PROGRAMMABLE POWER SUPPLY FOR AC SWITCHING MAGNET OF PROTON ACCELERATOR *

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Abstract

The 100 MeV PEFP (Proton Engineering Frontier Project) proton linac has two proton beam extraction lines for user experiment. Each extraction line has 5 beamlines and has 2.5 Hz operating frequency. An AC switching magnet is used to distribute the proton beam to the 5 beam-lines, An AC switching magnet is excited by PWM-controlled bipolar switching-mode converters. This converter is designed to operate at ±350A, 2.5 Hz programmable current step output. The power supply is employed IGBT modules and has been controlled by a Digital Signal Processor (DSP). This paper describes the design and test results of the power supply.

INTRODUCTION

The 100 MeV PEFP proton linac is supposed to generate a proton beam with the peak current of 20 mA, the pulse length of 2 ms, and repetition rate of 120 Hz. It will provide two proton beam extraction lines at 20 MeV and 100 MeV ends, for users experiments. Each extraction line will be branched to 5 beam-lines for 5 users at same time. In order to distribute proton beam to 5 beam-lines, an AC-type magnet will be used [1]. This magnet has been designed to have a cyclic frequency of 2.5 Hz (period: 400ms) and 8-step stairs bending field, so that 8 beam pulses are available during one period of AC magnet current. This AC-type magnet is excited by current-controlled PWM bipolar switching-mode converters. This converter is designed to operate up to ±350A, 2.5 Hz programmable stairs output as shown in Figure 1.

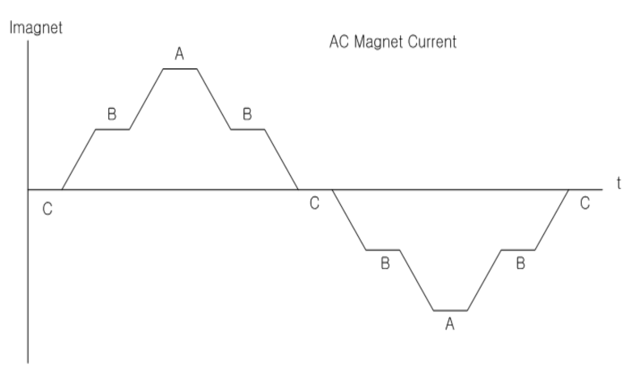

Figure 1:Required AC magnet current shape. A, B, C, D, E denotes each beamline.

SYSTEM DESCRIPTION

The power supply is employed IGBT modules and has been controlled by a DSP. Major specifications of system are follows;

- Magnet Inductance: 18.6 mH
- Magnet Resistance: 29 mΩ
- Maximum Output Current: 700 App stair type waveform
- Operating frequency: 2.5 Hz
- Maximum Output Voltage: 200 Vpp
- Switching Frequency: > 10 KHz

Figure 2 shows the simplified block diagram of an AC power supply. The topology is a full-bridge inverter, which can be a dc-to-ac inverter. The regulation is achieved by the pulse-width-modulation (PWM) method. Two dual packages of IGBT, Eupec IGBT type FF400R12KF4 (dual package), are used for switching devices due to their ruggedness and simple drive requirement in full bridge inverter.

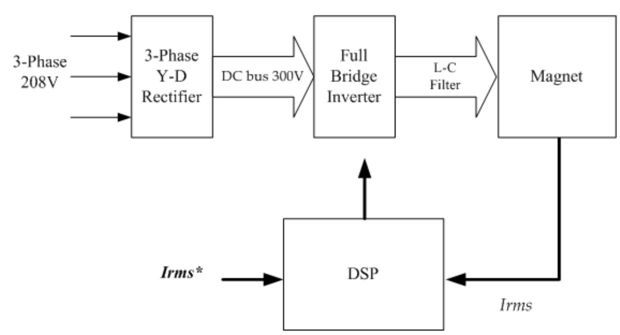

Figure 2: Block diagram of proposed AC power supply.

DC link design

The unregulated dc input bus voltage is required the minimum value to reduce the output ripple current without using any output filter, and is determined by the following expression [2]:

$$V_{in} = I_{pk}[(\omega L_m)^2 + R_m{}^2]^{1/2}\sin(\omega t + \phi) + I_{dc}R_m \quad (1)$$

Where I_{pk}=peak value of the ac current and

$\omega = 2\pi f$ (f = reference frequency)

$= 102.78\ [V]$

Required DC link capacitance is determined by the following expression:

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$$C = \frac{LI^2}{V^2} = \frac{0.0186 \times 350^2}{102.76^2} = 0.21577\ [F] \qquad (2)$$

Output Filter Design

As shown in Figure 3, output filter is composed of conventional L-C filter and additional R-C damper [3]. The R-C damper circuit allows only the high-frequency ripple current that may resonate between filter C_f and magnet inductance L_m. Designed filter had a slop of –20 dB per decade at the crossover frequency for safety. The frequency F_{esr} where the slope breaks from –40 dB into –20 dB is ~400 Hz. According to above assumption, calculated parameters are following:

Lf = 600μH, Cf = 4000μF, Cd = 16000μF, Rd = 1 Ω

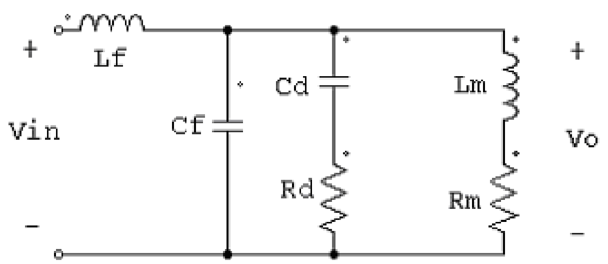

Figure 3: Output filter with magnet load.

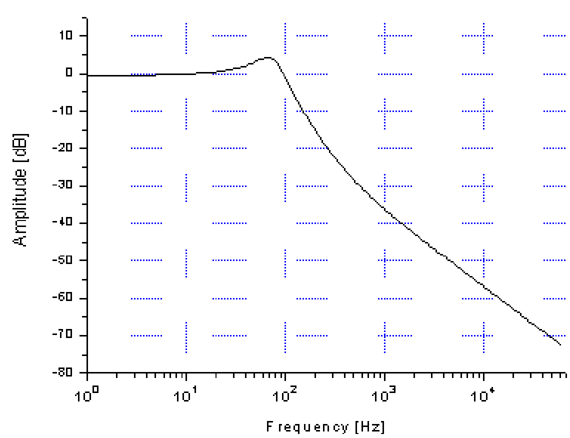

Figure 4: Amplitude responses of the designed filter, simulated by the PSPICE.

Simulation of proposed power supply

Figure 5 shows the model circuits of the proposed AC power supply were built with PSIM [4] that is a simulation package specifically designed for power electronic and motor controls. Thus the model of proposed power supply can be built using simple click and drag procedures at PSIM. It contains library models of almost typical power components. After building this model circuits, it is easy to extract any parameters inside the model. Figure 6 shows waveforms of simulated load current, load voltage and DC link voltage with given major specifications. In Figure 6, each stair is 50ms, transient time between each stair is about 23 ms and flattop is 27 ms.

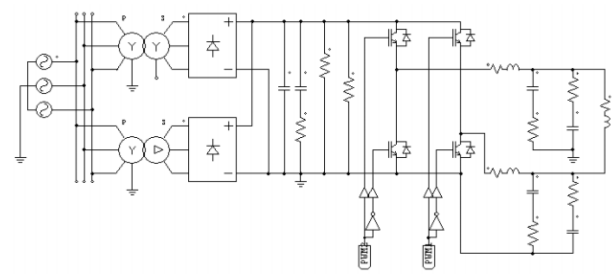

Figure 5: Model circuits of proposed AC power supply.

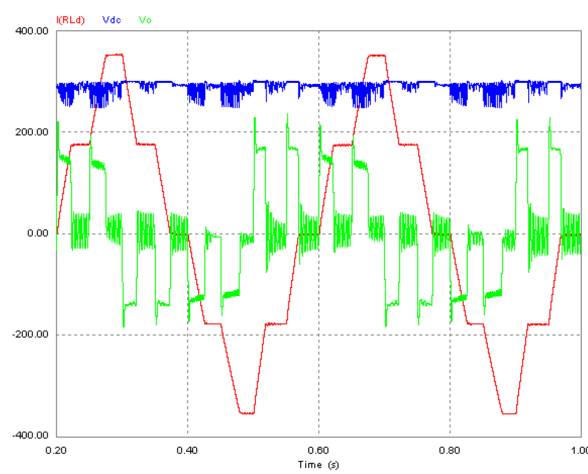

Figure 6: Simulation results of AC power supply, DC link voltage (300V), Load current (350App) and voltage (140V).

DSP Control

The dsPIC30F6010 digital signal processor from the Microship Technology Inc. was applied to control the AC magnet power supply. The DSP has a 16-bit architecture with an enhanced instruction, which has speed up to 30 MIPS. The switching frequency of pulse width modulation (PWM) of the power supply is 10 kHz, and the PWM duty cycle resolution is ~11-bit. To make circuits simple, an internal 10-bit ADC is used to digitize the output voltage of the 860R DCCT from Danfysik Co. for current feedback. The current errors which are differences between command and instantaneous load current were calculated every 1ms by the 16-bit fixed floating-point method. The output values of proportional and integral (PI) controller were limited to a certain value to prevent from overflow. There are small differences between modeled PI and physical PI coefficients which show critical damping responses of the load current. Three interrupt requests are handled in

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the PWM controller; 1) updates the PWM duty cycle while PWM is in progress, 2) calculates PI values every 1ms using the Timer2, and 3) scans the key pads every 100 ms using the Timer1. To prevent the IGBT failure, dead-time of 5 µs was provided for PWM I/O pin pairs. The PWM controller board can easily accept basic parameters such as P-gain, I-gain, step-width and etc. using the keypads and LCD panel on the board. The control program is composed using the C30 compiler. The object code of control program was simply loaded to a controller board through the USB port. Figure 7 shows the functional block diagram for the PWM controller.

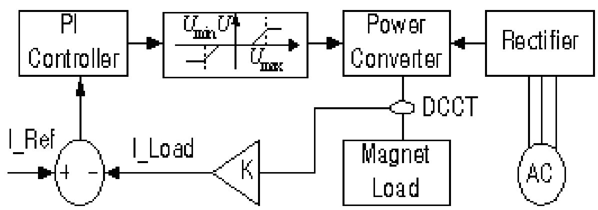

Figure 7: Control loop of DSP.

EXPERIMENT RESULTS

A prototype AC power supply has been built to test the performance. The quadrupole magnet of the PLS storage ring was used as a magnet load. The measured inductance is 21 mH and resistance 250 mΩ, which is similar with actual AC magnet characteristics. Figure 8 shows the output load current of magnet. A measured magnet current is stair waveform, 2.5 Hz frequencies and 175A peak with 136.8V of DC link voltage. Transient time between each stair is about 13 ms and flattop is 37 ms which is well agreed with simulation result. Figure 9 shows the fluctuation of DC link voltage while output current is supplied to magnet load. The measured fluctuation voltage is 5.8 Vpp at 175 A load current.

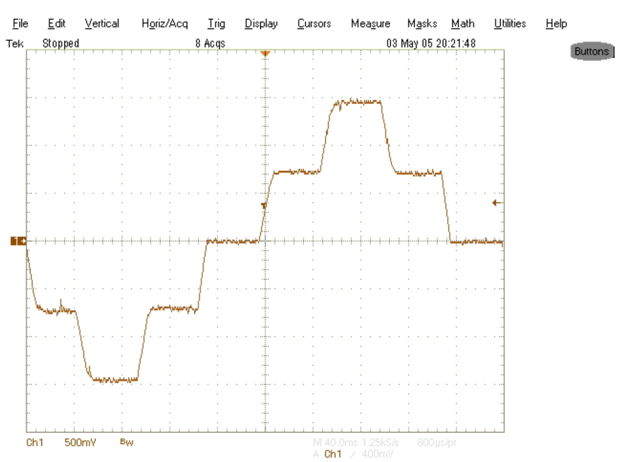

Figure 8: Actual load current of magnet.

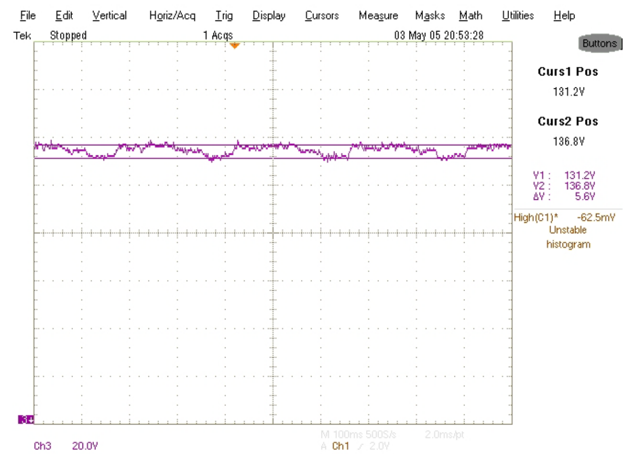

Figure 9: Fluctuation voltage of DC link.

CONCLUSION

In this paper a current-controlled PWM bipolar power supply for an AC switching magnet has been presented. This power supply is fully controlled by a DSP. From the simulation and experimental results with assembled power supply, output load current is well agreed with required current waveform for AC switching magnet of PEFP.

ACKNOWLEDGEMENT

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