Study of High-Voltage Power Supply for Electronic Beam Welder Based on Soft-switching Technology

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Abstract. Due to the lower frequency of traditional high-voltage power supply for Electronic Beam Welder (EBW) and larger volume and weight of transformer, the working frequency of the inverter circuit is improved to reduce the volume and weight of transformer. The soft switch of power tube is implemented using the LC resonant converter. Soft switch technology is also utilized to avoid the harmonic and to reduce the switching loss when the power tube opens and shuts off under high speed. The working principle of LC resonant converter is also analyzed. The fault that the voltage is hard to change by FM in lighter load is avoided using BUCK circuit to adjust busbar voltages. The rationality of design is demonstrated by debugging the high-voltage power supply for EBW, and analyzing the test parameters.

1. Introduction
Three-level electron gun for electronic beam welder (EBW) accelerates electron emitted by heating cathode, by means of high voltage electric fields produced by high-voltage power supply. The size of beam and the bunching of focusing power are adjusted through the electric fields generated by bias power supply. Eventually electron beams form, then go to bombard workpiece, so as to realize the welding of workpiece. The accelerating voltage for electron beam is provided by high-voltage power supply for EBW. The stand or fall of its performance directly determines the performance of electron beam [1-2]. Therefore, high-voltage power supply for EBW must have characteristics of a high stability and low ripple coefficient. At present, domestic high-voltage power supply for EBW uses medium and high-frequency power supply. The control strategy uses the pulse width modulation (PWM) technology, phase shift voltage modulation or the pulse frequency modulation (PFM). The volume and weight of high-voltage transformer of medium-frequency and high-voltage power supply are larger. While the volume and weight of high-voltage transformer of medium-frequency and high-voltage power supply are larger. While the volume and weight of high-voltage power supply are greatly decreased, due to the increase of frequency. So the high-frequency and high-voltage transformer is mainly studied now. High-frequency and high-voltage power supply, due to its high frequency, and if control strategy uses PWM or phase shift control, which are both control the duty ratio width, will produce higher harmonic. That will have a big impact on the circuit. PFM controls voltage by adjusting frequency. It can reduce the higher harmonic when power tube opens and shuts off. But the load of high-voltage power supply for EBW is a variable, it is not easy to adjust the output voltage when the frequency modulation. Moreover, frequency modulation range is relatively large in the lighter load, which is difficult to meet the practical needs. This paper adopts the way of LC series resonance, and adjusts busbar voltage when
the voltage modulation. In this way, it cannot only achieve soft switch of power tube, and reduce the harmonic, but also can adjust the size of output voltage\textsuperscript{[3-4]}.

2. The selection of control mode
This paper adopts LC series resonance. Cascading a capacitance $C$, in the transformer primary, has the effect of blocking, and prevents the bias of high-frequency transformer. When it adopts the way of adjusting the frequency, LC can be regarded as a voltage divider to divide the voltage in transformer primary, so the voltage gain is always less than one\textsuperscript{[5]}.

In the working process of the EBW, we will generally turn off the filament or transfer the bias power to the maximum when we adjust the position of weld workpiece, so that the welding torch will not let the electron beam out. So the high voltage can work under no-load condition for a long time. For high frequency transformer, in that case, high voltage will be induced in the vice side of transformer. If we adopt the way of FM at this time: First, it is very difficult to adjust the size of the output voltage because the load is too light; second, even if we can adjust the voltage, however, the frequency will change a lot.

Therefore, this paper adopts the fixed frequency and duty ratio to regulate busbar voltage. It can reduce busbar voltage, avoid high output voltage as well as be convenient for the regulation of output voltage when high-voltage power supply for EBW under no-load condition. Even though the changing of load, busbar output voltage can be conveniently adjusted to 60 kV. In this way, the soft switch of power tube can be realized by using LC resonance, and the effect of load on the LC resonance can be weakened\textsuperscript{[6-8]}. It can both satisfy the soft switch of power tube, and adjust the output voltage smoothly, making the output voltage meet the performance requirements of high-voltage power supply for EBW.

3. The main circuit system structure
Main circuit is made up of electromagnetic compatibility(EMC) filter, the uncontrollable whole bridge rectifier circuit, filter circuit, BUCK circuit, bridge inverter circuit, absorption circuit, LC resonant converter, and high-frequency and high-voltage transformer. Its working process is as follows: 380V three-phase AC voltage's harmonic is processed through the EMC filter circuit; Turning it into a stable DC voltage through the rectifier filter circuit; Regulating busbar voltages through the BUCK circuit;Making DC voltage convert to high-frequency AC voltage by whole bridge inverter circuit; Dividing voltage through the LC resonance circuit; Boosting voltage through the high-frequency and high-voltage transformer. The output voltage can be DC 60 KV and a maximum current of 100 mA after rectifier and filter. The voltage sampling uses the way of precise resistance outputting voltage in the high-voltage side and taking in low-voltage side. Then transmit voltage to the control system through the sensor to isolate. When the current sampling, using the way of sampling by adding sensors in high-voltage side. As shown in Fig. 1.

![Fig.1Circuit diagram](image)

4. The working principle of LC resonant converter
Fig. 2 is a simplified schematic diagram of LC resonant converter whole bridge circuit. In Fig. 2, $L_r$ is the resonant inductance, $C_r$ is the resonant capacitance. Voltage outputs from the inverter and finally adds to the transformer primary after the voltage division of $L_r$ and $C_r$. The output voltage will change with main vibration frequency when main vibration frequency $f$ is adjusted. The resonance frequency
\[ f_r = \frac{1}{2\pi\sqrt{Lr \cdot Cr}}. \]

In order to make the switch tube realize zero-voltage switch, current should lag behind voltage when switch tube is at work. It must make the resonant loop always work in the emotional state\(^9\)\(^-\)\(^10\).

Fig. 2 LC whole bridge circuit

As shown in Fig. 3, in the full bridge circuit, switch off power tubes T1, T4, and conduct T2, T3; In the same way, switch off T2, T3 when T1, T4 is conducted. It can avoid power tubes, in a bridge arm, conduct at the same time. Otherwise, it will damage power tubes. Moreover, two power tubes in a bridge arm should have enough dead zone time.

Fig. 3 Circuit waveform figure

The working process of LC resonant circuit is as follows.

(1) During the period of \(t_0\), \(t_1\) (as shown in Fig. 4), due to the reverse flow of resonance current, it forms current loop through diodes D1 and D4. The conduction of diodes D1 and D4 will clamp the voltage at the ends of power tubes T1, T4 at 0 V. At this time, the opening of power tubes T1, T4 can realize zero-voltage opening. Thus to realize the soft switch of power tubes T1, T4.

Fig. 4 t0-t1
(2) During the period of t1, t2 (as shown in Fig. 5), due to the conduction of power tubes T1, T4, current gradually circulates in the positive direction. When the time goes to t2, forward direction current is the largest. Since the positive circulation of current, voltages on capacitors C1, C4 are zero. When the time goes to t2, turn off T1, T4. Power tubes T1, T4 can achieve soft shut off because the voltage of capacitors C1, C4 cannot mutate.

(3) During the period of t2, t3 (as shown in Fig. 6), due to the harmonic current is positive, and power tubes T1, T4 shut off, the current loop forms through the circulation of D2 and D3. The conduction of diodes D2 and D3 will clamp the voltage s at the ends of T2, T3 to 0 V. The opening of T2, T3 can realize the zero-voltage opening of power tubes T2 and T3.

(4) At t5, reverse current is at its peak. At this time, power tubes T2, T3 can realize soft shut off because the voltages on capacitors C2 and C3 cannot mutate. After t5, power tubes, according to the analysis above, execute the work of next cycle, the whole process is the same as t0-t5.

5. Control circuit

This paper uses the characteristic of high-speed data processing of DSP. The control system adopts the controlling core chip based on TMS320F2812 DSP chip as the core. DSP chip is used signal sampling and PI adjustment. Finally it produces PWM signals sent to drive circuit.

When sampling the data, DSP F2812 has a module of analog-digital converter(ADC), which has a 12-place resolution ratio. The module is able to work with sixteen-channel, and can also be split into 2 respectively independent eight-channel module. Two eight-channel ADC conversion channels in F2812 correspond respectively to two sequence generators SEQ1 and SEQ2. They can both work alone and cascade with the ADC does. In DSP F2812, there is a SCI module, which can complete data transmission with PC. It can control the high-voltage power supply for EBW through the touch screen[11-12].

TMS320F2812 has two event managers, EVA and EVB. This paper uses the EVA for the output of PWM waveform. To control duplex driving waveform of a bridge arm of a inverter whole bridge by
using PWM1, PWM2 in EVA. To control another bridge arm by using PWM3, PWM4 and control the IGBT driving signal of BUCK circuit by using PWM5. To sample the high-voltage output voltage, and to form closed loop controlled circuit by PI adjustment to ensure the stability of circuit.

6. Testing results

This paper has designed a LC resonance high-voltage power supply for EBW by adjusting busbar voltage. The output of high-voltage power supply is 60 kV, the maximum current of load is 100 mA. High-voltage transformer adopts the way of two ignition coils cascading to boost voltage, and the material uses ferrite. In the experimental debugging, Lr resonant inductance, Cr resonant capacitance, the switch tube frequency of whole bridge inverter and the duty ratio and dead zone of the switch tube of whole bridge inverter should be determined. The load of high-voltage power supply is variable. Therefore, the inverter frequency, duty ratio and LC resonance parameters should be determined when it is the maximum of the output power of high-voltage power supply. It should be determined when the output of high voltage is 60 kV and 100 mA.

The experimental steps are as follows:

1. Determine the parameters of BUCK circuit. Because the BUCK circuit adjusts busbar voltage, and it has little influence on resonant parameter. It can take the frequency 20 KHz, and the duty ratio can vary from 0 to 0.9.

2. Determine the inverter parameters and resonant parameters. Assume the main vibration frequency $f=20$ kHz, resonant capacitance $Cr=2\mu F$, by $f > fr$, $\frac{1}{2\pi \sqrt{Lr * Cr}}$, we can calculate $Lr>20\mu H$. It can take $Lr=30\mu H$.

3. Adjustment of parameters. To set the inverter duty ratio 30%, and to boost the busbar voltage through the BUCK circuit. When the high voltage output is 30 kV, adjust the filament current to 15A, and make sure the bias voltage can ensure no beam outputs. Make the high voltage stabilize to 60 kV, and adjust bias power supply to ensure the maximum output beam is 100 mA. At this time, observe whether the opening status of the IGBT has realized soft switch or not.

In Fig. 7, line A is the driving waveform of IGBT, line B is the harmonic current waveform. It can be seen from the figure, when the driving waveform of IGBT opens, the harmonic current is 0, realizing soft switch to some degree. But as a result of IGBT’s opening and rising time, the soft opening, at this time, cannot be implemented very well. It is best that the harmonic current is less than 0 when the IGBT driving waveform opens. Now go to adjust parameters.

Fig.7 Results of experiment

(4) Correct the parameter. First of all, fine-tune the resonance parameters, and increase the resonant inductance to 40 uH. As shown in Fig. 8, it can be seen from the diagram, harmonic current is less than 0 when the driving waveform opens, which can realize the soft opening of IGBT very well. Because of the larger resonant current, adjust slightly the main vibration frequency to 28 kHz. As can be seen from the Fig. 9, it can achieve soft switch very well, and the harmonic current is reduced, finally the selected frequency is 28 kHz.
7. Conclusion
This paper designed a high-voltage power supply for EBW using LC resonance. LC resonant converter has the characteristic of realizing power tube’s soft switch. In high frequency, it can be used to reduce the harmonic and the loss and optimize the current waveform. Using the BUCK circuit to adjust the size of the busbar voltage to compensate for the occasion that adjusting the frequency cannot change voltage when the LC resonant converter is under the light load. Debugging the high-frequency and high-voltage power supply for EBW through the analysis, and meeting the actual needs by adjusting data. With the way of using LC resonance converter to adjust busbar voltage, we can make the high voltage output stabilize at 60 kV when the load changes. This paper adopts this method to realize the soft switch of power tube, which can guarantee the output stability of high voltage power supply’s voltage.

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