power control is a very significant requirement in the application of magnetron. The traditional linear power supply cannot fulfill power adjustment. Again, though the switch mode power supply can use anode voltage to achieve power control, it was rather difficult to design such a device. This paper proposed a new kind of power control method which used PWM signal to control the LLC resonant converter. By this means, it changed the duty cycle to accurately regulate the microwave output power of the magnetron. Consequently, the design of switch mode power supply became much easier. And it perfectly solved the problems of magnetron power control. Moreover, while the PWM signal was turned off, the switches were completely shut down. Thus, it didn’t possess any losses, thereupon the efficiency was improved obviously.

2. The Load Characteristics of LLC Resonant Converter with Multiplier
The LLC resonant converter with multiplier realizes ZVS in the whole load range, and thus obtains relatively higher conversion efficiency. Otherwise, through voltage multiplier rectifier, the voltage stresses of the rectifier diodes and the filter capacitors are reduced, so as to facilitate high voltage output. The gain characteristic of LLC resonant converter with multiplier was analyzed as below.

The basic topology of half-bridge LLC resonant converter with multiplier was showed in Figure 3. The resonant components consisted of the resonant capacitor $C_r$, the resonant inductance $L_r$ and the magnetic inductance $L_m$. This circuit had two resonant frequencies: $f_{r1} = 1/2\pi\sqrt{L_r C_r}$ and $f_{r2} = 1/2\pi\sqrt{(L_r + L_m) C_r}$, so accordingly it could separate the operational part of this circuit into three sections: Section 1: $f_{r2} < f_s < f_{r1}$, Section 2: $f_s > f_{r1}$ and Section 3: $f_s < f_{r2}$. Among them, Section 3 couldn’t realize ZVS. Therefore, in most cases, it wasn’t considered. Section 1 and Section 2 both fulfilled ZVS, yet in Section 1, it could realize the ZCS switch-off of rectifier diode so as to avert from reverse recovery current. To summarize, Section 1 possessed more favorable performance than Section 2.

Suppose the normalized switch frequency $f_s = \frac{f_s}{f_r}$, the proportional coefficient of inductance $k = \frac{L_m}{L_r}$, and the quality factor of circuit $Q = \sqrt{L_r/C_r} / \frac{4R_s}{\pi^2}$. By means of fundamental wave analysis, it obtained the voltage gain of the half-bridge LLC resonant converter with multipliers as follows:

$$M(k, f_s, Q) = \frac{V_o}{V_{in}} = \frac{1}{\sqrt{\left(1 + \frac{1}{k} + \frac{1}{k f_s^2}\right)^2 + Q^2 \left( f_s - \frac{1}{f_s}\right)^2}}$$  \hspace{1cm} (1)

In case $K=5$, the characteristics of voltage gain under various $Q$ values were shown in Figure 4.

Despite that LLC resonant converter with multiplier can realize ZVS in the whole load range and it possesses relatively higher efficiency, however, as to magnetron power supply, even tiny voltage gain fluctuation can bring about relatively larger load current changes. The violent change of load current indicates rapid jumping of $Q$ value. In case the control loop responds at low rate, it may occur to relatively larger voltage overshoot, and impose rather high requirements on the response rate of control loop.
Figure 3. Topology of LLC resonant converter with multiplier.

Figure 4. Voltage gain of half-bridge LLC resonant converter with multiplier.

It supposed the operational point at initial moment was point A in Figure 4, and its corresponding value of $Q=0.5$, frequency was $f_1$. In case the load changed suddenly at certain moment, the operational point would rapidly jump from point A to point C; the corresponding $Q=0.3$ and gain value was far beyond point A. To fulfill the stability of output voltage, it was supposed to adjust the switch frequency from $f_1$ to $f_2$. As to the load of magnetron, it might take little time for the operational point in jumping from point A to point C. Once the response time of control loop was too long, it might cause unexpected high voltage, even might occur to high-voltage breakdown and damage the circuit or equipment. On the other hand, if point E was selected as the operational point (here $f_n=1$), even if the load suddenly became empty load, the theoretical gain value in resonant network was still 1 in value. Therefore, it would not occur to accidental high voltage. As a result, near the special operational point $f_n=1$, the gain value $M$ changed little with the $Q$ values. The load characteristic was relatively more stable. Point E was proved to be an ideal operating point.

3. Methods of PWM Power Control
As analyzed in above section, ZVS could be realized relatively better near $f_n=1$ for LLC resonant converter with multiplier. At the same time, it could protect the load from dramatically changing and further causing unstable voltage issues. On the other hand, if the microwave output power was regulated by changing anode voltage, the voltage gain of resonant network would inevitably change. Its operation point was bound to deviate from this operation point. To solve this issue, it used fixed frequency control on LLC to ensure the operation point not to change. The microwave power was regulated by PWM controlling method. And it realized pulsation voltage on magnetron anode. The principle was shown in Figure 5.

Figure 5 The PWM power control of LLC resonant converter with multiplier.
The basic idea of PWM power control was: In case the rated switching frequency of LLC resonant converter was near \( f_n = 1 \), it can achieve favorable ZVS and thus obtain relatively higher stability. Next, PWM signals were used to control the driving signal of LLC resonant converter. When the PWM signal was at high level, LLC resonant converter worked at the maximum power; if the PWM signal was at low level, the driving signal would be shut down. Then the high voltage output power became zero, and the magnetron stopped outputting power. The duty cycle of PWM signal played a decisive role in regulating the mean power of actual output microwave. By adjusting the duty cycle of PWM signal, it realized accurate control on the microwave power. This controlling style also met the requirements of pulsation voltage for magnetron anode.

Suppose the load power was \( P_0 \) without PWM control, then after PWM power control, the actual output power was:

\[
P_{\text{out}}^\text{on} = P_0 \frac{T_{\text{on}}}{T} = P_0 D_T
\]

As long as the duty cycle of PWM signal \( D_T \) changed, the actual output power could be adjusted. The maximum value was \( P_0 \) and the minimum value could be reduced to zero.

This paper proposed an intermittent operation style to fulfill power control. It used a kind of low-frequency pulse to control the driving signals of the switches. When the switches were turned off, the power supply stopped working. Therefore, it didn’t output energy to the load anymore; so naturally no loss occurred. The output power is adjustable via changing the duty cycle of low-frequency PWM signal. During the switching period of the PWM signal, energy-storage losses occurred at the output circuit. Therefore, the frequency of the PWM signal was not supposed to be high. Generally, the power control PWM signal was set as several dozens of Hz. In comparison with dozens of KHz switch frequencies, these losses could be negligible.

4. Experimental Results

This paper presented a new design of industrial magnetron power supply. Its technical parameters were as follows. The input voltage was 270±10Vdc; the voltage between anode and cathode was -4000V; the mean output was 1000W; the filament voltage was 3.3V/10A. When the duty cycle of output pulsing waveform was 50%, its peak power was 2000W. Therefore, the output power of the converter were supposed to be designed as 2000W. The switch frequency was selected as 50KHz; and the frequency of power control PWM signal was 60Hz, so the switch frequency was far greater than that of control signal. The topology of the power supply was as shown in Figure 5. The parameters of main circuit were shown in Table 1.

| Parameter                  | Value                  |
|----------------------------|------------------------|
| \( V_{\text{in}} \)        | 260-280VDC             |
| \( V_o \)                  | 4000V                  |
| resonant frequency \( f_r \) | 50KHz                  |
| PWM frequency \( f_c \)     | 60Hz                   |
| resonant capacitor \( C_r \) | 345.5nF                |
| resonant inductance \( L_r \) | 29.4\( \mu \)H        |
| magnetizing inductance \( L_{\text{m}} \) | 117\( \mu \)H        |
| turnsratio of transformer \( n_p:n_s \) | 1:15                  |
| rectifier diode D1, D2     | RHRP30120*4            |
| filter capacitor C1, C2    | 10nF/2500V*2           |

Above parameters were used in the PSPICE simulation analysis. The simulation results were shown in Figure 6. In Figure 6(a), from the top down, it showed the PWM power control signal, the switch driving signal as well as the high-voltage output of the anode. While the driving signal was switched off, the output voltage reduced from 4000V to 2000V step by step. Accordingly, the high-voltage pulsation output voltage was produced and it fulfilled the requirements on magnetron power supply. In Figure 6(b), from top to bottom, it showed the waveforms of the resonant inductor current, the switch drain-
source voltage and the switch driving signals. As shown in the Figure, before the switch was turned on, the drain-source voltage had dropped to zero and the resonant current was at negative value. It perfectly achieved ZVS.

![Simulation waveforms](image1)

Figure 6. Simulation waveforms

The designed prototype was shown in Figure 7. The experimental waveforms were respectively shown in Figure 8 and Figure 9.

![Power supply circuit of magnetron](image2)

Figure 7 Power supply circuit of magnetron

The waveforms of driving signal $V_{gs}$ and the drain-source voltage of the switch $V_{DS}$ were shown in Figure 8. Figure 8 (a) showed the waveforms under the conditions of empty-load, and Figure 8 (b) showed the waveforms under the conditions of full-load. Regardless of full load or no load, the drain-source voltage $V_{DS}$ had dropped to zero before the switch turned on. It could ensure the switch to turn on in ZVS under both conditions.

![Waveforms of driving voltage and the drain-source voltage of switch tube](image3)

(a). No-load condition

(b). Full-load condition

Figure 8 Waveforms of driving voltage and the drain-source voltage of switch tube
Figure 9 showed the waveforms of the output voltage. Figure 9 (a) showed the waveform that 16K resistance load was connected with the power supply. The output peak to peak voltage between anode and cathode was about 4000V in pulsation. Therefore, it met the requirements of magnetron. Figure 9 (b) showed the waveform of the output voltage when the actual magnetron was connected with it. Given that relatively larger parasitic capacitance existed between the anode and the cathode of magnetron, it was a slow process when the output high-voltage pulse changed to zero. However, as to the magnetron, the minimum value of its pulsation voltage was only supposed to be lower than its cutoff voltage. As a result, it could still meet the requirements on magnetron power supply.

![Figure 9](https://example.com/figure9)

(a). Test results of resistance load connection  (b). Test results of magnetron connection

Figure 9 High-voltage waveform of the output voltage

When 260-280V voltage was input into the power supply, the respective input current and efficiency were shown in table 2. The output voltage summits were all about 4000V. By adjusting the PWM duty cycle, the output powers were all regulated as 1000W. Seen from this table, within the requested range of input voltage, all tested efficiencies were above 93%, consequently it realized relatively higher efficiency.

| $U_{in}$ (input voltage)/V | $I_{in}$ (input current)/A | $\eta$ (efficiency) % |
|---------------------------|--------------------------|----------------------|
| 260                       | 4.1                      | 93.8                 |
| 270                       | 3.97                     | 93.4                 |
| 280                       | 3.84                     | 93.1                 |

5. Conclusions
This paper discussed the design of a magnetron power supply system. This system, with the LLC resonant converter with multiplier as the main circuit, could output high-voltage power and reduce the voltage stress on electronic components, and via PWM power control, it ensured accurate regulation on the output power of microwaves. Experiment results confirmed that the circuit could achieve a high efficiency of more than 93%, and the microwave power could be controlled precisely and stably. Therefore, it met the application requirements on microwave facilities and thus had good prospects of application.

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