

Analysis on Feedback Loop Design of Power Supply in SEAM and its Processing Characteristics

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Abstract: To find out the best match between precision of the workpiece surface and efficiency in short electric arc machining (SEAM), the article analyzes the gain characteristics of the power supply system in SEAM, and the simulation model of the power supply based on Matlab is established to verify the feasibility and stability of the power supply feedback loop in SEAM. Through short arc electric cutting machining experiment, we analyze the electrical characteristics of the power supply in SEAM, and work to figure out the relationship between precision of workpiece surface and efficiency in SEAM, which provides important technical support for the short electric arc machining mechanism research. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Short electric arc machining (SEAM), Gain characteristic, Matlab simulation, Characteristic analysis.

1. Introduction

The successful application of SEAM technology can solve technology problem which is the long-standing machinery manufacturing hard facing materials processing of the widespread and it can effectively machine high hardness, high strength and difficult processing conductive materials [1, 2].

In the process of SEAM, each short electric arc discharge process is divided into four parts: establishing a plasma channel; medium thermal decomposition, melting and gasification's thermal expansion of electrode materials; throwing the electrode materials; the deionization of between electrode dielectric. And it is very important for the quality of SEAM to establish the discharge passage. The formation of plasma channel of SEAM is: when the two electrodes get near, the gas will discharge because of the voltage in the high points of the two electrodes, namely, the closest point. After the

formation of the discharge channel, the voltage drops rapidly [3].

In the process of SEAM, to make it more effectively and easily be established for arc discharge channel, and the electrical characteristics of the power supply in SEAM meet the requirement of experiment, it is necessary to design the feedback loop of power supply which can meet the needs of short electric arc machining experiments.

Short electric arc machining precision and machining efficiency are the unity of opposites, and ultimately depends on the short electric arc machining machine tool pulse power supply. Through the short arc electric cutting machining experiment, we can work out with the best match between precision of the workpiece surface and efficiency in SEAM and optimize the technology of SEAM, which can provide important technical data for short electric arc machining mechanism research.

2. Feedback Loop Design of Power Supply in SEAM

2.1. Working Principle of the Feedback Loop

Fig. 1 is the overall structure of the power supply. By the picture, the power supply includes pulse voltage generating circuit part and digital control circuit section. The former is mainly composed of input circuit, primary modulation circuit and the secondary modulation circuit; the latter includes ARM digital controller acquisition circuit, driver circuit, voltage and current sampling circuit and voltage regulator control circuit, etc.

Its working workflow is: inputting 380 V three-phase alternating current (AC), passing full bridge rectifier circuit and filter circuit, the voltage is seen as the input DC bus voltage of the DC/DC converter, and inverter circuit transform DC voltage into AC square wave voltage, after the high frequency power step-down transformer, rectifier, LC filter circuit for low voltage direct current (DC), finally, through chopping circuit, provide continuous adjustable duty ratio, frequency of working voltage for SEAM. ARM controller provide the control which include short electric arc testing and control, power supply output voltage, current and other parameters of the short electric arc power supply [4].

Fig. 2 (a) is the power supply's principle diagram of the feedback loop in SEAM.

Its working principle is: the small, slow changes of V_o 's voltage caused by the change of power input or load is detected by resistance partial pressure sampling network which is made up of R1, R2. And the voltage of V_o are inputted to the error amplifier inverting side and are compared with the voltage of V_{ref} . EA output voltage V_{ea} relatively slow changes along with V_o 's voltage, and is inputted to A point of PWM modulator. After the input DC voltage V_{ea} and the triangle wave voltage of V_t which is about 0~3V V_t is compared by PWM modulator, get rectangular pulse at the output end (PWM pulse).

As shown Fig. 2(b), the t_{on} width of the PWM is the time, ranged from the begin moment of triangular wave t_0 to the cross-point between V_t and V_{ea} . Compared inverting terminal voltage with no inverting terminal sample voltage, and its output signal with the triangular wave which oscillator generates, the junction points decides the size of phase angle. Thereby it can change the duty cycle of the output pulse, ultimately keep the output voltage constant [5].

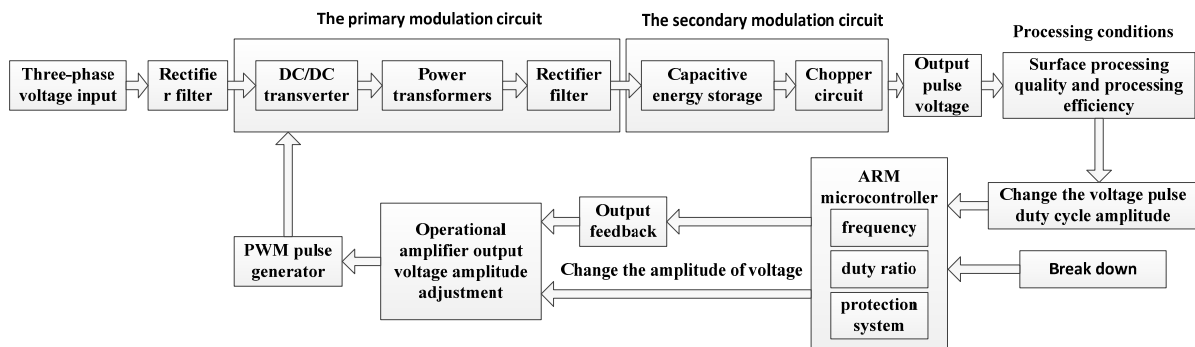


Fig. 1. Power supply system structure diagram.

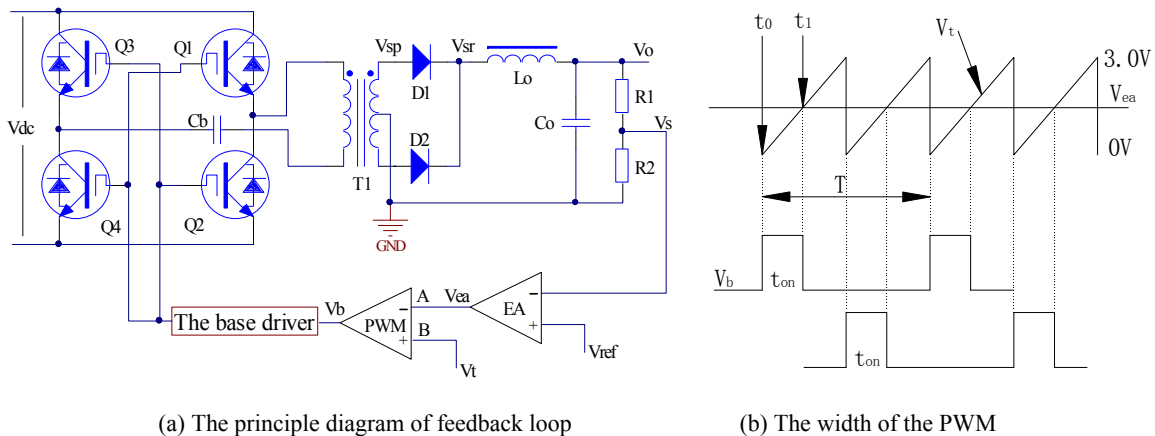


Fig. 2. The power supply closed-loop feedback loop in SEAM.

2.2. Design of the Feedback Loop

The PID control system should be designed based on the analysis of the whole system which included amplitude-frequency characteristic and phase-frequency characteristic. First, select transfer function compensation network structure through the type of transfer function [6]. And according to the frequency characteristic curve, set zero and pole of compensation network. Finally, based on expect through frequency of the system frequency characteristic curve of the open loop transfer function, adjusting gain compensation network, we can get feedback control of the transfer function of compensating network [7, 8].

Main parameters of the power supply in SEAM has the following several aspects: $V_0 = 5\sim 36$ V adjustable voltage; I_0 (nom) = 2000 A; the primary modulation circuit's switch frequency is 20 kHz.

2.2.1. Output LC Filter Gain Characteristic

Most filter capacitance have inner equivalent series resistance – R_{ESR} , and the equivalent series resistance must be taken into consideration during the design of error amplifier. The output LC filter gain characteristic can be equivalent to Fig. 3. When the beginning frequency is higher than F_{CNR} , the impedance at C_0 is greater than R_{ESR} 's. This time, and the real impedance is only impedance of C_0 . In this range, the slope is -2 . At higher frequencies, the impedance of the C_0 is far less than R_{ESR} , and the effective impedance which range V_0 to GND is R_{ESR} . In this frequency range, therefore, the output LC filter gain characteristic can be regarded as LR circuit rather than the LC circuit. Meanwhile, the impedance of L_0 increases quickly at a rate of about 20 dB/Dec and R_{ESR} remains the same, so gain slope down to -1 [9].

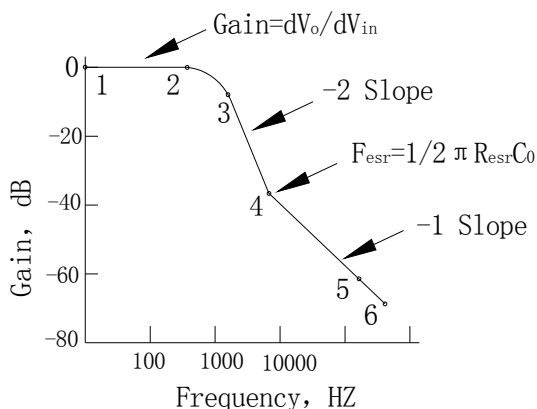


Fig. 3. LC filter gain characteristic.

2.2.2. Pulse Width Modulator Gain

As shown Fig. 2 (b), when V_{ea} equal to the lowest point of the triangle wave, the conduction time of pulse or pulse width at V_{ea} is zero. At this time the average voltage at V_{ea} is zero, because $V_{ea} = (V_{sp}-1) (t_{on}/T)$; in the formula, V_{sp} is the peak voltage of secondary coil. When V_{ea} is equal to the highest point of the triangle wave, $t_{on}/T = 0.5$, $V_{ea} = 0.5(V_{sp}-1)$. Therefore, the modulator gain between V_{ea} and V_{sr} is:

$$G_{pwm} = \frac{0.5(V_{sp}-1)}{3} = \frac{0.5(37-1)}{3} = 15.6 \text{ dB}, \quad (1)$$

The gain has nothing to do with the frequency.

2.2.3. Sample Network Gain

As a result of the existence of sampling network R_1 and R_2 , there will be gain attenuation G_s (negative gain). The power supply uses UC3879 PWM chip their inverting side voltage in the error amplifier is 2.5 V. When the sample voltage is +36 V output voltage, namely, $R_1=14.4R_2$, the gain of between V_s and V_0 is 23.2 dB.

2.2.4. The Design the Transfer Function of Error Amplifier and its Amplitude Frequency Characteristic Curve

Overall gain $G_t = (\text{LC filter gain} + \text{PWM modulator gain} + \text{output voltage sampling resistance gain})$. G_t determines the error amplifier gain. At through frequency, error amplifier gain is G_t 's opposite number and it is straight line near F_{CO} . By G_t this curve, and according to the criteria for the robust stability of the system, we can design the error amplifier gain and phase frequency characteristics.

Usually, we choose F_{CO} for $1/4\sim 1/5$ of switch frequency. The primary modulation circuit's switch frequency is 20 kHz, so $F_{CO} = 4$ kHz.

In order to ensure that the system open loop through frequency F_{CO} is zero, in the Bode diagram, should make the error amplifier gain at F_{CO} equal G_t gain's opposite number, so it can meet the system's through frequency is zero. In addition, the slope of the gain curve G_t at F_{CO} is -1, in order to guarantee the slope of the system through the frequency to be -1, so the error amplifier at F_{CO} slope

should be 0, namely, a horizontal line. Therefore, we adopt single zero-single pole compensating network [9], as shown in Fig. 4.

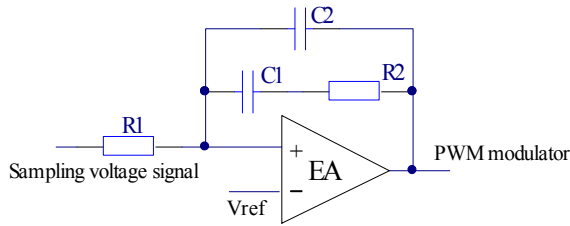


Fig. 4. Single zero-single pole type error amplifier.

First calculate output LC filter parameters and its corner frequency. We choose $L_o = 98 \mu\text{H}$, $C_o = 4000 \mu\text{F}$. Therefore, LC filter's corner frequency as follows:

$$F_o = \frac{1}{2\pi\sqrt{L_o C_o}} = \frac{1}{2\pi\sqrt{98 \times 10^{-6} \times 4000 \times 10^{-6}}} = 258\text{Hz}, \quad (2)$$

The ESR zero frequency as follows:

$$F_{\text{ESR}} = \frac{1}{2\pi R_{\text{ESR}} C_o} = \frac{1}{2\pi \times 65 \times 10^{-6}} = 2500\text{Hz}, \quad (3)$$

Through frequency selected as 1/5 of the switching frequency, namely 4 kHz.

Assume that the phase margin is 45° , according to Table 1, $F_{\text{CO}}/F_{\text{ESR}} = 1.6$, the zero point through frequency at F_{ESR} makes phase lag of 122° at F_{CO} .

Table 1. F_{ESR} in zero phase lag caused by the F_{CO} .

$F_{\text{CO}}/F_{\text{ESR}}$	Phase lag	$F_{\text{CO}}/F_{\text{ESR}}$	Phase lag
0.25	166°	2.5	112°
0.50	153°	3	108°
0.75	143°	4	104°
1.0	135°	5	101°
1.2	130°	6	99.5°
1.4	126°	7	98.1°
1.6	122°	8	97.1°
1.8	119°	9	96.3°
2.0	116°	10	95.7°

So only permit error amplifier with $360^\circ - 45^\circ - 122^\circ = 193^\circ$ phase lag. According to Table 2, we can see that if we choose $K = 10$, error amplifier has 191° phase lag and enough to meet the requirements. When $F_{\text{CO}} = 4 \text{ kHz}$ and $K = 10$, zero frequency F_z is 400 Hz, and the pole frequency F_p of 40 kHz. Error amplifier gain curve can be

obtained. According to LC filter, sampling points and compressive resistance, modulator and error amplifier gain, uses graphic method to calculate the total gain of the open-loop system curve, as shown in Fig. 5.

Table 2. Different $K (= F_{\text{CO}} / F_z = F_p / F_{\text{CO}})$ value corresponding to the phase lag error amplifier.

K	Phase lag
3	164°
4	146°
5	136°
6	128°
10	191°

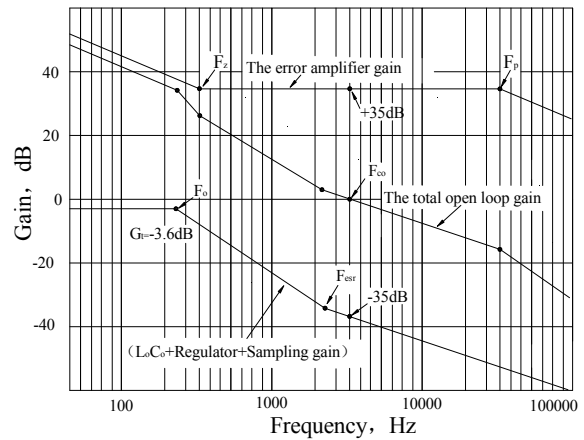


Fig. 5. The power supply system overall gain.

2.2.5. Calculate the Structure of the Transfer Function of Error Amplifier and the Zero and Pole

$$G(s) = \frac{dV_o}{dV_{\text{in}}} = \frac{(1+sR_2C_1)}{sR_1(C_1+C_2)(1+sR_2C_2)}, \quad (4)$$

Zero frequency as follows:

$$F_{z1} = 1/2\pi R_2 C_1, \quad (5)$$

Frequency of the pole is:

$$F_{p1} = C_1 + C_2 / 2\pi R_2 (C_1 C_2) \approx 1/2\pi R_2 C_2, \quad (6)$$

2.2.6. Error Amplifier Element Parameter Calculation

If $R_1 = 1 \text{ k}\Omega$, the gain at through the frequency equal to 35 dB, and algebraic gain is 56, so the $R_2 = 56 \text{ k}\Omega$. According to the frequency of the two zero and pole can be calculated:

$$C_1 = 1/2\pi R_2 F_z = 1/2\pi \times 9100 \times 40 = 7.1 \times 10^{-9}, \quad (7)$$

$$C2 = 1/2\pi R2Fp = 1/2\pi \times 9100 \times 1000 = 7.1 \times 10^{-12}, \quad (8)$$

Therefore, the transfer function of error amplifier is:

$$G_v(s) = \frac{397.6 + 10^6}{13.36 \times 10^{-6} s^2 + 7.17s}, \quad (9)$$

The transfer function of $G_{LC} + G_{PWM} + G_S$:

$$G_{LC} + G_{PWM} + G_S = \frac{0.66}{1.14 \times 10^{-9} s^2 + 3.2 \times 10^{-3} s + 1}, \quad (10)$$

So the system total open-loop transfer function $G_0(s)$ as follows:

$$G_0(s) = \frac{262s + 66 \times 10^4}{1.52 \times 10^{-15} s^4 + 51 \times 10^{-9} s^3 + 23 \times 10^{-3} s^2 + 7.71s}, \quad (11)$$

Detecting voltage loop PI regulator features with Matlab software, as shown in Fig. 6.

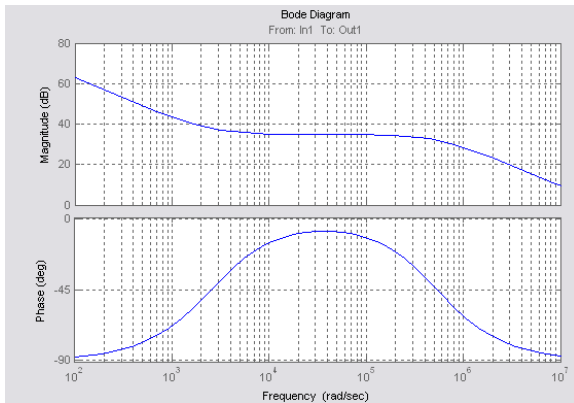


Fig. 6. PI regulator Bode diagram.

The simulation system of the open loop transfer function after correction, as shown in Fig. 7.

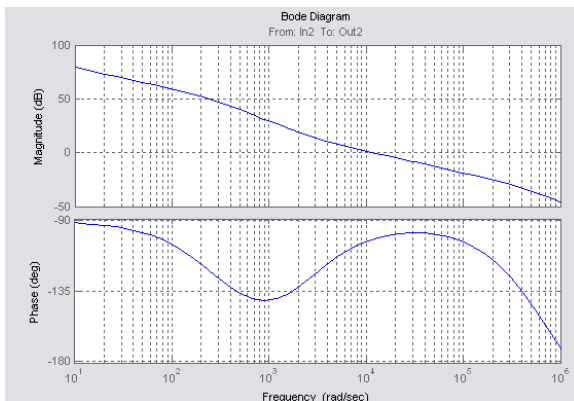


Fig. 7. PI system Bode figure of open loop transfer function

As can be seen from the Fig. 7 that the power supply system gain margin and phase margin can satisfy the requirements of system stability.

3. The Experimental Simulation Based on Matlab Software

Matlab software has a powerful scientific computing functions, and it has become a basic analysis tool in dynamic system simulation [10, 11]. In this paper, we established the simulation of experiment platform power supply by using Matlab's basic unit in Simulink, SimulinkExtra and SimPowerSystems module library etc.

3.1. The Establishment of Simulation Model

3.1.1. Phase Shifting Pulse Generator Model

When we build phase shifting pulse generator UC3879 chip model of short electric arc machining pulse power supply, only need to make the model of the input and output signals established by us and the chip model's be the same. Phase shifting pulse generator is considered as a function module, including the pulse signal generator, phase shifting signals generator and dead band time setting module, as shown in Fig. 8. Among them, the pulse signal generator generate complementary pulse square wave which is fixed frequency and duty ratio for 50%; phase shifting signals generator generate complementary pulse square wave which has certain phase difference relative to the pulse signal generator's, and the size of the phase difference is decided by the output of the regulator, less than half of the square wave pulse cycle; Dead band time setting module respectively set the dead zone between the two group of complementary and square wave pulse time.

3.1.2. The Establishment of Jump Device Model

The resistance is made up of the load with jump device of R_1 and R_2 . The composition of jump device S1 and S2 is shown in Fig. 9 that the load resistance will change from R_1 to R_2 at $t = 0.14$ s to test the system in the dynamic response of the load changes.

3.1.3. Simulation Experiment Platform Model of the Power Supply

In this paper, the simulation experiment platform pulse power supply in SEAM is shown in Fig. 10. On the platform test simulation model of 36 V/2000 A/72 KW. The circuit parameters as shown in Table 4.

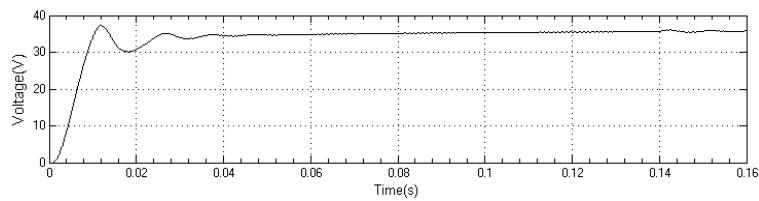
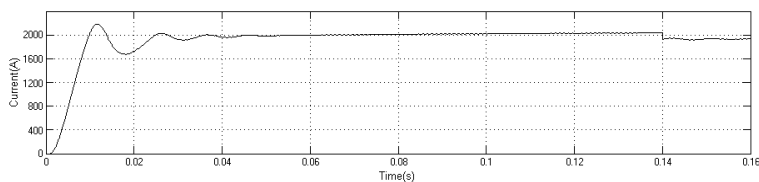
Table 4. Simulation model parameters of the power supply.

Variable Name	Parameter Values	Variable Name	Parameter Values
V _{in}	514	R1/Ω	0.018
n	10:1	R2/Ω	0.019
D	0.8	Coefficient of sampling	0.0694
f _s /kHz	20	SatuRation	15
L _r /H	0.4	zero-frequency gain	5.2×10 ⁶
L _o /H	0.098	zero/kHz	400
C _o /F	0.004	pole/kHz	4×10 ⁴

3.2. Results of Simulation

The simulation waveform is shown in Fig. 11 and Fig. 12.

Can be seen from the diagram, after mutation at 0.014 s, Fig. 12 output voltage fluctuation is less than 1 %, and become stability after about 2 ms; The Fig. 12, the output current begin mutation at 0.014 s and reduce rapidly and steadily. The simulation results show that power supply is characterized by their smooth output voltage; the interference is small and the advantages of fast response. Provide a precise output voltage for the power supply secondary modulation circuit (chopper circuit) and meeting the power supply design requirements in SEAM.

**Fig. 11.** Output voltage waveform.**Fig. 12.** Output current waveform.

4. Experiment

In order to verify the design of the pulse power supply whether meet the requirements of SEAM experiment, we produced an experimental prototype power supply based on ARM-STM32F103. The power supply parameters as follows Table 5.

Table 5. Experiment prototype power supply parameters.

Variable Name	Parameter Values
Input voltage	380V _{-15%} ^{+15%} (three phase current)
Frequency	50 Hz
Output voltage	5~36 V adjustable
Output current	I _{o max} =2000 A
Duty ratio	1 %~95 % adjustable

Through the SEAM experiment, we can verify the experiment prototype power supply whether or not meet the experimental requirements. Fig. 13 is 10 V, 15 V, 20 V no-load voltage waveform. The output voltage frequency is 50 Hz and duty ratio is 50 %.

Use PicoScope 6402 oscilloscope to sampling: probe 1 (blue) collect output voltage signal; probe 2 (red) collect output current signal. Output current is measured by CE-IZ04-86C3 current sensor to sampling current signal, and sampling ratio is 200 A/V.

Can be seen from the Fig. 13, the no-load voltage waveform of experiment prototype power supply satisfies the requirement of SEAM experiment.

For testing 10 V, 15 V, 20 V full load voltage and current waveform, we design the full load testing experiment device, and its principle diagram is shown in Fig. 14.

The working principle of full load experiment of the pulse power supply is: resistance about 0.04 Ω adjustable resistor is placed in the sink, when full load job, most of energy the power supply generated in the load is consumed in the form of heat energy, which ensure the heat load fevered, can being absorbed by water in the pool, so as to ensure the normal order of the experiment.

Fig. 15 is 10 V, 15 V, 20 V full load voltage and current waveforms (short circuit) of the experiment prototype power supply in SEAM.

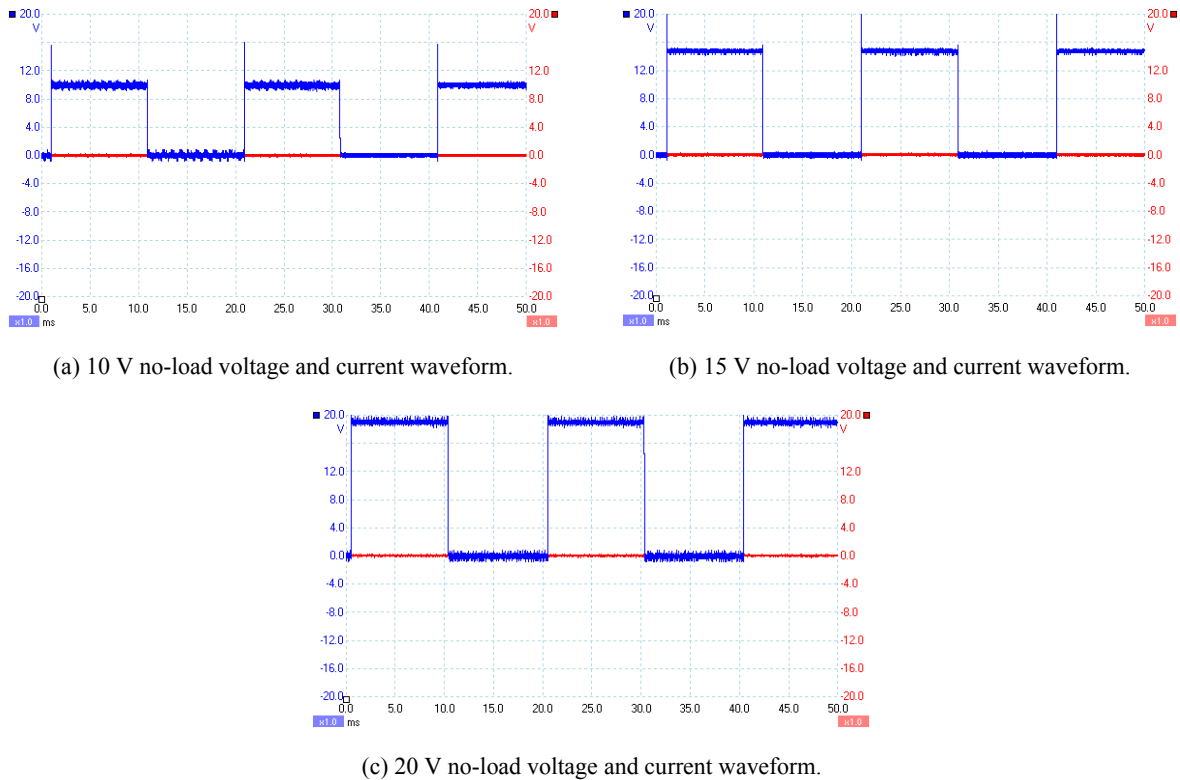


Fig. 13. The experiment prototype power supply 10 V, 15 V, 20 V no-load voltage and current waveform.

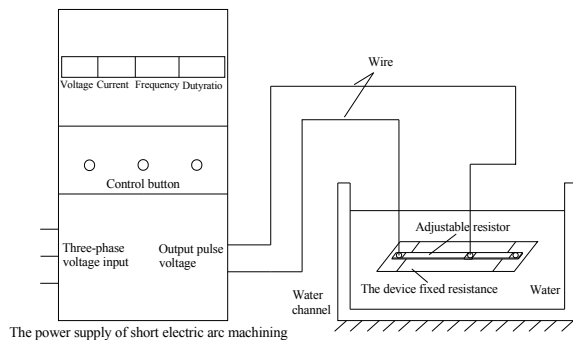


Fig. 14. The experiment prototype power full-load working principle of the experiment device.

From Fig. 16, the volt ampere characteristics of the pulse power supply, we can see that when the short electric arc machining began to processing, the voltage fell sharply, and the current rise rapidly, thus ensuring high current in a very short period of time to ensure that the plasma channel is more likely to establish.

Fig. 17 for short electric arc machining experiment prototype power 10 V, 15 V, 20 V in a short electric arc milling machine processing when the voltage and current waveform. The output voltage frequency is 50 Hz and the duty ratio is 50 %; Cooling adopts water vapor mixing: the water pressure is 0.8-1.2 MPa and pressure is 0.1-0.4 MPa; processed specimen material is nickel-base superalloy GH4169.

As can be seen from the Fig. 17 three picture, when machining voltage is 10 V, the times

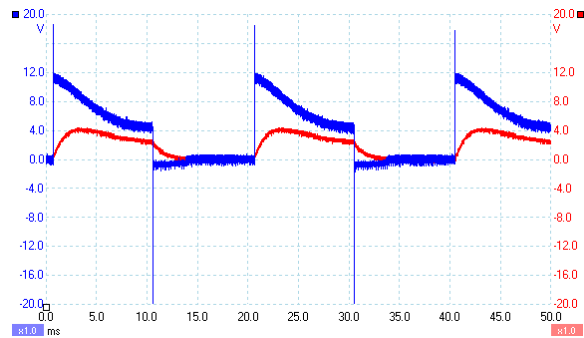
establishing discharge channels is the shortest; the times of 15 V take second place; 20 V is the slowest. Voltage and discharge current, on the other hand, processing of 20 V discharge current can reach more than 1600 A; the discharge current of 15 V take second place; largest discharge current minimum 10 V, about 700 A.

Fig. 18 to specimen processing, can be seen from the diagram, the left-most machining specimens of 20 V voltage parameters, the maximum discharge current, surface roughness, machining and discharge hole left by the material removal is larger; rightmost specimen machining voltage of discharge current minimum 10 V, the corresponding processing has good surface roughness, material removal left by the discharge crater is small, processing voltage of 15 V center.

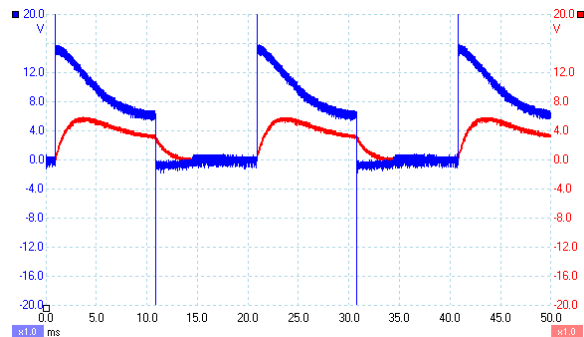
Experiment Results Analysis:

1) In the process of an arc discharge, the surface accuracy is inversely proportional to cutting current. The arc discharge energy is proportional to the cutting current. When the current is big, arc metal removal is large amount, low surface precision, surface roughness of workpiece with the increase of discharge current and degradation. The energy of the arc discharge size, directly affects the machining surface roughness, because the greater it is, the discharge energy will make the material melting depth more deepening, discharge hole left by the workpiece surface is also big resulting from material removal. And the size of the discharge hole depth is an important index of surface roughness. When the depth of discharge hole is deep and protuberant point is tall, the surface roughness is worse.

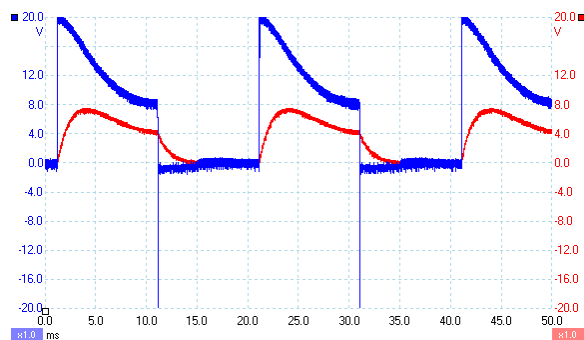
2) In the process of an arc discharge, the cutting efficiency is proportional to the cutting current. When cutting large current is large, the discharge energy is big, and the surface material is more likely to be removed, so the processing efficiency is higher, vice versa.



(a) 10 V full-load voltage and current waveform



(b) 15 V full-load voltage and current waveform



(c) 20 V full-load voltage and current waveform

Fig. 15. The experiment prototype power supply full-load 10 V, 15 V, 20 V voltage and current waveform.

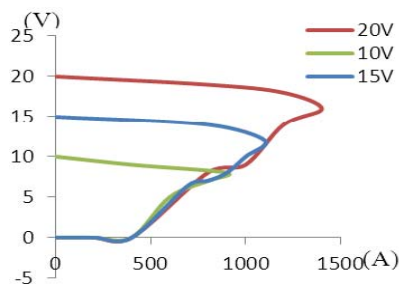
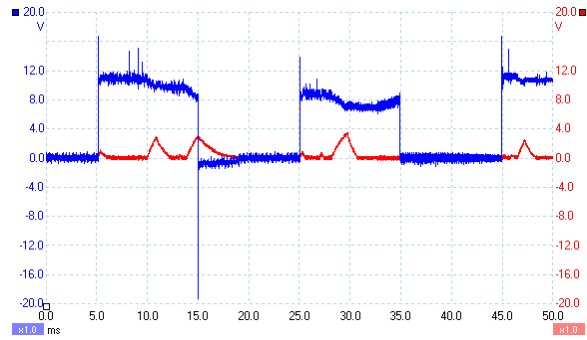
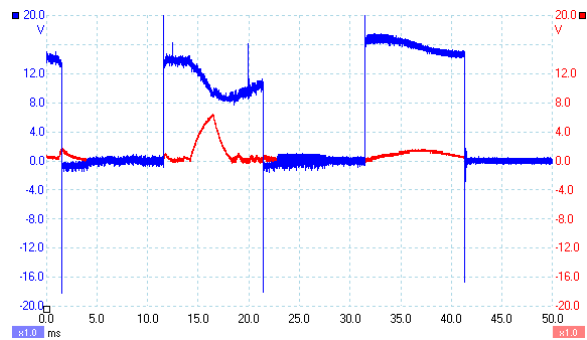


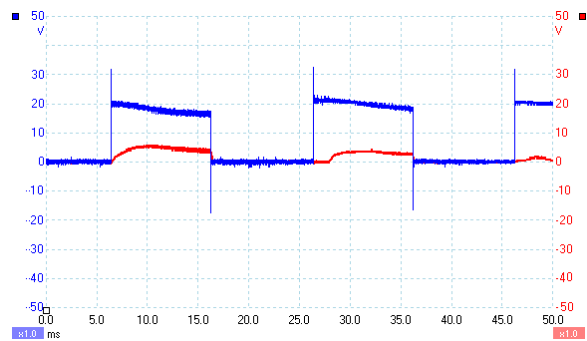
Fig. 16. Volt ampere characteristics of the power supply.



(a) 10 V machining voltage and current waveform



(b) 15 V machining voltage and current waveform



(c) 20 V machining voltage and current waveform

Fig. 17. Short electric arc NC milling machine 10 V, 15 V, 20 V machining voltage, current waveform Figure.

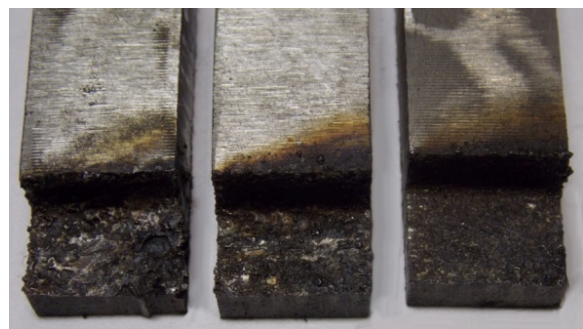


Fig. 18. Short electric arc NC milling machine 20 V, 15 V, 10 V machining drawing.

5. Conclusion

The chapter analyzes the gain characteristics of the power supply system in SEAM, and the

simulation model of the power supply based on Matlab is established to verify the feasibility and stability of the power supply feedback loop in SEAM. Through the short arc electric cutting machining experiment, we analyze the electrical characteristics of the power supply in SEAM, and find the relationship between precision of workpiece surface and efficiency in SEAM, which provides important technical support for the short electric arc machining mechanism research.

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