PROGRAMMABLE POWER SUPPLY FOR DISTRIBUTION MAGNET FOR 20-MEV PEFP PROTON ACCELERATOR

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Abstract

The distribution magnet is powered by bipolar switching-mode converter that is employed IGBT module and has controlled by a DSP (Digital Signal Process). This power supply is operated at ±350 A, 5 Hz programmable stair output for beam distribution to 5 beamlines of 20-MeV PEFP(Proton Engineering Frontier Project) proton linac. Various applications for the different power supply are made simple by software. This paper describes the design and test results of the power supply.

INTRODUCTION

The 100 MeV PEFP proton linear-accelerator 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 can do their experiments at same time. In order to distribute proton beam to 5 beam-lines, a distribution magnet will be used as shown in Figure 1[1], where A, B, C, D, E denotes each beam-lines.
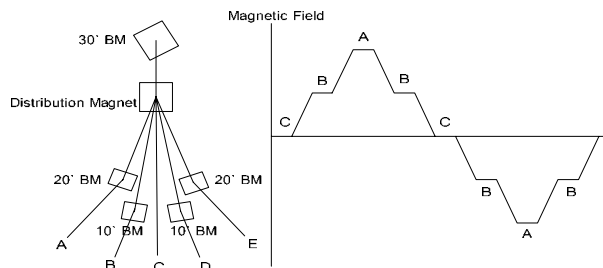

Figure 1: Required magnetic field shape. A, B, C, D, E denotes each beamline.

This magnet has been designed to operate with a cyclic frequency of 2.5 Hz (period: 400 ms) and 8-step stairs bending magnetic field, so that 8 beam pulses are available during one period of magnet field. Major specifications of magnet are as follows;

Magnet Inductance: 18.6 mH
Magnet Resistance: 29 mΩ
Bending Angle: ±20°
Maximum field: 0.4523 T at 20° bending
Magnet length: 0.5 m
Magnet gap width : 0.3 m
Magnet gap height: 0.05 m

In order to make magnetic field as shown in Figure 1,

the magnet need to excite by current-controlled PWM bipolar switching-mode converter. This converter is designed to operate up to ±350 A, 2.5 Hz programmable stairs output as shown in Figure 1. Since this stairs output makes sure that a proton beam with a finite pulse length can be transported along the beam-lines without beam loss. The proposed programmable power supply has been realized using single-chip DSP320F2812 digital signal processor from the Texas Instrument. It is well known that digital control has several advantages compared to analog control. The main advantages of digital approach over its analogue counterpart are; low sensitivity to changes in the environment such as temperature, supply voltage fluctuation, aging of components, and so on, and the possibility of a lower part count, thus increasing the integration level and improving the reliability as well as reducing assembling costs [2]. This paper describes the development of a programmable power supply (PPS) using switch-mode power conversion for the distributing magnet of the 20-MeV PEFP proton linear-accelerator extraction beam line.

SYSTEM DESCRIPTION

The topology is a full-bridge inverter, which can be a dc-to-ac inverter. The switching frequency is 10 kHz synchronized with main clock. This PPS is water-cooled. The power supply employed IGBT modules and has been controlled by a DSP. Major specifications of system are as follows;

Maximum Output Current: 700 App stair type
                              bipolar waveform
Operating frequency: 2.5 Hz
Maximum Output Voltage: 200 Vpp
Switching Frequency: > 10 KHz

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. From DSP to driver for switch is communicated with optic for noise rejection. The current measuring device is a zero-flux current transducer (CT). 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 [3]:

$$V_{in} = I_{pk}[(\omega L_m)^2 + R_m^2]^{1/2} \sin(\omega t + \phi) + I_{dc}R_m \qquad (1)$$
$$= 102.78\ [V]$$

Where I_{pk} = peak value of the ac current and $\omega = 2\pi f$, f = reference frequency.

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Required DC link capacitance is determined by the following expression:

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

DSP CONTROLLER MODELING

The equivalent circuits of the PWM AC power supply with a LC output filter and magnet load were shown in Figure 2. A damped filter, which is series circuits of a resistor and a capacitor, to reduce the output peak was not shown to make calculation simple.
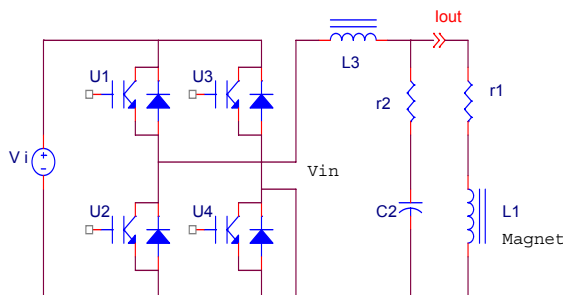
Figure 2: PWM inverter used in AC power supply for magnet.

The voltage to current transfer function above circuits is given:

$$P(s) = \frac{Iout(s)}{Vin(s)} = \frac{4e^{-5}s + 1}{4.464e^{-9}s^3 + 7.75e^{-7}s^2 + 0.0192s + 0.029} \quad (3)$$

where filter inductor L3 is 20 μH, filter capacitor C2 is 400 μF, ESR of the capacitor $r_2 = 0.1 \ \Omega$, the inductance of the magnet L1 is 18.6mH and resistance is 0.029 Ω.
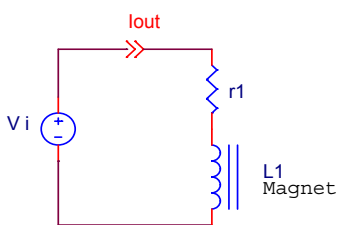
Figure 3: Reduced Model for digital controller design.

The Figure 2 could be reduced to Figure 3, because, in equation (3), high-order terms are much smaller than the first order of magnet model. Thus the transfer function (3) might be replaced with the simplified transfer function:

$$P(s) \cong \frac{1}{sL_1 + r_1} \qquad (4)$$

A PI controller is used for the AC power supply:

$$Gc(s) = \frac{Kps + Ki}{s} \qquad (5)$$

Then the closed-loop control system for the AC power supply given Figure 4.
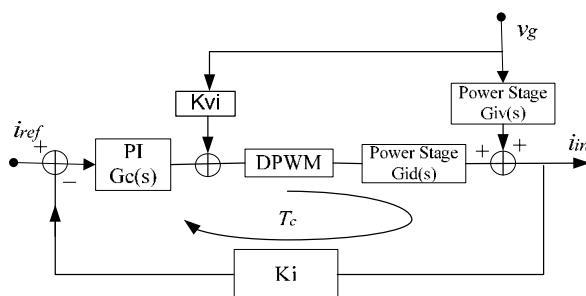
Figure 4: Block diagram of complete current loop system.

The discrete current loop gain, *Tc* is:

$$Tc(s) = Gc(s) \bullet Gid(s) \bullet Ki \qquad (6)$$

The closed-loop transfer function of the power supply is given by:

$$\tilde{i}_{in}(s) = \tilde{i}_{ref}(s)\frac{CG_{id}}{1+T_C} + \tilde{V}_g(s)(\frac{G_{iv}}{1+T_C} + K_{vi}\frac{G_{id}}{1+T_C}) \ (7)$$

The Bode plot was drawn with kp =10 and Ki = 30 in Figure 5, where the steady-state error to velocity input and the damping factor for critical were chosen as $\zeta = 1$ and error ess = 0.001, respectively.
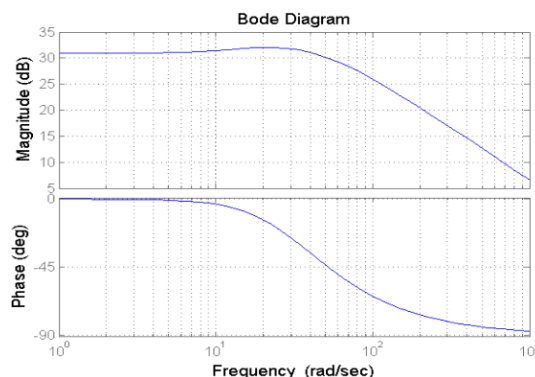
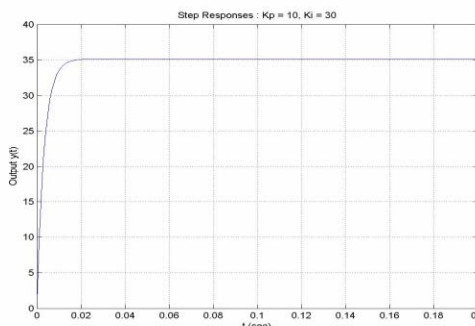Figure 5: Bode plot of the given closed-loop control system.

Figure 6: Step responses when Kp=10 and Ki=30. Output y(t) meant the output current which reached to the 350 A within 10 ms.

Figure 5 and Figure 6 show the Bode plot and step responses for the power system loop using the MATLAB. The shape of Bode plot was seen simple at a glance, but it really was a little more complicated one with output filter circuits**.**

DSP320F2812 is adapted for the power supply intended for the PWM application, which is a 150 MIPS, 16-bit fixed-point digital signal processor from Texas Instrument. This DSP implements a digital proportional-integrated feedback and feed-forward controller using 12-bit analogue to digital converters for reading the output current and link voltage. Applying for feed-forward loop in the control scheme, output current variation by the link voltage variation can be achieved more stabilization.

The sensed link voltage was used to modify the duty cycle. The updated duty cycle is expressed as

$$d_{update}(k) = d(k) + G_v \Delta d(k), \text{ where } \Delta d(k) = (V_{ref} - v_{in}(k))/V_{ref}$$

and G_v is the feed-forward gain. Two PWM channels and compare registers are associated with each PWM channel pair to generate PWM outputs, which are connected directly to the IGBT drive board.

The control loop was updated by 1 ms timer interrupt and switching frequency was 10 kHz with about 12-bit resolution in up-down count mode. The loop has eight processing states mapping to the each eight different current set and each state was initialized to have corresponding duty cycle to the current in order to reduce the response time. The PWM control was turned off during the increasing or decreasing periods as shown in Fig. 7.

The output current was increased the fastest rate with applying the link voltage to the magnet by turning on two IGBTs about 20ms without any PWM control, and, while decreasing magnet current, all IGBTs are turned off so that the stored energy of the magnet was discharged through the wheeling diodes of the IGBTs by the time constant of the magnet circuits itself. The current waveform on the magnet, link voltage and PWM control signal were shown in Fig. 7.

To make circuits simple, an internal 12-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-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 modelled PI and physical PI coefficients which show critical damping responses of the load current. Two interrupt requests are handled in the PWM controller; 1) updates the PWM duty cycle while PWM is in progress and reads the output current from the ADC, 2) calculates PI values every 1ms using the Timer 2. To prevent the IGBT failure, dead-time of 5 μs was provided for PWM I/O pin pairs. The control program is composed using the CCS2000 from Texas Instrument. The object code of control program was simply loaded to eZdspF2812 board through the JTAG.

EXPERIMENT RESULT

A prototype power supply has been implemented to verify 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 distribution magnet characteristics.
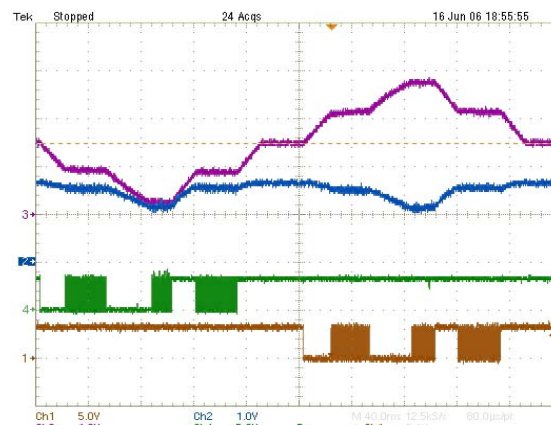

Figure 7: Actual load current of magnet, DC link voltage and IGBT PWM voltage.

Figure 7 shows the test results of PPS. This figure shows the output current, DC link voltage and PWM waveform of IGBT each. The first two waveforms are the output current and fluctuation voltage of DC link. The bottom two waveforms are PWM waveform of IGBTs. A measured magnet current is stair waveform, 2.5 Hz frequencies and 560 App with about 60 Vpp fluctuations for 158 V of DC link voltages. Transient time between each stair is about 27 ms and flattop is 23 ms which are a little different from each stage because of time constant of magnet.

CONCLUSION

This paper deals with a current-controlled PWM bipolar power supply for a distribution magnet of 20 MeV PFEP proton linac extraction beamline. 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 distribution magnet of PEFP.

REREFENCES

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[2] Vallittu. P, "Digital Control of Power Supplies-Opportunities and Constraints" Industrial Electronics Society, 1998. IECON '98. Proceedings of the 24th Annual Conference of the IEEE Volume 1, 31 Aug.-4 Sept. 1998, p. 562.

[3] Y. G. Kang, "Design and Development of Bipolar Power Supply for APS Storage Ring Correctors," Proceeding of PAC 1993, Washington, D.C., U.S.A, p. 1268.