Design of an LCC Resonant Converter for Furnace Power Supply during Electron Bean Melting

Zhang Haifeng* Non-member, Wang Peng† Non-member

(Manuscript received Jan. 11, 2017, revised May 16, 2017)

High-power converter applications are usually realized using the hard-switching technology under a low-switching frequency condition; moreover, the isolation transformer size must be larger. To reduce transformer size, the switching frequency must be increased; however, this increase directly results in the increase of switching loss. This paper proposes a high-voltage (HV) and high-power supply by using a thyristors-controlled rectifier and LCC series parallel resonant converter (LCC-SPRC). The introduced dc-dc converters are connected in parallel at the input side and in series at the output side, and soft-switching technology is applied to reduce the switching loss by using the frequency control mode. In addition, an equivalent mathematical model of LCC-SPRC with discontinuous current model (DCM1) was analyzed in detail. For obtaining accurate parameters of LCC-SPRC, the Matlab/Simulink software was employed to calculate the system parameters, and provide the system with dynamic simulating curves. The simulation and experimental results verify that the LCC-SPRC design scheme of for supplying furnace power during the electron beam melting (EBM) is feasible in applications.

Keywords: electron beam melting furnace, high voltage DC power supply, LCC series and parallel resonant converter, soft-switching technology

1. Introduction

EBM is one of the best way in which high reactive metal, such as titanium and zirconium, can be refined. Under the vacuum environment, the impurities in metal can be effectively removed by using EBM method. HV dc power supply is the important part of the EBM furnace and Its performance directly affects the stability of EBM system. For obtaining output dc HV, the traditional HV power supply of EBM furnace usually adopts the structure of industrial frequency or medium-frequency step-up transformer with diode rectifier (silicon stack). However, the both volumes of the transformer and output-filter are very huge, and the output voltage ripple of power supply is also higher. Thus, according to the technical drawbacks of the traditional EBM power supply, a dc power supply with high frequency resonant converter is proposed, which can realize zero voltage and zero current switching (ZVS/ZCS) of IGBTs, at the same time, reducing the switching loss and the volume size of step-up transformer and output-filter.

In fact, a key element of EBM furnace power supply is the resonant converter. At present, the resonant converter is mainly divided into LC Series Resonant Converter (LC-SRC), LC Parallel Resonant Converter (LC-PRC) and LCC-SPRC. The feature of LC-SRC is that If the switching frequency of power devices deviates from resonance frequency range, the output current of the LC-SRC is almost not affected by the load, so the converter is considered as a current source. However, with the change of the load, the output voltage ripple is to become large, so the LC-SRC is just suitable for the light load. Comparing with the LC-SRC, the output voltage of the LC-PRC changes slightly with the load variation, the converter is presented as a voltage source. When the LC-PRC is operated with the frequency control mode in continuous current mode (CCM), the output voltage can be controlled under no load. But, its efficiency will be decreased under light load condition, so the LC-PRC is more suitable for low voltage and high current applications. By contrast with the aforementioned converters, the LCC-SPRC keeps the advantages of the LC-SRC and LC-PRC, and it is more suitable for different loads, meanwhile, providing a good voltage gain and the feature of circuit. Based on the above converter types, in (4)–(6), the features of the LCC-SPRC in DCM have been analyzed and the equivalent mathematical model of the converter is also proposed. Further, to verify theoretical analysis, the experimental waveforms showing the soft switching operation process is given. In (7)–(9), a trajectory analysis method has been discussed under CCM, in which the operation for system control is implemented. In (10) (11), the theoretical analysis based on the steady state model of the LCC converter is given, which lays the foundation for the experimental research. In (12) (13), the design parameters of the resonant converter for the energy loss have been mentioned, and the switching loss of the IGBTs is also described under multiple control modes. In addition, for the new energy application, a power supply device of LCC resonant converter is presented in (14), and for increasing the efficiency of the power system, lossless buffer capacitors are added in this circuit.

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In this paper, the structure of EBM furnace power supply with parallel at input side and series at output side is employed. Considering the limit of transformer capacity (single maxim power of nanocrystalline core transformer is 150 kW), the input three elements are arranged in parallel and each element power is 150 kW, so total power of the system reaches 450 kW. In order to obtain output dc HV (~30 kV), at the secondary side of transformer, three diode rectifiers are connected in series (single rated output voltage is ~10 kV), which can ensure that total output voltage arrives ~30 kV. In addition, for reducing switching loss of high power devices, LCC-SPRC topology is chosen as the structural form of resonant converter on EBM furnace power supply, which can availably realizes the soft switching of power devices when this circuit operates in frequency control mode with DCM1. The MATLAB is used to simulate and compare the resonance process. At last, experiment and simulation results verify the feasibility of the mentioned solution.

2. Operation Principles

2.1 HV Power Supply Topology for EBM Furnace

From Fig. 1, the proposed system consists of an input thyristor rectifier (dc source), dc filter inductor and capacitance (\(L_d\) and \(C_d\)), three LCC-SPRC and HV load (electron gun). The key elements of the HV power supply are the three resonant dc-dc converters, which offer the important function of the needed isolation and voltage regulation between dc link and the load. For shunting, at the input side, the three LCC-SPRCs are set in parallel, and in order to increase output voltage, at the output side, the three LCC-SPRCs are set in series. A cold cathode electron gun with the rated power of 450 kW is used as the load of HV power supply.

2.2 HV Power Supply Design for EBM Furnace

In recent years, for EBM furnace, the development trend of dc power supply is the directions of HV and high power. In order to increase the voltage and power of the converter, multi module structure is widely proposed and applied. In this paper, the structure of input-parallel and output-series on the converter is adopted as the basic form of EBM power supply. The main advantages of this topology are that the current of switching devices can be obviously reduced at input-side, and the withstand voltage of rectifier devices is also decreased at output-side so that the reliability of the whole power supply is improved. At the same time, due to using this structure, the thermal stress of each power module is uniformly dispersed. As mentioned above, this topology is well suited for applications of input low voltage, output high voltage and high power. During the design of EBM power supply, the key parameters of laboratory set up are summarized in Table 1.

1) thyristor rated voltage

In the three-phase bridge rectifier circuit, the positive and negative maximum voltage of each thyristor is the peak value of input voltage.

\[ U_m = \sqrt{6}U_N \]  

(1)

Where \(U_m\) is the positive and negative maximum voltage of thyristor; \(U_N\) is the phase voltage (220 V). Therefore, the selected rated voltage of thyristor.

\[ U_{VN} = (2 \sim 3)U_m = (2 \sim 3) \times \sqrt{6} \times 220 \]

2) thyristor rated current

On-state average current of thyristor: \(I_{Dmin} = 1040 \text{ A} \)

3) thyristor rated voltage

Filtered voltage has a ripple of 300 Hz before filtering, and the voltage ripple is completely appended on the smooth- des. So, to ensure continuity of current, \(L_d\) can be expressed as:

\[ L_d \geq \frac{3\sqrt{6}U_N}{\pi \alpha I_{Dmin}} \left( 1 - \frac{\pi \sqrt{3}}{6} \right) \sin \alpha \]  

(5)

On-state average current of thyristor:

\[ I_{Dmin} = \frac{3\sqrt{6}}{\pi} U_N \cos \alpha \]  

(6)

Table 1. Parameters of the laboratory setup

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MBI1400VX3-120P-50 IGBT</td>
<td>1200V/1400A</td>
</tr>
<tr>
<td>MTC1000A/1500V SCR</td>
<td>1500V/1000A</td>
</tr>
<tr>
<td>Smoothing reactor (L_d)</td>
<td>1mH/1000A</td>
</tr>
<tr>
<td>STM-1200-1.0-BP11 snubber capacitor</td>
<td>1.0μF/1200V</td>
</tr>
<tr>
<td>2C1150V/20A Output Diodes</td>
<td>150V/20A</td>
</tr>
<tr>
<td>The parallel resonant capacitor (C_d)</td>
<td>RMJ-1200Vdc-1.5pF</td>
</tr>
<tr>
<td>The serial resonant capacitor (C_i)</td>
<td>MKP-LS-1200V-10μF</td>
</tr>
</tbody>
</table>

Where the rated voltage is \(U_{VN} = 1500 \text{ V}\).

Where \(\eta\) is the power efficiency.

Current RMS of thyristor \(I_E = 816 \text{ A}\):

\[ I_E = \sqrt{\frac{2}{3}}I_D = 0.816I_D \]  

(4)

Where \(I_D\) is output dc current 1000 A (input power 500 kW divides output dc voltage 500 V).

On-state average current of thyristor: \(816 \text{ A}/1.57 = 520 \text{ A}\), taking into account the current safety margin, thyristor rated current:

\[ I_F = 1040 \text{ A} \]
Figure 3 shows the main circuit of LCC-SPRC for EBM, where the transformer core is made of nanocrystalline magnetic material, which can significantly decrease the magnetic loss and the transformer size, and it includes the resonant inductor and the leakage inductor of HV transformer at secondary side converted to primary side. The high frequency HV transformer is the key element of EBM power supply, and its performance directly relates to the system efficiency.

Calculation of turns
The turns of the primary winding can be expressed as:

\[ N_p = \frac{U_{in} \cdot 10^3}{K_f \cdot A_e \cdot B_m \cdot f_s} = 2.604 \]  

(7)

Where \( U_{in} \) is the primary voltage of transformer, 400 V; \( K_f \) is wave coefficient; \( A_e \) is effective cross section area of nanocrystalline core, 64 cm²; \( B_m \) is saturation magnetic density, 0.3 T; \( f_s \) is the operation frequency of transformer, 20 kHz. Considering the variation of \( U_{in} \), finally, \( N_p \) is chosen 5.

The turns formula of the secondary winding is expressed as:

\[ N_s = N_i \frac{U_o}{U_{in}} = 5 \times 10000/400 = 125 \]  

(8)

Due to voltage dropping of the capacitor and inductor for resonant converter, \( N_i \) needs to be increased, and final value is 176.

Figures 2(a) and (b) show the external and internal structure of HV transformer, where the transformer core is made of nanocrystalline magnetic material, which can significantly decrease the magnetic loss and the transformer size, and it also has higher permeability and saturation induction.

2.3 LCC-SPRC Operating Principle in DCM1
Figure 3 shows the main circuit of LCC-SPRC for EBM, in which \( S_1 \sim S_4 \) are four IGBTs, \( D_1 \sim D_4 \) are four anti-parallel diodes with IGBTs. Series resonant capacitor \( C_s \), inductor \( L_s \) and parallel resonant capacitor \( C_p \) consist of the LCC-SPR tank. \( L_s \) is the total leakage inductor, which includes the resonant inductor and the leakage inductor of HV transformer at secondary side converted to primary side.

\( C_p \) is the parallel capacitor, which incorporates the resonant capacitance and the reflected capacitance of secondary side converted to primary side in the HV transformer. \( T_r \) is the step-up transformer, and its turns ratio is defined as the 1:\( K \), \( K = 35 \). \( D_{R1} \sim D_{R4} \) four diodes form secondary rectifier. Generally, in a HV dc-dc converter, output-filtering inductors can’t be used on the HV side due to HV drop. Therefore, output filtering capacitance \( C_o \) is used at secondary side.

In general, for LCC resonant converter control method, there are two kinds of the DCM (DCM1 and DCM2). By analyzing principle of the resonant converter, the main difference between the two methods (DCM1 and DCM2) lies in the difference of the voltage \( v_{cp} \) during \( t_1 \sim t_3 \). As shown in Fig. 4, when the resonant inductor current \( i_{ls} \) is reversed, if the voltage \( v_{cp} \) can be changed from \( V_o/K \) to \(-V_o/K \), then the converter will operate under the DCM1, otherwise it is DCM2. In Ref. (5), according to analyzing of operating condition for two kinds of DCM, we can conclude that the forward time of \( i_{ls} \) is to be fixed when the converter operates under the DCM1. However, if the converter runs in the DCM2, the forward time of \( i_{ls} \) will be various. Thus, by comparing with two control methods, DCM1 is considered easier to perform because the turn-on time of IGBTs is constant, and the DCM1 has the better features of frequency modulation and voltage regulation. So in this paper, DCM1 method is adopted as the control strategy of the resonant converter. There are four operation modes in a switching cycle for DCM1.

1) Switching mode 1 [\( t_0 \sim t_1 \)] Prior to \( t_0 \), the current \( i_{ls} = 0 \), the voltage \( v_{cs} \) of \( C_s \) is negative. \( S_1 \) and \( S_4 \) are turned on with zero current switching (ZCS). Then, resonant inductor current \( i_{ls} \) rises from zero, and \( C_s \) and \( C_p \) are charged by \( i_{ls} \). The voltage \( v_{cp} \) is clamped to \( V_o/K \) by output voltage \( V_o \). At this time, \( D_{R2} \) and \( D_{R3} \) of the transformer secondary are turned on naturally. The energy is transferred to the load through this resonant converter.
3) Switching mode 3 At \(t_3\), resonant current \(i_{Ls}\) becomes zero, \(C_p\) begins to discharge and the voltage \(v_{cp}\) gradually reduces, \(D_{R1}\) and \(D_{R4}\) are turned off naturally, the equivalent circuit is shown in Fig. 5.

2) Switching mode 2[\(t_2 \sim t_3]\) At \(t_2\), resonant current \(i_{Ls}\) is gradually becoming negative, the freewheeling diodes \(D_4\) and \(D_2\) are turned on, then S4 and S1 are turned off with zero voltage switching (ZVS). Due to \(C_p\) discharging, the resonant voltage \(v_{cp}\) decreases from \(V_o/K\). The converter energy is transferred from the resonant rank \(L_s\), \(C_s\) and \(C_p\) to dc link. In addition, during this interval, the whole secondary rectifier diodes are turned off, and no energy is transformed the load. Therefore, the load energy is only provided by the output filter capacitor \(C_o\), an equivalent circuit is shown in Fig. 6.

3) Switching mode 3[\(t_3 \sim t_4]\) At \(t_3\), the resonant voltage \(v_{cp}\) reaches \(0\), \(D_{R1}\) and \(D_{R4}\) are turned off naturally, the resonant inductor current \(i_{Ls}\) becomes negative, and flops through \(D_4\), \(T_1\), \(L_s\), \(C_s\) and \(D_1\). During this interval, \(L_s\) and \(C_s\) produce resonant, and the energy is transferred to the load through the transformer \(T_1\) and \(D_4\), \(D_1\). At \(t_3\), the resonant inductor current \(i_{Ls}\) is zero, \(D_{R1}\) and \(D_{R4}\) is turned off, this stage is end. The equivalent circuit is shown in Fig. 7.

4) Switching mode 4[\(t_4 \sim t_5]\) During this stage, all of diodes and IGBTs are turned off, \(i_{Ls}\) becomes zero, the voltages \(v_{cs}\) and \(v_{cp}\) keep constant, the load energy is provided by output filter capacitor \(C_o\). The equivalent circuit is shown in Fig. 8.

At \(t_4\), the \(S_2\) and \(S_3\) conduct with soft switching (ZCS), then LCC-SPRC will start the next cycle. After \(t_5\), in the second half period of \([t_4 - t_5]\), the operation mode is exactly the same as the first half period.

### 2.4 The Analytic Method of State Equations in DCM1

According to the mentioned mode equivalent circuits, the mode equations, which are obtained by the method of analyzing state equation, are as follows:

The state equations of switching mode 1:\(^{(12)}\):

\[
\begin{align*}
L_s \frac{di_{Ls}(t)}{dt} + v_{C_s}(t) + \frac{V_o}{K} &= V_in \\
C_s \frac{dv_{C_s}(t)}{dt} &= i_{Ls}(t) \\
v_{C_p}(t) &= \frac{V_o}{K} \\
\end{align*}
\]

(9)

The initial conditions of Eq. (1) are \(I_{Ls}(t_0) = 0\), \(V_{Cp}(t_0) = V_o/K\). The base value of voltage is \(V_in\), the base value of current is \(V_o/Z_o\). These state equations can be solved by substituting initial conditions into Eq. (9):

\[
\begin{align*}
V_{C_s}(t) &= 1 - V_o/KV_in \\
&- [1 - V_o/KV_in - V_{C_s}(t_0)] \cos \omega_o(t - t_0) \\
V_{C_p}(t) &= V_o/KV_in \\
i_{Ls}(t) &= [1 - V_o/KV_in - V_{C_s}(t_0)] \sin \omega_o(t - t_0) \\
\end{align*}
\]

(10)

Where \(\omega_o = 1/\sqrt{L_s/C_s}\), which is the resonance angular frequency of \(L_s\) and \(C_s\), \(Z_o = \sqrt{L_s/C_s}\), where \(Z_o\) is the characteristic impedance of \(L_s\) and \(C_s\).

The state equations of switching mode 2:

\[
\begin{align*}
L_s \frac{di_{Ls}(t)}{dt} + V_{C_s}(t) + V_{C_p}(t) &= V_in \\
C_s \frac{dv_{C_s}(t)}{dt} &= i_{Ls}(t) \\
C_p \frac{dv_{C_p}(t)}{dt} &= i_{Ls}(t) \\
\end{align*}
\]

(11)

The initial conditions of Eq. (11) are \(I_{Ls}(t_1) = 0\), \(V_{Cp}(t_1) = V_o/K\), and state equations are solved by substituting initial conditions into Eq. (11), finally obtaining new Eq. (12):
\[
\begin{align*}
\left\{ \begin{array}{l}
i_{Ls}(t) = \frac{1}{\sqrt{1 + \sigma}} [1 - V_o/KV_m - V_C(t_1)] \sin \omega_c (t - t_1) \\
V_C(t) = \frac{1}{\sqrt{1 + \sigma}} [1 - V_o/KV_m - V_C(t_1)] \\
V_C(t) = \frac{\sigma}{\sqrt{1 + \sigma}} [1 - V_o/KV_m - V_C(t_1)] \\
V_C(t) = \frac{\sigma}{\sqrt{1 + \sigma}} [1 - V_o/KV_m - V_C(t_1)]
\end{array} \right. \tag{12}
\]

In Eq. (12), \( \omega_c = 1/\sqrt{L_s C_p/(C_s + C_p)} \), where \( \omega_c \) is the resonance angular frequency for \( L_s, C_s \) and \( C_p \). \( \sigma = \frac{C_p}{C_s} \) is the ratio factor for \( C_s \) and \( C_p \).

The state equations of switching mode 3:

\[
\begin{align*}
L_s \frac{di_{Ls}(t)}{dt} + v_{C_s}(t) - \frac{V_o}{K} &= V_m \\
C_s \frac{dv_{C_s}(t)}{dt} &= i_{I_s}(t) \tag{13} \\
V_{Cp}(t) &= -\frac{V_o}{K}
\end{align*}
\]

The initial condition is \( V_{Cp}(t_2) = -\frac{V_o}{K} \) for Eq. (13). The state equations are solved by substituting initial condition into Eq. (13), then new state equations are obtained:

\[
\begin{align*}
\left\{ \begin{array}{l}
I_{Ls}(t) = [1 + V_o/KV_m - V_{Cp}(t_2)] \sin \omega_c (t - t_2) + I_{Ls}(t_2) \cos \omega_c (t - t_2) \\
V_{Cp}(t) = I_{Ls}(t) \cos \omega_c (t - t_2) - [1 + V_o/KV_m] \\
- V_{Cp}(t_2) \cos \omega_c (t - t_2) + 1 + V_o/KV_m \\
V_{Cp}(t) = -V_o/KV_m
\end{array} \right. \tag{14}
\]

where \( \omega_c \) is the resonant angle frequency of \( L_s \) and \( C_s \). Combining Eqs. (10), (12) and (14), the solved time can be expressed as:

\[
\begin{align*}
t_{01} &= \frac{\pi}{\omega_o} \tag{15} \\
t_{12} &= \cos^{-1} \frac{1 + \sigma M^2 - 2M - 2\sigma M}{\sigma (1 + \sigma) M^2} / \omega_o \tag{16} \\
t_{23} &= \frac{1 - tg^{-1} \eta / \omega_o, \ tg^{-1} \eta \leq 0}{(\pi - tg^{-1} \eta) / \omega_o, \tg^{-1} \eta > 0} \tag{17}
\end{align*}
\]

Where \( M \) is the base voltage gain, \( M = V_o/KV_m \).
\( \eta \) is the angle radians of the system in the operation period of \( t_1 \rightarrow t_2 \).

\[
\eta = \frac{-2 \sqrt{M^2 + \sigma M - \sigma M^2}}{1 + M - \sqrt{M^2 + 2M + 2\sigma M - 2\sigma M}} \tag{18}
\]

At the same time, the Eq. (19) based on voltage gain is derived:

\[
M = \frac{1}{2\sqrt{\pi} Q} \left[ \pi \sigma Q + 2f_sN + 4\sigma f_sN \right]
\]

\[
- \sqrt{\pi^2 \sigma^2 Q^2 + 4\pi \sigma f_sNQ + 8\pi \sigma^2 f_sNQ + 4f_sN^2}
\]

\[
+ 16\pi f_sN + 16\pi^2 f_sN^2 \tag{19}
\]

Where \( Q \) is the quality factor of the resonant tank \( Q = \frac{2\pi f_m}{\omega_m} \), \( f_m \) is the P.U. value of switching frequency.

### 2.5 The Determination of LCC Resonant Tank Parameters in DCM1

According to Ref. (15), if the converter operates at DCM1 condition, the following Eqs. (12) and (13) should be satisfied:

\[
V_{o} < \frac{\sigma}{\sigma + 1} KV_m \tag{20}
\]

Assuming:

\[
V_f = \sigma KV_m/(1 + \sigma) \tag{21}
\]

Where ordering \( V_f = \gamma V_o \), it is then substituted \( V_f = \gamma V_o \) into the Eq. (21), as follows:

\[
\sigma = \gamma V_o/(KV_m - \gamma V_o) \tag{22}
\]

In Ref. (15), the equations of \( C_s \) and \( C_p \) can be given for the resonant rank, as follows:

\[
C_s = \frac{M(M-1)K^2}{2R_o f_s (2M - 4\sigma + 4\sigma M)} \tag{23}
\]

\[
C_p = \frac{C_s}{\sigma} \tag{24}
\]

In addition, to ensure that the system operates in DCM1, the Eqs. (15) and (16) also must satisfy the following condition:

\[
t_{01} + t_{12} + t_{23} \leq \frac{1}{2f_s} \tag{25}
\]

According to the above equations, under rated load condition, assuming \( V_o = 400 \text{ V}, V_f = 10 \text{ kV} \) and rated switching frequency = 20kHz. The file compiled with MATLAB is adopted to solve these equations, and obtains the system parameters, these parameters are \( C_s = 14 \mu \text{F}, L_s = 1.8 \mu \text{H}, C_p = 4.6 \mu \text{F} \) and \( K = 35 \), respectively.

### 3. Simulation and Experiment

According to Eq. (19), the voltage gain \( M \) only is determined by the load resistance and switching frequency if the converter parameters are fixed. Thus, in this paper, the MathCAD is used to obtain relationship curves between output voltage and switching frequency for different loads, as shown in Fig. 9.

By analyzing these waveforms, the change regulation between output voltage and switching frequency can be described. Obviously, in Fig. 9, under operating condition

![Fig. 9. Relationship curve between output voltage and switching frequency for different loads](image-url)
based on DCM1, there is nearly a linear relationship between the output voltage and the frequency when switching frequency is lower. With the gradual increase of the frequency, the output voltage is closer to the rated value, which presents a nonlinear feature.

In order to verify the accuracy of the calculation parameters, the resonant converter system is simulated and analyzed, and the simulation waveforms are shown as follows:

In Fig. 10, the simulated waveforms show that the converter has achieved ZCS of IGBTs at different loads.

In order to verify the operation principle of the resonant converter, the experimental devices used in the EBM furnace are built in the laboratory as shown in Fig. 11. It consists of three identical converter elements from Fig. 1. There are two controllers in this power supply, the one is the thyristor rectifier controller, which mainly achieves the control for dc link voltage, and the other is the inverter controller, which is developed to realize soft switching through adjusting system frequency and achieves the control of output high voltage as shown in Fig. 11(a).

Some other units, such as resonant capacitor $C_s$, IGBTs, thyristors and filter capacitor $C_d$ etc., are arranged on the back of power converter as shown in Fig. 11(b). In order to validate the mentioned principle, in the laboratory, a actual hardware prototype is designed to perform the HV experiment at light load as shown in Fig. 11(c).

In laboratory power capacity, the load experiment is implemented in the case of light load. According to the calculated parameters $C_s = 14 \mu F$, $L_s = 1.8 \mu H$, $C_p = 4.6 \mu F$ and $K = 35$, the LCC-SPRC experiment is finished. In Fig. 12, the driving pulses of resonant converter are used to be active low. The typical experimental waveforms are shown in Figs. 12(a)–(d). In Fig. 12(a), the IGBTs full-bridge output voltage $v_{AB}$ and the driving pulses are shown. Importantly, when the driving pulse is on or off, due to the existence of the resonant tank capacitor and inductor, the output voltage $v_{AB}$ occurs an oscillation, in a certain way, and can then realize ZVS operation for IGBTs. Figure 12(b) shows the transformer primary voltage $v_{cp}$, when $v_{cp}$ can arrive at $V_o/K$, the system will run at DCM1. Figure 12(c) shows the series capacitor voltage $v_{cs}$, during the driving pulse on or off, $v_{cs}$ basically keeps constant. When the driving pulse is on or off, Fig. 12(d) shows waveforms for the output voltage $v_{AB}$ and the resonant current $i_{Ls}$. As shown Fig. 12(d), IGBTs are turned off with ZVS and turned on with ZCS/ZVS in the test.

Figure 13 shows output waveforms at silicon stack rectifier side. As the provided load is pure resistive light load, the rise time of the high voltage is very short and the fall time is longer.

4. Conclusion

In this paper, a HV furnace power supply for EBM is discussed, and a new topology of multi-cell converters, transformers and rectifiers is proposed, which includes the three cells in parallel at the input side and in series at the output side. In order to reduce magnetic loss and the transformer size, the transformer core is made of nanocrystalline
magnetic material within each cell. At the same time, LCC-SPRC technology is adopted as the operation mode of the dc-dc converter. LCC-SPRC by using control frequency method can operate under DCM1 condition, and can realize the soft switching. An experimental laboratory prototype is designed and tested. Simulations based on Matlab are carried out for EBM furnace power supply, and the simulation waveforms of soft switching at different loads are given. Simulation results are compared with experimental waveforms, and the results show that the simulation and experimental waveforms are basically consistent, which verifies the feasibility of the design scheme.

References

(15) B. Xia: “Research on LCC Resonant Converter for High Power and High Output Voltage Applications”[D], Nanjing University of Aeronautics and Astronautics (2008)
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