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Research on μ-CT High Voltage Power Supply

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Abstract

With CT high voltage power supply systems are moving towards higher performance and smaller doses, CT technology needs to provide more stable and reliable high-voltage power supply. This article is based on μ-CT machine design requirements, completed Construction of μ-CT high-voltage power supply prototype. The high-voltage power supply prototype completes full digital control of the entire system through the upper computer, using STM32H750VBT6 as the control core, the resonant soft switching technology is used to achieve coordinated control of high-voltage acceleration power supply and cathode filament heating power supply. By analyzing the experimental data and waveform of the prototype, it achieved precise control of three parameters: high-voltage output, filament current, and exposure time.

Keywords

High voltage accelerating power supply; filament heating power supply; resonant soft switch.

1. Project research background

1.1. Overview and working principle of μ-CT machine

Since the discovery of X-rays by German physicist Roentgen in 1895, X-rays have been widely used in scientific research, medical treatment, industry and other fields, such as detecting the fine structure of substances, medical diagnosis, and industrial flaw detection. Moreover, the successful development of computed tomography is a significant achievement in the field of radiation medicine[2].

The CT machine is mainly composed of high-voltage DC power supply, X-ray tube, X-ray detector, data acquisition system, industrial control computer, operation display platform, and bed body. The framework of the CT machine is shown in Figure 1. The specific working principle is that the filament power supply is applied to the cathode of an X-ray tube. When the filament is heated to a certain temperature, a large number of electrons are released. The electrons accelerate under the action of a high-voltage electric field, and high-speed flying electrons collide with the anode target surface of the tube. The vast majority of energy is converted into heat loss, and only a small amount is released in the form of X-photons to form X-rays. After passing through the collimator and the detection object, the X-ray detector generates an electrical signal, At the same time, the data acquisition system collects the output of the detector, which is processed and transmitted to the image reconstruction system to complete three-dimensional reconstruction, multi-level reconstruction, organ surface reconstruction, etc., and finally sent to the display storage device.

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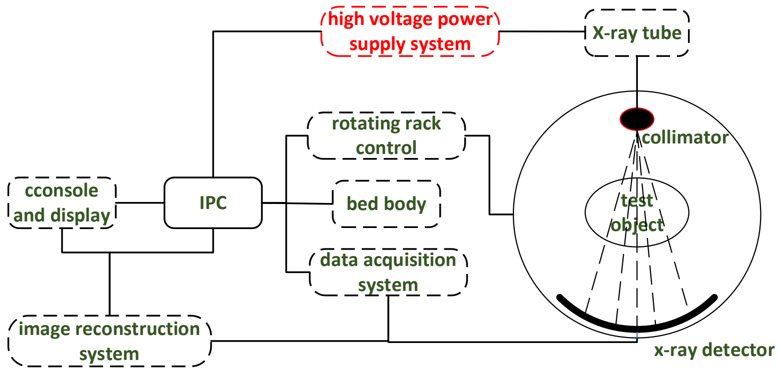

Figure 1： CT machine framework diagram

The CT machine high-voltage system mainly includes a high-voltage power supply and a tube. The tube voltage of the X-ray tube determines the quality of the X-ray. The higher the tube voltage, the higher the quality and the brighter the image. The product of tube current and exposure time determines the dose of X-ray and reflects the clarity of the image. The quality and quantity of X-rays directly affect the quality of CT imaging. Therefore, μ-CT high-voltage power supply system occupies a very important position.

1.2. Development Status at Home and Abroad

Compared to foreign countries , the development of CT machines started relatively late in China. With GE, Philips, and Siemens monopolizing over 50% of the domestic market capacity for high-end medical imaging equipment. Domestic enterprises still need to catch up and surpass. The development of high-voltage DC power supply has a significant gap compared to foreign countries in terms of technology and stable performance. During the period when industrial frequency machines have been completely phased out in developed countries, China has not yet completely phased out the use of industrial frequency machines. The current development direction of CT machine high-voltage power supply system is towards higher performance and smaller dosage. The application of digital high-frequency technology will bring about improvements in high-voltage power supply efficiency, accuracy, and response speed.

In recent years, China has made significant progress in the basic theory, key technology research, device development, and equipment research in aspect of development of CT[4]. In terms of CT data preprocessing, image reconstruction, and other aspects, it is basically synchronized with the international forefront. China's independently developed industrial CT machine partially meets the needs of national defense and civilian use. Although significant progress has been made in the development of core components such as CT ray sources and detectors in China, there is still a huge gap in technological level compared to developed countries.

1.3. Research Content of the Project

This article mainly focuses on μ- CT high-voltage power supply to achieve precise control of three parameters: high-voltage output, filament current, and exposure time. Using STM32H750VBT6 as the control core and resonant soft switching technology to achieve the coordinated control of high-voltage acceleration power supply and filament heating power supply[1].

(1) Hardware design of high-voltage power supply system. Adopting high-power electronic device IGBT and combining PWM and harmonic soft switching technology to achieve precise voltage regulation of high-voltage power supply and precise control of filament current.

(2) Software design of high-voltage power supply system. STM32H750VBT6 performs PI calculation and adjustment based on the digital quantity collected by ADC, then outputs the corresponding PWM pulse signal, amplifies and isolates the signal through the driving circuit,

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and adjusts the voltage by changing the duty cycle of the IGBT module to achieve closed-loop control of the system.

(3) Upper computer control of high-voltage power supply system. By designing a human-machine interaction interface through a touch screen, the parameters of the entire power supply system can be set and stored on the screen, enabling the start and stop control of two sets of power supplies, real-time display of the main parameters and operating status of the high-voltage power supply system, and achieving full digital operation of the entire system.

2. The System Structure and Working Principle of μ-CT High Voltage Power Supply

The system structure of the μ-CT high-voltage power supply is shown in Figure 2. Single-phase 220V AC power is rectified and filtered through full bridge uncontrolled rectification to obtain smooth DC power. Then, high-frequency full bridge inverter is used to complete DC/AC conversion[3]. The square wave voltage output by the inverter is boosted by a high-frequency transformer in the high-voltage oil tank, and then filtered through voltage doubling rectification to obtain stable high voltage output. Using precision resistor network to sample the high-voltage feedback signal, it is processed and sent to the CPU for digital PI adjustment. By changing the PWM duty cycle, the output high-voltage voltage can be adjusted to achieve closed-loop control.

The filament heating power supply also adopts closed-loop control, mainly composed of a full bridge uncontrolled rectification and filtering circuit, synchronous Buck circuit, half bridge inverter circuit, LC series resonance circuit, filament transformer, high-frequency rectification and filtering circuit, control circuit, etc. After uncontrolled rectification and filtering, 220V AC mains power is output to the filament transformer through a half bridge inverter after synchronous Buck circuit voltage reduction. The feedback winding on the filament transformer is sampled, and directly rectified and filtered by Schottky diodes before being sent to ADC. After PI calculation, the corresponding PWM signal is generated, which is amplified by drive isolation and sent to IGBT for closed-loop control. And LC series resonance can achieve soft switching of the filament power supply under frequency modulation, which can effectively improve the efficiency of the filament power supply when it operates at less than half the resonance frequency.

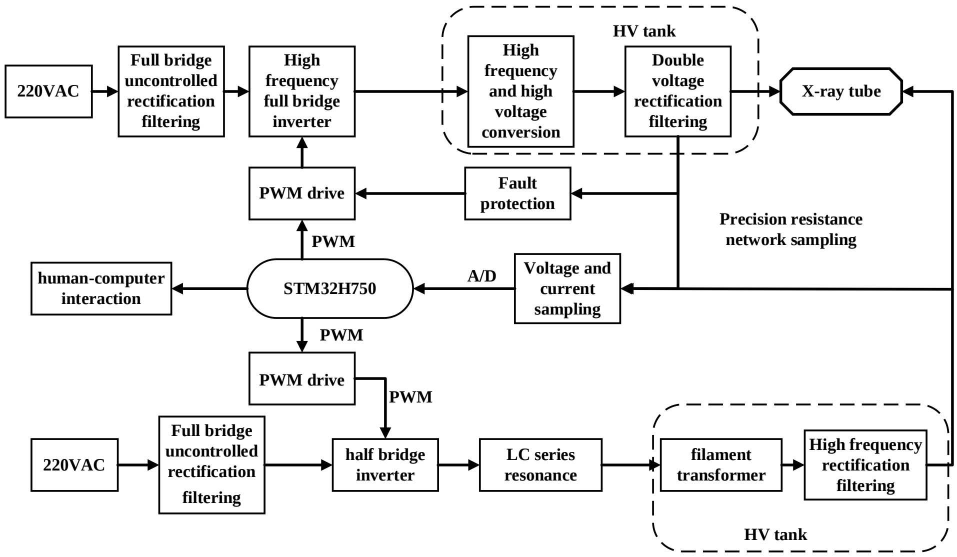

Figure 2 : System structure diagram of μ- CT high-voltage power supply

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3. Hardware Design of μ-CT High Voltage Power Supply System

3.1. Design of High Voltage Acceleration Power Supply

3.1.1. Main circuit of high-voltage acceleration power supply

As shown in Figure 3, a full bridge uncontrolled rectification and filtering circuit is used to convert 50Hz single-phase 220V mains power into stable and reliable DC power. The full bridge inverter circuit is used to output AC power, which is boosted by a high-frequency high-voltage transformer in the HV tank. Finally, a stable high voltage is output through voltage doubling rectification and filtering. In order to achieve closed-loop control, the high-voltage feedback signal is obtained by a precision resistor network. The analog quantity is converted into digital quantity through an A/D module and sent to STM32H750VBT6 for PI calculation and processing. The duty cycle of PWM is adjusted in real-time, thereby changing the value of the output high-voltage. And through the human-machine interface, the start and stop control of the entire system is achieved, and the real-time display and adjustment of power parameters fully demonstrate the characteristics of high voltage digital power supply, such as high efficiency, small size, light weight, fast response, and convenience.

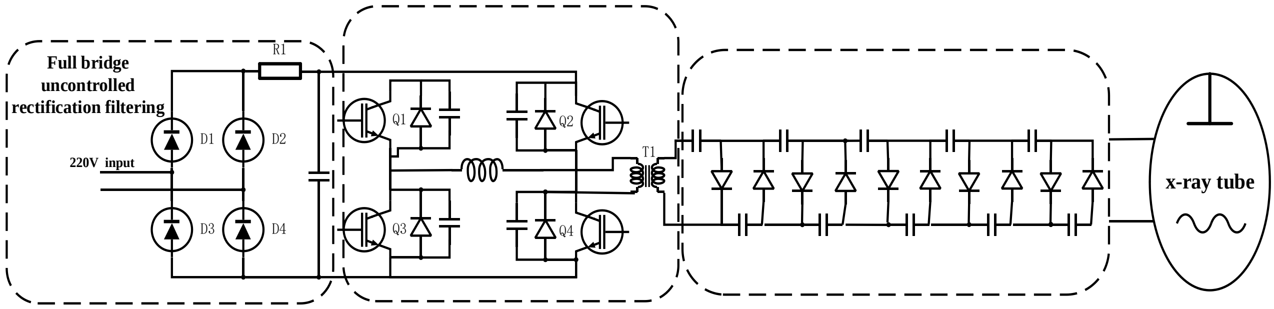

Figure 3: Main Circuit of High Voltage Acceleration Power Supply

3.1.2. Voltage doubling rectifier filter circuit

Using a 10 times voltage odd half wave rectification circuit as shown in Figure 4, the principle analysis is as follows: when the input AC voltage is positive for half a cycle, diode D1 conducts, and capacitor C1 begins to charge. After charging is completed, the voltage at both ends of C1 is equal to the input AC voltage; When the AC input is converted from positive half cycle to negative half cycle, the cathode of diode D1 is cut off due to the reverse voltage. At this time, diode D2 conducts, and the AC input and C1 simultaneously charge the C2. After charging, the voltage at both ends of C2 is twice the input AC voltage; When the AC input is converted from negative half cycle to positive half cycle, diode D3 conducts, and the AC input and C2 simultaneously charge C3. After charging, the voltage at both ends of C3 is three times the input AC voltage, and so on. When the AC input is converted from positive half cycle to negative half cycle, diode D10 conducts, and the AC input and C9 simultaneously charge C10. After charging, the voltage at both ends of C10 is 10 times the input AC voltage. The multi-level voltage doubling rectification method reduces the turn ratio of the step-up transformer, greatly reducing the insulation design requirements of the transformer and the withstand voltage requirements of the rectifier diode, reducing the difficulty of insulation and the volume of the high-voltage power supply, it’s suitable for small powers μ-CT high-voltage power supply applications.

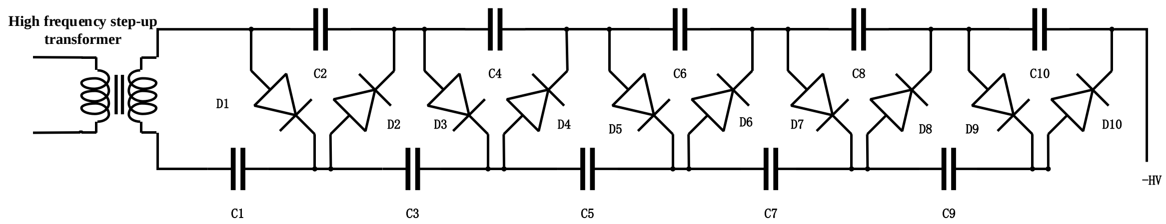

Figure 4 : Voltage Multiplying Rectification Filter Circuit

3.2. Design of filament heating power supply

3.2.1. Principle analysis of filament heating power supply

The current of the X-ray tube filament determines the emission characteristics of the electrons in the filament. The higher the filament current, the higher the density and quantity of emitted electrons. When the output high voltage is constant, the tube current changes with the change of electron density, that is, with the filament current, so the stability of the filament current plays a very important role in the normal operation of the high voltage system[6]. The structural block diagram of the filament heating power supply is shown in Figure 5. After the single-phase 220V AC power passes through the uncontrolled rectification filtering and DC-DC converter, it is transmitted to the filament transformer by the series resonant half bridge inverter circuit. Finally, the voltage and current of the filament are sampled through the rectification filtering, and the sampled feedback signal is adjusted to the PWM duty ratio after analog digital conversion and PI operation to achieve closed-loop control of the power supply.

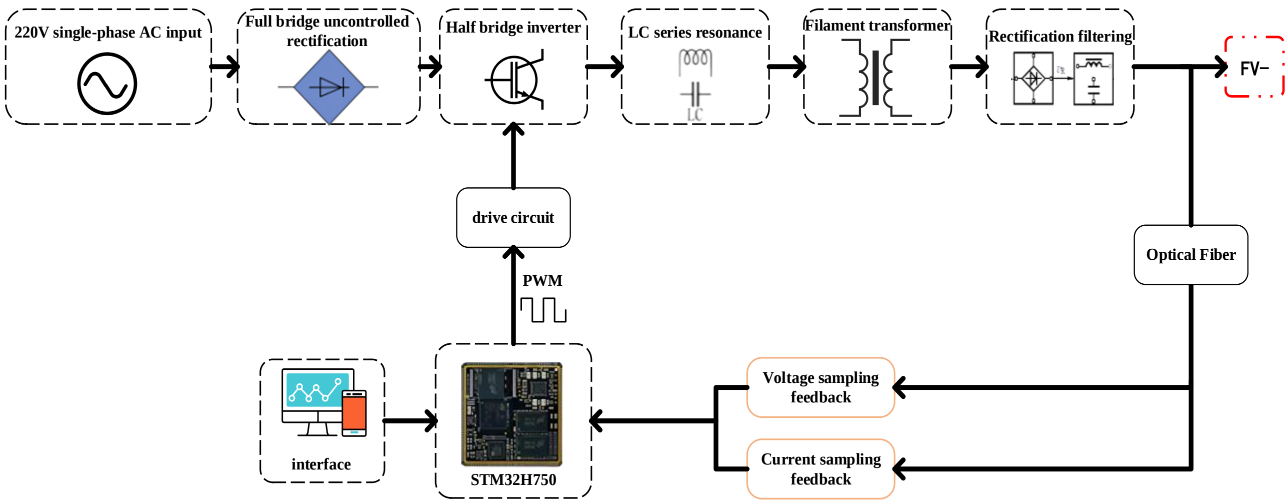

Figure 5 : Structure diagram of filament heating power supply

3.2.2. Soft switching analysis of series resonant inverters

The resonant converter utilizes the principle of resonance to change the current and voltage in the load according to sinusoidal or quasi sinusoidal laws, which is beneficial for the switching device to achieve soft switching. Figure 6 shows the topology of a half bridge series resonant inverter. To simplify the analysis of the resonant converter, the double voltage circuit is simplified as an ideal model, ignoring its voltage drop.

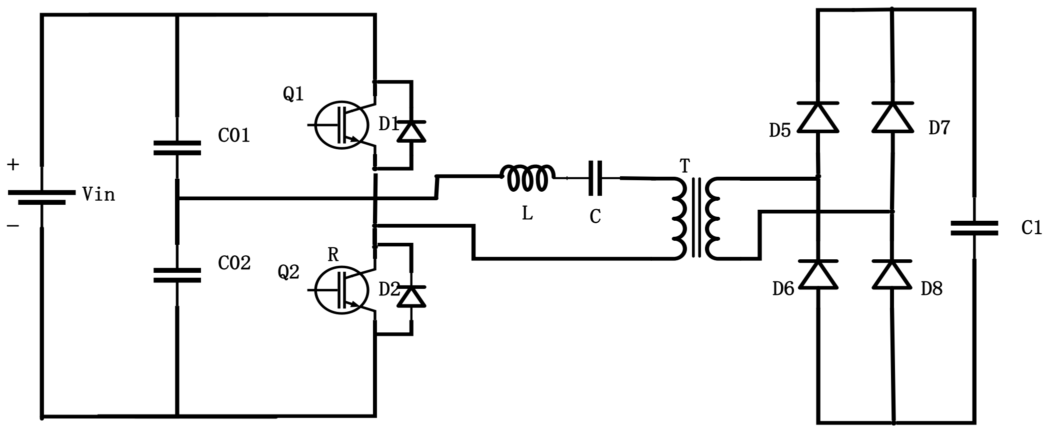

Figure 6 : Half bridge series resonant inverter circuit

In the circuit, the resonant inductor L and resonant capacitor C form a series resonant circuit, where fs is the switching frequency, fr is the resonant frequency, M is the voltage gain, and Q is the quality factor.

$$Z = R + j\left(\omega_s L - \frac{1}{\omega_c C}\right) \tag{1}$$

When $\omega_s = 1/\sqrt{LC}$ when resonance occurs, the resonance frequency formula is as follows:

$$f_r = \frac{\omega_s}{2\pi} = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

When $\omega_s = 1/\sqrt{LC}$ when resonance occurs, the quality factor $Q = \omega_r L/R = \frac{\sqrt{L/C}}{R} = 2\pi f_r L/R$ the voltage gain formula is as follows:

$$M = \frac{1}{1 + j(\frac{\omega_s L}{R} - \frac{1}{\omega_s CR})} = \frac{1}{1 + jQ(\frac{f_s}{f_r} - \frac{f_r}{f_s})} \tag{3}$$

When resonance occurs, the impedance exhibits resistance and the voltage and current are in phase. As the load increases, the quality factor decreases, and the gain curve approaches the horizontal line without resonance peaks, thus it does not have the ability to adjust under light and no-load conditions. As the load decreases, the quality factor increases. Within the same frequency range, the voltage gain obtained has a larger range of variation and a larger range of power regulation[5].

When overloaded with high quality factor, series resonance has three operating modes: ①fs<fr/2, which is the discontinuous current mode(DCM), the switch tube is zero current on, zero current/zero voltage off, the switch tube loss is low and the interference is small; ②fr/2< fs <fr, in continuous current operation mode (CCM), the switch tube is in a hard on and soft off state;③fs>fr, in the continuous current operation mode (CCM), the circuit operates in an inductive state, and the switch is in a soft on and hard off state. The switch has high losses and interference. This article selects a DCM with low switching loss, and the working waveform of the series resonant zero current switching converter is shown in Figure 7.

When fs<fr/2, the series resonant converter operates in discontinuous current mode (DCM). Q1 and Q2 in Figure 7 are the trigger pulse waveforms of the switch, and iL is the resonant current waveform. Assuming that all components in the circuit have ideal switching characteristics and no switching losses, the working process of the series resonant converter is divided into four stages for discussion based on the conduction and turn off conditions of each component[7].

t0~t1 interval: At t0, the switch Q1 is on. Since the starting current is zero, the switch is turned on at zero current. Then, L and C resonate, the inductance current iL begins to increase. After Tr/2, the inductance current resonates to zero at t1.

t1~t2 interval: Due to the maximum voltage of the resonant capacitor Vin, the current in the circuit can resonate in reverse until the switch Q1 is turned off at t2.

t2~t3 interval: When the switch Q1 is turned off, the current flows in reverse, and the current continues to resonate through the anti parallel diode until the current resonates to zero at t3.

t3~t4 interval: Both switch tubes Q1 and Q2 are in the off state, and the current resonates to zero at t3. During this period, the current will not resonate in the forward direction and will remain at zero until the next cycle.

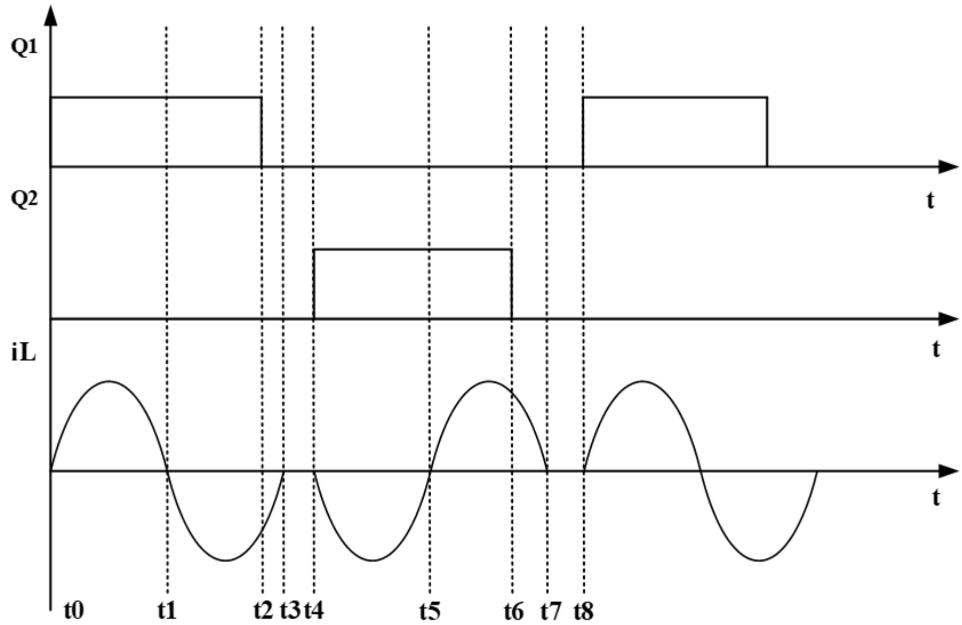

Figure 7 : Working Waveform of Series Resonant Zero Current Switching Converter

So under the condition of fs<fr/2, the resonant current iL of the main circuit is intermittent, and the anti parallel diode is naturally on and off. By controlling the switch pulse width to meet Tr/2<ton<Tr, zero current on and off of the power switch can be achieved, thereby reducing switch losses[8].

4. Software Design of μ-CT High Voltage Power Supply System

4.1. Programming

The STM32H750 controller software program consists of a main program and several subroutines: AD sampling subroutine, PWM interrupt program, touch screen communication program, etc. The main program flowchart is shown in Figure 8.

After the CPU is powered on, system initialization is carried out first: initialization of GPIO port, initialization of PWM and USART high-speed communication registers, etc. Then communication is carried out with the touch screen to display real-time parameters, operating status, fault information, etc.

As shown in Figure 9, after the program enters the PWM interrupt, priority is given to interrupt protection, and all feedback signals of the power system are immediately sampled and processed. Then, through the PI algorithm adjustment of the high-voltage acceleration power supply, filament heating power supply, and beam current, each PWM pulse signal is generated, which is then isolated and amplified by the driver and sent to the IGBT to achieve closed loop control of μ-CT high-voltage power supply system. If there is a fault signal in the system, the PWM signal will be forced to brake immediately after entering the interrupted service, and all IGBT devices will be turned off to make the high-voltage power output zero, thus achieving software programming protection for the hardware platform and displaying the fault information through the touch screen.

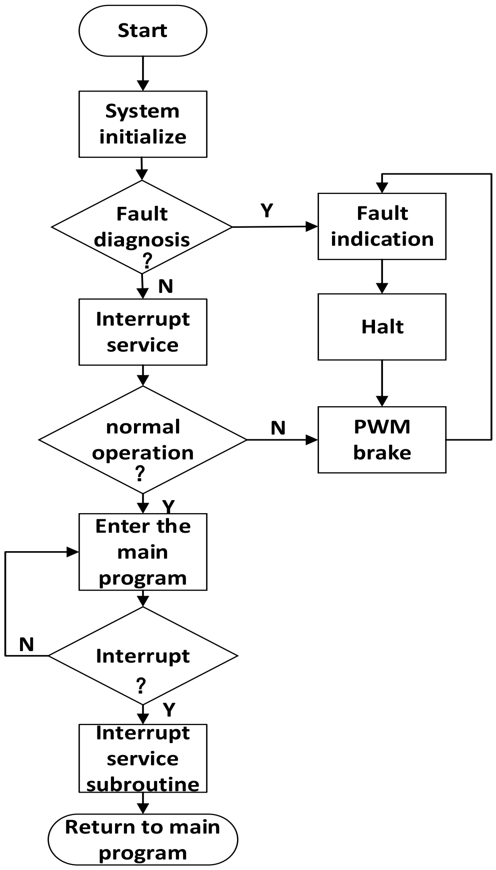

Figure 8 : Main program flowchart

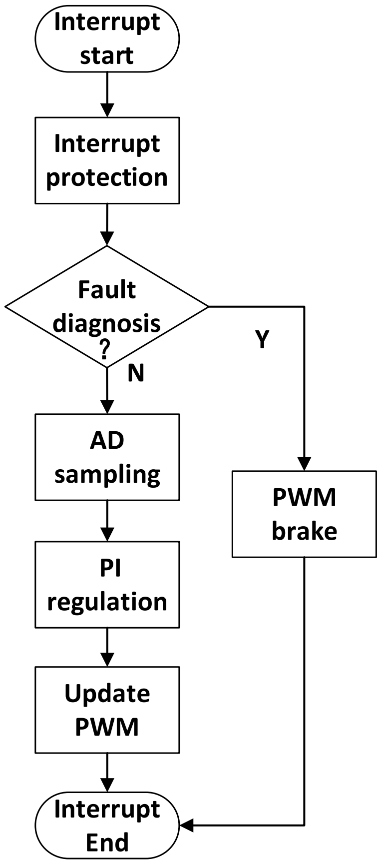

Figure 9 : Interrupt service flowchart

4.2. PI closed-loop control design

The PI closed-loop algorithm is a widely used control strategy in PWM pulse width regulation. Compared to other advanced control algorithms in fully digital circuits, this control strategy is relatively simple in adjusting control parameters and has low dependence on the system's own parameters. It is highly reliable in PWM regulation of digital switching power supplies.

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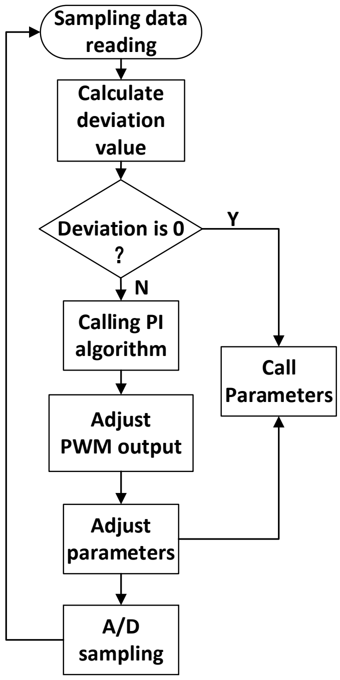

Figure 10 : PI Control Block Diagram

The PI control block diagram is shown in Figure 10. Under the effects of both difference and no difference adjustments, while reducing the output error of the inverter bridge and minimizing the static error, through the PI algorithm to achieve the width adjustment of the PWM pulse signal. According to the PI closed-loop algorithm formula, after completing 16 bit high-precision sampling in the ADC channel, the actual voltage and current calculations are completed in the interrupt service function to obtain the true value of the external output U_n and I_n then, compare with the set high voltage and beam current U_g and I_g compare the difference of command parameters to obtain the difference E_V and E_I among them E_V=U_n-U_g、 E_I=I_n-I_g. According to the magnitude of the difference and the positive and negative, the PI algorithm is called to output the corresponding PWM pulse duty cycle, thereby forming a closed-loop regulation.

5. μ-CT high-voltage power supply system testing

5.1. Experimental waveform analysis

5.1.1. PWM pulse and driving waveform

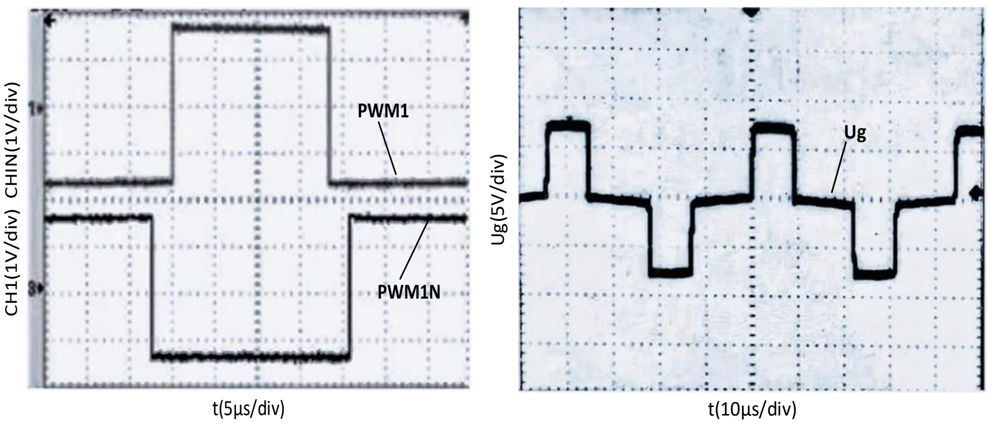

Figure 11 : High voltage power drive waveform

From Figure 11, it can be seen that STM32H750VBT6 can output a complementary PWM pulse signal with a 2.5us dead time, which is controlled to turn on and off the switch tube after driving the isolation amplification circuit.

5.1.2. Filament power supply test

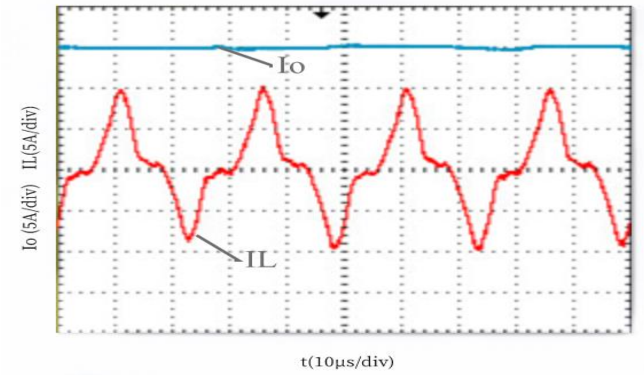

Figure 12 : Filament current 15A output waveform

As shown in Figure 12, the 15A waveform of the primary input and output of the filament current and the waveform analysis of the primary voltage are analyzed. Based on the design of the cathode filament power supply, the resistance value of the filament is about 0.2 Ω, and the voltage at both ends is adjustable within the range of 0-6V. From the waveform, it can be seen that the current output is stable.

5.2. Human machine interface debugging

Figure 13 : Initial interface display

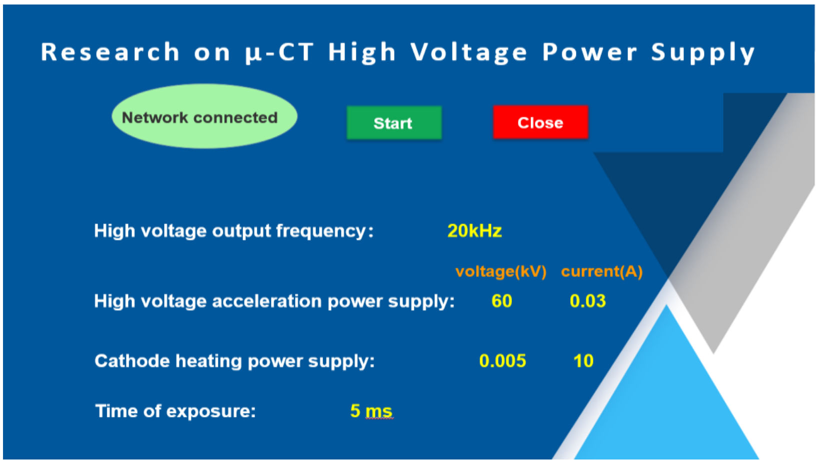

Figure 14 : Monitoring Interface Display

The initialization interface displays information related to the project. The monitoring interface is an important means of human-computer interaction for this power supply. The parameter

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information of this power supply can be visually observed on the monitoring interface, and the parameters of the power supply can be modified through the touch interface.

6. Conclusion

With the development of CT machine high-voltage power supply system towards higher performance and smaller dosage, micro nano CT technology needs to provide more stable and reliable high-voltage power supply. In response to the current shortcomings of adjustable output voltage and large fluctuation of output voltage in X-ray machine power supply, resulting in low X-ray imaging quality and significant harm to the human body, this article mainly studies the small power control based on STM32H750VBT6. The preliminary design of the high-power CT machine in the laboratory stage was completed through structural design, hardware circuit design, PCB circuit welding debugging, software programming, and platform building testing for the high-voltage power supply system of the CT equipment.

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