Design and test of the power supply for a fast kicker magnet

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Abstract

To perform fast beam switch during spot scanning and energy modulation procedure, a fast kicker magnet system is adopted in HUST-PTF (Huazhong University of Science and Technology Proton Therapy Facility). The rising/falling time is expected to be less than 100 μs, and the maximum repetition rate should be up to 500 Hz. To meet the dynamic performance of the power supply, a solution with two separate DC link scheme is present in this paper. Since the Kicker is closed to other sensitive equipment, an output filter is installed to prevent electromagnetic disturbances from propagating along the cables. The optimized design of out-put filter and comparison measurement results of the power sup-ply are introduced as well. Here, a trade-off between the voltage oscillation, dynamic performance and engineering implementation has been made.

INTRODUCTION

A proton therapy facility based on spot scanning technique is under development at HUST. For HUST-PTF, a fast kicker magnet system is placed upstream from the degrader to perform fast beam ON/OFF switch during beam spots and the energy modulation procedure. And it can also work in DC mode to provide a function of fast beam stop in case of emergency with safety interlocks.

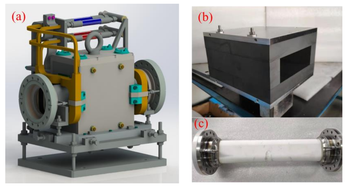

Figure 1: (a) Assemble view of the kicker magnet; (b) Kicker core, fixed by gluing and connecting bolts; (3) Racetrack ceramic vacuum chamber.

Table 1: Design parameters of the fast kicker magnet.

TABLE I
THE DESIGN PARAMETERS OF THE FAST KICKER MAGNET

Parameters	Kicker magnet
Deflected energy (MeV)	250
Deflection angle (mrad)	10.36
Max. magnetic field (T)	0.1
Magnet length (mm)	200
Uniformity	± 0.5%
Repetition rate (Hz)	500
Rising/falling time (μs)	<100
Resistance (mΩ)	1.7
Inductance (μH)	44
Drive current (A)	510

The schematic design of the power supply was completed in October 2018, the optimized design of output filter and the test of the power module were completed in May 2019.

REQUIREMENTS

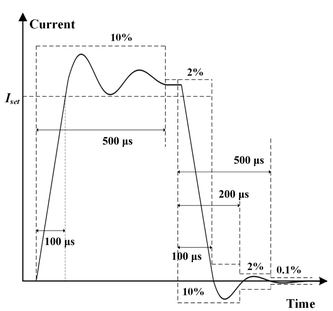

Figure 2: The requirements for dynamic response and accuracy of the kicker.

Fig.2 shows the waveform requirements of the Kicker. For the Kick ON state, the proton beam is deflected to the beam stop (a Faraday cup). The field accuracy at Kick ON state is relaxed, 10% overshoot at rise time and 2% stability at flat-top time can be accepted. For the Kick OFF state, the output current should be less 2% of normalized current within 200 μs to reduce the disturbance of the downstream beamline.

The design difficulty of the kicker converter is to meet the EMC requirements, especially in such a medical application. Special care should be taken to avoid the high frequency voltage oscillation and by that EMC noise. Thurs, an output filter is adopted to reduce Electromagnetic Interference (EMI).

TOPOLOGY OF THE POWER SUPPLY

Fig.3 shows the block diagram of the power supply and the timing sequence diagram of the control signals. To meet the dynamic performance of the kicker magnet, the high DC link voltage should increase or decrease the load current rapidly, the low DC link voltage should keep the output current with low ripple.

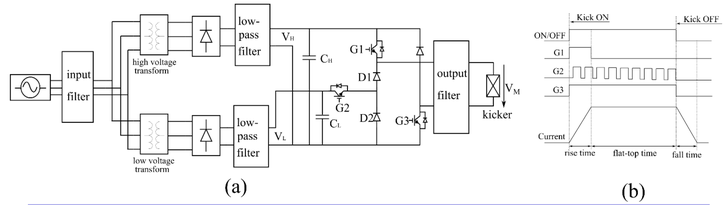

Figure 3: (a) Block diagram of the power supply; (b) Timing sequence diagram of control signals.

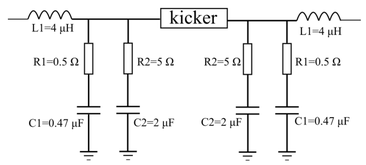

Figure 4: Circuit of the output filter.

It is crucial in selecting the value of the resistance R1, R2, the capacitance C1, C2 and the inductance L. The value of L is required to be less than one tenth of the kicker inductance to ensure the current change rate. The output filter capacitors should be minimized to reduce the power consumed in the resistances. A trade-off between the voltage oscillation, dynamic performance and engineering implementation should be made.

WAVEFORMS WITHOUT OUTPUT FILTER

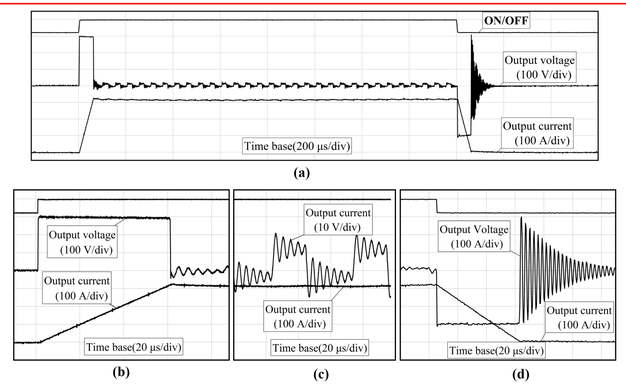

Figure 5: (a) Waveforms of measured load current and load voltage; (b) Kick ON state; (C) steady state; (d) Kick OFF state.

Fig.5 (a) shows the measurement results of a 310 A pulse of approx. 2 ms duration. The load current reaches its reference value after approx. 60 μs. The high DC link voltage is 300 V and the low DC link voltage is 13V. Fig.5 (b) show the waveforms of the Kick ON state. The output current is increasing linearly and there is even no current overshoot. Fig.5 (c) shows the waveforms of the steady state. the voltage oscillation is significant during the pulse width modulation of G2, which mainly caused by switching transient of D1, D2 and stray parameters in the circuit. Fig.5 (d) shows the waveforms of the Kick OFF state. After the load current reaches 0, the load and the circuit stray capacitance forms a free oscillation with underdamping. The voltage oscillation is approx. 300V at a frequency of about 200 kHz.

The voltage oscillation in Fig.5 (c) and Fig.5 (d) has little influence on the output current, but it would lead to a negligible Electromagnetic Interference (EMI).

WAVEFORMS WITH OPTIMIZED FILTER

Figure 6: Simplified filter

To verify the features of the output filter, a simplified filter was built with non-inductive solenoid resistors, film capacitors and magnetic rings, shown in Fig.6. Since there is no water circuit for the resistors, the output waveforms can only be measured with single pulse.

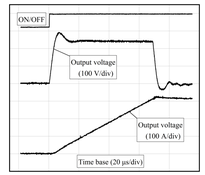

Figure 7: Kick ON state.

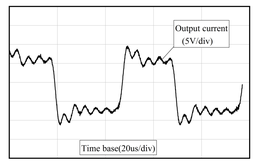

Figure 8: steady state.

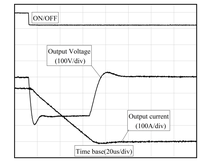

Figure 9: Kick OFF state.

Fig.7 shows the waveforms of the Kick ON state. With additional output filter, the current rising rate is reduced. It takes about 70 μs to reach the reference value (310A). The output filter causes the load voltage to overshoot by approx. 50V.

Fig.8 shows the waveform of the steady state. The output voltage oscillation of approx. 22 V in Fig.4 (c) is reduced to approx. 6V.

Fig.9. shows the waveform of the Kick OFF state. High-frequency voltage oscillations disappear and there is a 5% current undershoot. It takes about 50 μs to eliminate the current resonance.

However, the requirements given in Fig.2 can also be exceeded.

CONCLUSIONS

The optimized design of output filter and test of the power supply for kicker magnet in HUST-PTF has been completed. The features of output filter and control topology were verified on the test bench with two DC regulated power supply for DC link voltage. With output filter, the current rise rate is reduced, the output filter causes the load voltage to overshoot, and there will be current resonance during the kicker OFF state. However, it can also meet the physics requirements of the kicker function.

The drive current of the kicker magnet is 510 A and the high DC link voltage will be up to 400V. The assembly and commissioning of the kicker converter is expected to be completed in the end of this year.

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