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DESIGN OF SCANNING MAGNET POWER SUPPLY FOR HUST-PTF *

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Abstract

An active scanning proton therapy facility is being developed at Huazhong University of Science and Technology (HUST). By controlling the deflection position of the beam with scanning magnets at different times, the superposition of discrete spot beams will form a specified shape and dose distribution conformal to the target tumour. A high precision and fast response power supply is required to deflect the beam quickly and accurately. In this paper, the TOSCA module in Opera3D is used to model and simulate the scanning magnets and to obtain the equivalent inductance of the magnet. Then the calculated equivalent resistance inductance instead of the magnet is used to design the scanning magnet power supply. A high-voltage bridge is utilized to achieve fast response speed, and a low voltage bridge and PI control algorithm is adopted to ensure power supply accuracy. The Simulation result shows that the designed power supply meets the requirements of response speed and accuracy.

INTRODUCTION

Due to the Bragg peak characteristics of protons, proton therapy has attracted attention from various countries in recent years. With supported by National Key Research and Development Plan, an active scanning proton therapy facility is being developed at Huazhong University of Science and Technology (HUST). The 250MeV proton beam provided by superconducting cyclotron and it can vary from 70 MeV to 230 MeV by modulated via the energy selection system (ESS). Two orthogonal H-type scanning magnets (SMY and SMX) in the nozzle will controlling the deflection position of the beam and the superposition of discrete spot beams will form a specified shape and dose distribution conformal to the target tumour. And Huazhong University of Science and Technology Proton Therapy Facility (HUST-PTF) has a 30 × 30 cm^2 radiation area at the iso-center[1]. In order to ensure that the beam can be deflected quickly and accurately, a high precision and fast response power supply is required. This paper mainly describes design of scanning magnet power supply for HUST-PTF.

SCANNING MAGNET

The main parameters of the scanning magnets are designed as shown in Table 1.The midpoint between the two scanning magnets is about 2.665m upstream of the iso-center: This establishes the SAD of the nozzle [2]. The gap of SMY keeps constant cross-section, while the gap of SMX adopts variable taper cross-section to accommodate the deflection envelope of the SMY and reduce excitation current, Different schemes were used tooptimize the integration field uniformity of SMY and SMX to less than ±0.25%. The TOSCA module in Opera3D is used to model and simulate the scanning magnets and to obtain the equivalent inductance of the magnet. The inductance of the scanning magnet can be calculated as

$$L = \frac{2 \times E}{I^2} \quad (1)$$

Where L means the equivalent inductance of the scanning magnet (unit: H), E means the energy of the magnet (unit: J), I means the coil current (unit: A).

Table 1: Main Parameters of Scanning Magnets

Parameter	Units	SMY	SMX
Max Deflection Angle	mrad	60	70
SAD	m	2.8525	2.4525
Max Field Strength	T	0.49	0.53
Pole Length	mm	225	275
Pole Width	mm	110	140
Pole Gap	mm	70	86 - 120
Horizontal Good field region	mm	64	66
Designed Max Current	A	334	407
Max Current for treatment	A	285	330
Horizontal integration field uniformity		±0.25%	±0.25%
Inductance	mH	6	11
Resistance	mΩ	46	70

POWER SUPPLIES

Requirements

The spot spacing of HUST-PTF is 5 mm, and the excitation currents of the SMY and SMX are 9.5A and 11A, respectively. The excitation current adjustment times of SMY and SMX between spot and spot are 100μs and 400μs, and maximum current slope are 95 kA/s and 27.5 kA/s. And they are also required to control their currents to a level of 100 ppm. One of the essential parameters in power supply design is maximum current slope. Due to SMY and SMX power supplies are similar, this paper only focuses on the design of SMY power supply that demands more stringent specifications. Taking the scan width as ±10mm as an example, the ideal spot scan current pattern of the SMY power supply is shown in Fig. 1. Based on scan current and scan magnet parameters, the maximum dynamic output voltage can be calculated as[3]

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$$V(t) = L_M \times \frac{\mathrm{d}I(t)}{\mathrm{d}t} + R_M \times I(t) \quad (2)$$

The steady state output voltage can be calculated as

$$V(t) = R_M \times I(t) \quad (3)$$

The maximum dynamic output voltage is ±570V, the maximum current for treatment is 285A, and the steady state output voltage is 13.1V. The actual designed maximum power supply current is 334A, and the steady state output voltage is 15.36V.

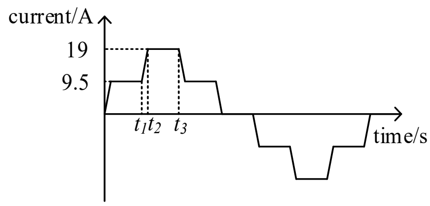

Figure 1: Ideal spot scan current pattern of the SMY power supply.

Power Topology

The Eq.(5) shows that the load current can be controlled by changing the voltage of the load, and the higher the load voltage, the greater the rate of current change.

$$\int_{t_1}^{t_2} V(t)\,\mathrm{d}t = L_M \times I(t)\Big|_{t_1}^{t_2} + R_M \times \int_{t_1}^{t_2} I(t)\,\mathrm{d}t \quad (4)$$

$$\rightarrow \Delta I = I(t_2) - I(t_1) = \frac{\int_{t_1}^{t_2} V(t)\,\mathrm{d}t - R_M \times \int_{t_1}^{t_2} I(t)\,\mathrm{d}t}{L_M} \quad (5)$$

The designed topology of the power supply is composed of two parts, rectification and inverter, as shown in Fig. 2.The rectifying part supplies power to the inverter bridge through the filter capacitor. A high voltage inverter bridge (IGBT units) is used to ensure the response speed of the power supply. A low voltage inverter bridge (MOS units) and PI control algorithm to ensure power supply accuracy [4]. The switching frequency of pulse width modulation (PWM) of the IGBT and MOS are 20kHz and 100kHz respectively. The voltage supplied by the high voltage bridge is set to 570V. In order to stabilize the current at the maximum current, the voltage supplied by the low voltage bridge is set to 20V with a certain adjustment margin.

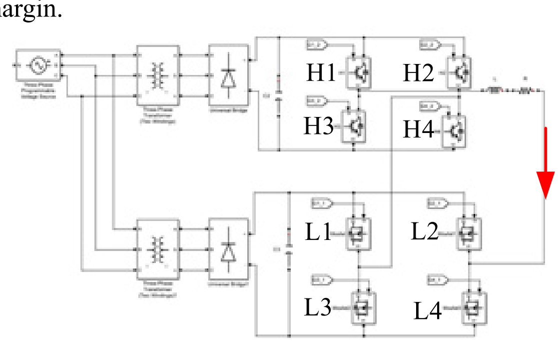

Figure 2: The topology of the power supply.

Switch State Design

The relationship between the spot scan current and the control voltage across the load is shown in Fig. 3. Due to the load is not applied with voltage, the current of the load is always slowly approaches to 0. Therefore, when the load current and the target current deviate greatly, the high-voltage mode (low-voltage flag is 0) is used to quickly change the load current to make the deviation smaller. And the load current should be between 0 and the target current; while the deviation of load current and the target current is less than the threshold, switch to the low voltage mode (the low voltage flag is 1) and maintain the low voltage mode until the difference between the load current and the target current becomes large again. In the low-voltage mode, the PI algorithm is used to control the duty cycle so that the load voltage is switched between the applied low voltage and the un-applied voltage, and finally the current is stabilized at the target value.

Since the current of the inductor cannot be changed abruptly, the switching state of the H-bridge must be designed according to the positive and negative of the current. According to the positive or negative current and the reference current trend, scan current is divided into four phases: A, B, C and D, as shown in Fig. 3.

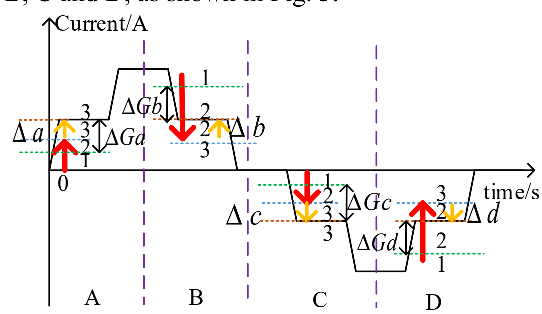

Figure 3: Schematic diagram of scan current and load control voltage (red is high voltage mode, yellow is low voltage mode).

Phase A: When the current is positive and the reference current changes, the reference current at the next moment is greater than the previous moment.

Phase B: When the current is positive and the reference current changes, the reference current at the next moment is less than the previous moment.

Phase C: When the current is negative and the reference current changes, the reference current at the next moment is less than the previous moment.

Phase D: When the current is negative and the reference current changes, the reference current at the next moment is greater than the previous moment.

It is worth noting that the positive current here means that the current is greater than a small threshold (e.g. greater than 0.01A), and the negative current refers to the current being less than a small threshold (e.g. less than -0.01A). This is because when the target current is 0A, the load current may not be completely zeros, but slightly larger or slightly smaller than 0A. When the load current is adjusted to 1nA and the target current at the next time is -

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9.5A. The C-phase control strategy should be implemented, however, since the current is not less than 0A, the adjustment is out of control. Therefore, this paper considers the current between the current value [-0.01A, 0.01A] as a whole, and records it as the phase E.

Define the difference between the target current and the current value as I_{diff}. According to the different I_{diff},the A, B, C, and D phases are further subdivided into phase 1, 2, and 3, as shown in Fig. 3. Phase 1: The low voltage flag is 0 and the power supply is in high voltage mode. Phase 2: The low voltage flag is equal to the low voltage flag at the previous time. The current voltage mode of the power supply depends on the voltage mode at the previous time. Phase 3: The low voltage flag is 1 and the power supply is in low voltage mode. The current direction indicated by Fig. 2 is the positive direction of the current. The switch states at different phases are shown in Table 2.

Table 2: The Switch States at Different Phase

Phase	H				L			
	1	2	3	4	1	2	3	4
A1	1	0	0	1	1	0	0	0
A2	Keep last time mode							
A3	1	0	0	0	1	0	0	PI
B1	0	0	0	0	1	0	0	0
B2	Keep last time mode							
B3	The same as A3							
C1	0	1	1	0	0	1	0	0
C2	Keep last time mode							
C3	0	1	0	0	0	1	PI	0
D1	0	0	0	0	0	1	0	0
D2	Keep last time mode							
D3	The same as C3							
E1	The same as A1							
E2	All 0							
E3	The same as C1							

Simulation Results

Since the designed scanning power supply is a controllable current source, the current of the power supply output is mainly analysed by SIMULINK of MATLAB. When the target current value is at most ±285A and the minimum ±9.5A, the waveforms of the target current and the actual current are as shown in Fig. 4. The red line in the figure is the target current and the blue line is the actual current. The simulation results show that when the target current is 285A and -285A, the actual current always has a certain gap with the target current. This is because the larger the current value, the larger the voltage component of the equivalent resistor in the load, and the voltage across the equivalent inductor becomes smaller. Therefore, it is not easy to rise the current. The current fluctuations of 100 ppm corresponding to the current of 285A and 9.5A are 0.0285A and 0.001A, respectively. When the current is ±285A, the current accuracy and ripple level are in the range of 100ppm. When the target current is ±9.5A, the ripple of the current is approximately 0.001A, which meets the design requirements. When the target current is other values, the same method is used to analyze the results. The result shows that the designed power supply also can meet the requirements. The regulation time of the current is defined as rising from 10% of the steady state to 90% of the steady state. The simulation results show that the rise time of the current can be controlled within 100μs, and the current can be stabilized at the target value within 200μs and control their currents at a level of ±100 ppm.

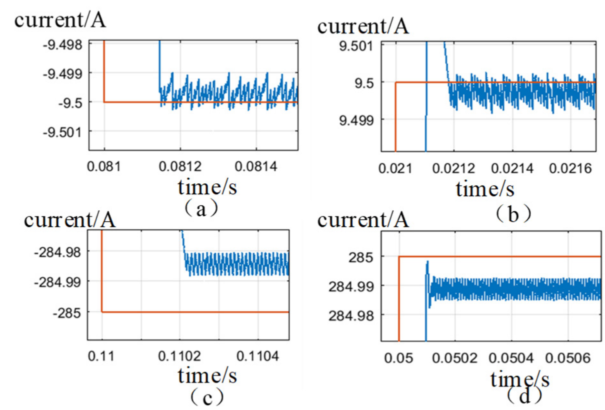

Figure 4: The waveforms of the target current and the actual current, as the target current value is at most ±285A and the minimum ±9.5A.

CONCLUSION

In this paper, the simulation and design of the scanning magnet power supply which is developed by Huazhong University of Science and Technology is presented. The TOSCA module in Opera3D is used to model and simulate the scanning magnets and obtain the equivalent inductance of the magnet. The control strategy of load current is analyzed, and the scanning power supply parameters, topology and switch state are designed. The simulation results show that the rise time of the current can be controlled within 100μs, and the current can be stabilized at the target value within 200μs and control their current at a level of ±100 ppm.

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