Design of Bias Power Supply for Magnetron Sputtering with Automatic Equalization Current

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Abstract—High power switching power supply with modularization faces the challenges of equalizing voltage and current between each module. It is difficult to guarantee the reliable equalizing current by controlled equalizing current method while the large current is changing in the arc process of magnetron sputtering. A high power BPSMS based on the input parallel output parallel phase shifted full bridge converter (IPOP-PSFB) was developed. The power supply could realize AEC via the transformer secondary side crossed rectification without adding additional control strategy. The operating mode of the main circuit and the steady-state equalizing current principle were analyzed. Finally, a 20kW experimental prototype was designed to verify the effect of AEC.

Keywords—Bias power supply for magnetron sputtering (BPSMS); Combined full bridge; Crossed rectification; Automatic equalization current (AEC)

I. INTRODUCTION

Magnetron sputtering ion plating technology, with the advantages of low substrate temperature, high deposition rate and good adhesion strength is widely used in the treatment of material surfaces. With the increase of vacuum chamber and target area, BPSMS, which is composed of a single converter, is difficult to meet the industrial demand. Series and parallel connection between internal device of converter and series and parallel of independent power supply module have become the main development trends. The problem of equalizing voltage and current aroused.

IPOP combined converter mostly includes a full-bridge converter or a half-bridge converter. These converters have the properties of a Buck converter. The output

characteristic of Buck working in CCM mode is equivalent to a voltage source which consists of a series of an ideal voltage source V_i and a small value resistance R_j [1]. Due to the parameter difference, the output current of each module cannot be equalized. Now, the more mature control methods are droop method, active method and so on [2]. However, they increase the difficulty and cost. AEC method can realize the equalizing current by changing the converter topology without complex control methods, and it has the characteristic of high stability and low cost [3]. There is a load mutation of plasma load during starting process and the arc discharge phenomenon, the stability and fast response of bias power supply are very important [4]. The method of control equalizing current cannot carry on equalizing current reliably for the short time and large current plasma discharge condition. It may lead to a single module excessive current. In this paper, AEC method on crossed rectification was studied for bias power supply, which can be fast and steady equalizing current.

II. DESIGN OF MAIN CIRCUIT

PSFB was used as the basic module of BPSMS. The soft switch was used to improve the power supply efficiency and reliability. The power level was increased through parallel. The crossed rectification was adopted in the secondary side of transformer, as shown in Fig.1, The rectified output of two half wave cycle of plus and minus in the same module was connected to different output filter inductance [5]. There was a blocking capacitor in the secondary side, in order to ensure each module equalizing output current when there were parameter differences.

Figure 1. IPOP-PSFB main circuit of secondary side crossed rectifier

A. Analysis of Operation Modes of the Circuit with the Same Duty Cycle(SDC)

The operation time sequence of the switch tube for module 1 and 2 were exactly the same. There was a 1800 difference of driving pulse between leading leg S_{11} and S_{12} , The same for lagging leg S_{13} and S_{14} . PSFB was controlled by adjusting the driving pulse open time of lagging leg. The PSFB-IPOP had 12 operation modes. The main waveform is shown in Fig. 2. Key assumptions for the study:

- (1) The dynamic and static characteristics of all devices are completely consistent,
- (2) All the devices are ideal devices, neglecting the loss of the switching tube.

$$(3) \quad C_{11} = C_{12} = C_{21} = C_{22} = C_{lead} \\ C_{13} = C_{14} = C_{23} = C_{24} = C_{lag},$$

$$(4) \quad L_1 \gg L_{r1} / k_{T1}^2, \quad L_2 \gg L_{r2} / k_{T2}^2,$$

k_{T1} and k_{T2} are the transformer ratio of the module 1 and 2.

Mode 1 [$t_0 - t_1$]: As shown in Fig. 1 and 2, S_{11} , S_{14} , S_{21} and S_{24} are conducted. Module 1 provides energy to the inductance L_1 through diode D_{11} and D_{14} . The current of L_1 increases linearly. Similarly, the current of L_2 increases linearly. Blocking capacitor voltage of transformer primary vice side keeps on rising. The voltage of C_{11} , C_{12} are as shown in the formula (1).

$$U_{c11} = -U_{c11m} + \frac{i_{T1p}}{C_{11}}(t - t_0) \\ U_{c12} = -U_{c12m} + \frac{i_{L1}}{C_{12}}(t - t_0) \quad (1)$$

Mode 2 [$t_1 - t_2$]: S_{11} and S_{21} are turned off at the same time at t_1 moment. i_{T1p} and i_{T2p} are respectively transferred from S_{11} and S_{21} to capacitance C_{s11} , C_{s12} and C_{s21} , C_{s22} , while C_{s11} and C_{s21} are charged, C_{s12} and C_{s22} are discharged, S_{11} and S_{21} are zero voltage turn off. The vice side holds the operation mode of mode 1. Due to the filter inductance L_1 , L_2 and resonant inductance L_{r1} , L_{r2} are in series, to assume that the i_{T1p} and i_{T2p} are unchanged, at the same time the voltage changes of parallel resonant capacitor are shown in the formula (2):

$$u_{cs11}(t) = \frac{i_{T1p}(t_1)}{2C_{lead}}(t - t_1)$$

$$u_{cs12}(t) = V_{in} - \frac{i_{T1p}(t_1)}{2C_{lead}}(t - t_1) \quad (2)$$

At t_2 moment, the voltage of C_{s11} and C_{s21} rise up to supply V_{in} , the voltage of the C_{s12} and C_{s22} discharge to zero. Anti parallel diodes on S_{12} and S_{22} start to forward conduct. The voltage of S_{12} and S_{22} are clamped at zero by diode. The maintenance time of the state is shown in the formula (3):

$$t_{21} = t_2 - t_1 = \frac{2C_{lead}V_{in}}{i_{T1p}} \quad (3)$$

Figure 2. Waveform of the converter (SDC)

Figure 3. Waveform of the converter(DDC)

Mode 3[$t_2 - t_3$]: S_{12} and S_{22} are driven at t_2 moment, but the current on it's anti parallel diode is not zero. There is no current on S_{12} and S_{22} . The blocking capacitor of primary vice side is charged by L_1 . Meanwhile, the current of L_1 and the vice side current of transformer both decrease. Primary side current of transformer of module 1 is shown in the formula (4) and the current of module 2 is similar.

$$i_{T1p}(t) = \frac{i_{L1}(t)}{k_{T1}} \quad (4)$$

Mode 4[$t_3 - t_4$]: S_{14} and S_{24} are turned off at t_3 , the primary side currents of transformer of two modules are respectively streaming through C_{s13} , C_{s14} and C_{s23} , C_{s24} . At the same time, C_{s13} , C_{s23} are discharged and C_{s14} , C_{s24} are charged by the primary side current. Due to the existence of capacitance, S_{14} and S_{24} are zero voltage turned off. Assuming that the primary side currents are respectively I_{T1p} and I_{T2p} , the vice side enters freewheeling, all the rectifier diodes begin freewheeling. Because the time is short, the voltage of primary side blocking capacitor is almost unchanged. It is also considered that the voltage on vice side blocking capacitor is approximately constant. At t_4 moment, when the voltage on C_{14} and C_{24} rise up to V_{in} , the reverse parallel diode of S_{13} , S_{23} conduct. The maintenance time of mode 4 is shown (5):

$$t_{34} = \frac{1}{\omega_1} \arcsin \frac{V_{in}}{Z_1 I_{T1p}} \quad (5)$$

$$Z_1 = \sqrt{L_{r1} / (2C_{lag})}, \omega_1 = 1 / \sqrt{2L_{r1}C_{lag}}$$

Mode 5[$t_4 - t_5$]: The reverse parallel diodes of S_{13} , S_{23} conduct at t_4 moment, meanwhile S_{13} , S_{23} may be able to conduction, which will be zero voltage conduction. But there is no current through S_{13} and S_{23} , i_{T1p} is shown in the formula (6):

$$i_{T1p}(t) = I_{T1p}(t_4) - \frac{V_{in}}{L_{r1}}(t - t_4) \quad (6)$$

At t_5 moment, i_{T1p} and i_{T2p} decrease to zero, the reverse parallel diodes are turned off, the maintenance time of this state is shown in the formula (7):

$$t_{45} = L_{r1} I_{T1p}(t_4) / V_{in} \quad (7)$$

Mode 6 [$t_5 - t_6$]: At t_5 moment, the current on primary side of transformer is zero-crossing. S_{13} and S_{23} begin to conduct and provide loop for transformer current. Since the primary side current is not sufficient to supply the current for load, the rectifier diodes of secondary stage are still freewheeling. When the winding voltage of transformer is approximately zero, the current on primary side of transformer of mode 1 is shown in the formula (8):

$$i_{T1p}(t) = -\frac{V_{in}}{L_{r1}}(t - t_5) \quad (8)$$

At t_6 moment, when i_{T1p} rises up to the load current of transformer, this mode is over. At this moment, D_{11} , D_{14} and D_{21} , D_{24} are turned off, all the load current flow through D_{12} , D_{13} and D_{22} , D_{23} . Module 1 provides energy to L_2 through D_{13} and D_{12} . The current of L_2 increases linearly. Module 2 provides energy to L_1 through the diode D_{23} and D_{22} , the maintenance time of mode 6 is shown in the formula (9):

$$t_{56} = \frac{L_{r2} I_{L2}(t_6) / k_{T2}}{V_{in}} \quad (9)$$

Modes 7-12[$t_6 - t_{12}$]: The operation from mode 7 to mode 12 are the same as the previous modes except the direction of powering path.

B. Analysis of Equalizing Current with the Same Duty Cycles(SDC)

By analyzing the working modes with SDC, it can be seen that C_{12} and C_{22} are charged when the transformer current is positive, and discharged when the current is negative. L_1 and L_2 is large enough, the current of capacitance can be assumed to change linearly. The charging and discharging time of the capacitance are all $T/2$. The average currents of steady-state of L_1 and L_2 are I_{L1} and I_{L2} . It can be concluded that the current in one cycle when the vice side blocking capacitor is steady as shown in the formula (10):

$$I_{c12} = (TI_{L1} / 2 - TI_{L2} / 2) / T$$

$$I_{c22} = (TI_{L2} / 2 - TI_{L1} / 2) / T \quad (10)$$

The average current of capacitance in one cycle is zero, so the formula (11) can be obtained from the formula (10):

$$I_{L1} = I_{L2} \quad (11)$$

The output current auto-equalizing can be achieved by the transformer secondary side crossed rectification and vice side blocking equalizing-voltage capacitor.

C. Analysis of Equalizing Current with the Different Duty Cycles(DDC)

Duty cycles of the two modules are not identical when there are some differences among driving parts. Suppose the duty cycles of module 1 is d_1 , and module 2 is d_2 , and d_2 is greater than d_1 . Also, assume that S_{24} is in the positive half cycle and S_{23} is in the negative half cycle conduct first. As shown in Fig. 3.

Mode 1[$t_0 - t_1$]: At t_0 moment, L_2 is charged through S_{24} and S_{21} , module 2 enters the positive half cycle first to provide energy for the load. The current flows through S_{21} , primary winding of T_2 , S_{24} and to the negative

of power supply. S_{13} and the anti parallel diode of S_{11} conduct streaming. L_1 begins the commutation stage first because of the inductance cross. This will make the circulation feedback time shorter, make module 1 to enter into the positive half cycle in advance, and reduce the difference of duty cycles. The simulation and experiments proved that each module could rapidly equalize current when there were parameter differences in duty cycles, internal resistance, inductance and so on.

III. DESIGN OF THE EXPERIMENTAL PROTOTYPE

The experimental prototype of 20kW based on IPOP-PSFB combination converter was developed in this paper. The parameters is shown in table 1. The parameters design and device selection of each module can refer to the basic PSFB.

TABLE I. MAIN CIRCUIT PARAMETERS

U_{in}	U_0	i_0	f	
530[V]	0~1000[V]	0~20[A]	50[kHz]	
L_{r1}/L_{r2}	L_1/L_2	C_{12}/C_{22}	C_0	C_{11}/C_{21}
20[uH]	1[mH]	1[uF]	2[uF]	4[uF]

IV. ANALYSIS OF EXPERIMENT AND SIMULATION

A. Analysis of Pspice Simulation

These IPOP-PSFB were studied in Pspice environment. When $d_1 = 50\%$, $d_2 = 55\%$, the simulation results are shown in Fig.4, the direct parallel figure is shown in 4(a), the filter inductance currents of the two module have a current difference when there is load change. After entering the steady state again, the current difference is $\Delta I = 2.5A$. The cross parallel figure is shown in 4(b), the filter inductance currents of the two module are almost same and it can realize automatic equalization current when there are other less than 10% parameters difference such as resistance and inductance.

B. Experimental Research of AEC when the Parameters are Different

In order to simulate the difference of internal resistance, 0.5Ω resistance is in series at rectifier output of the diode in the module 1. As shown in Fig.5(a), The $L1/L2$ current waves are basically the same and the output error is 0.2A, current sharing

Figure 4. The $L1/L2$ current when the duty ratio is different.

(a) R is not consistent

(b) Duty ratio is not C

Figure 5. The L1/L2 current waves

error is 1% and the load current of 16A is averaged. The dynamic changes are almost the same for the two modules when the load current changes from 10A to 16A.

When the duty cycles are not consistent ($d_1 = 50\%$, $d_2 = 55\%$), As shown in Fig.5(b), The current error at steady-state is 0.1A. The current sharing error is 0.7% and the current of the two inductance are also consistent with the dynamic change.

The experiments were set up to prove that the power supply prototype could realize dynamic and steady state equalizing current rapidly with the difference of duty ratio, internal resistance, and inductance in each module.

V. CONCLUSION

The transformer secondary side crossed rectification was applied to BPSMS based on IPOP-PSFB to meet the requirements of high voltage and large current output. The bias power supply could realize current AEC and the soft switch was achieved also. The 20kW experimental prototype was made, the output voltage and current were 0~1000V, 0~20A. The power supply could well meet the requirements in the field of magnetron sputtering, high efficiency, low cost, and the design method is simple.

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