STAIR CURRENT OUTPUT POWER SUPPLY FOR SWITCHING MAGNET*

Seong-Hun Jeong#, Ki-Hyeon Park, Heung-Sik Kang, Dong-Eun Kim, Jin-Hyuk Choi,
PAL, Pohang, 790-784, Korea

Abstract

The switching magnet for beam distribution is served with Digital Signal Processor (DSP) controlled PWM switching-mode power supply (SMPS). This SMPS is employed phase-shifted parallel (PSP) operation of IGBTs. This technique allows ± 350 A, 2.5 Hz stair output, and ± 350 A at bipolar mode operation. Current feedback and input voltage feed-forward control schemes are applied to improve the output current stability. Experimental results showed that the implemented converter achieved a useful versatile power supply.

INTRODUCTION

High current sources are needed in accelerators to bend and focus of electron beam. For these application, the power supply demands several types of output. In some cases, high stability current source for stringent specification of load was required.

The DSP had been developed primarily for application in various high speed digital signal processing. Due to its fast computational speed nowadays, the DSP has replaced much of the complex control hardware. The applications of high-performance DSP in complicated power electronic systems have found great potential in synthesis of sophisticated control algorithms and PWM switching schemes [1].

In order to achieve requirements of accelerator current source, DSP based current-controlled PWM bipolar SMPS using the TMS320F2808 from the Texas Instrument was developed for universal purposes. This SMPS is possible to operate in two modes by program. The one mode is arbitrary waveform current source and the other is bipolar current source. Each mode use phase-shifted parallel operation of IGBTs, so, it is possible to increase power rating and operating frequency by a factor of 2 [2].

Conventionally, the regulation circuits of a SMPS are realized using analog circuit technique. Analog controller is easy to implementation and good for simple circuits. With a good DAC and the other fine circuits, a high stability SMPS can be archived. But, analog control technique also has its demits in complex circuit design, low reliability, non-flexibility, and higher manufacturing cost.

This paper describes the development of a programmable power supply (PPS) using a DSP-controlled phase-shifted parallel SMPS for accelerator magnet.

*Work supported by Ministry of Science and Technology of Korea.
#jsh@postech.ac.kr

SYSTEM DESCRIPTION

The simple diagram of the power supply with LC output filter and magnet load were shown in Figure 1. The SMPS scheme consists of two full bridge rectifiers followed by each full bridge inverter. Two DC-links of full bridge rectifiers are connected to each other to maintain same voltage. The topology is full bridge parallel inverter, which can be a dc-to-ac inverter. The basic concept of operation mode is phase-shifted parallel operation of IGBTs modules, where each IGBT has shared equal average current that is inherent in the PSP operation mode. This power supply has two operation modes. First mode is arbitrary current waveform generator and second is bipolar SMPS.

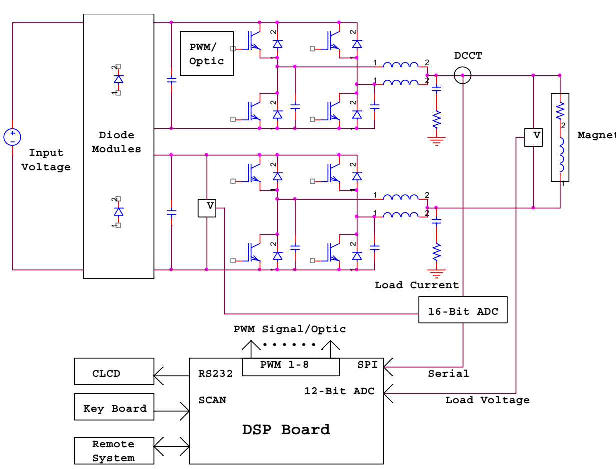

Figure 1: System Schematic Diagram.

Figure 1 shows control signal flow between the IGBT modules and the DSP and external devices.

This PPS was configured as a parallel full bridge type for driving higher load current, where each full bridge can drive 200A at 10 KHz switching frequency.

Owing to the PSP, the system operating frequency is doubled to 20 kHz and each IGBT current burden is one half of total current. Another advantage of PSP is one that the inductance value for output filter was reduced to one half comparing to the single full bridge type.

Current feedback and input voltage feed-forward control schemes are applied to improve the output current stability. The switching device is four dual packages of IGBT FF400R12KF4 from Eupec. The fiber optic connector HFBR series from Agilent Co. is used to interface from DSP to driver board for IGBT to improve system noise susceptibility and ground isolation. Two external 16-bit ADCs AD977A from Analog Devices are used to digitize the output voltage of the 860R DCCT from Danfysik Co. for current feedback. The current errors which are differences between reference current and averaged load current is calculated every 0.5 ms, and duty ratio is updated to make error as small as possible. Output filter is composed of conventional L-R-C filter which includes an R-C damper circuit to make good filter response.

DSP CONTROLLER MODELING

The filter and magnet load part of the Figure 1 could be reduced to Figure 2, because the values of filter components are much smaller than that of the magnet model.

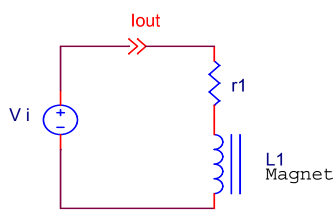

Figure 2: Simplified magnet model for digital controller design.

Thus the transfer function might be simplified as follow:

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

A conventional PI controller is used for the PPS:

$$Gc(s) = \frac{Kps + Ki}{s} \qquad (2)$$

Where, *Ki* and *Kp* are coefficients of integral and proportional gain, respectively. The PI coefficients are calculated directly using the characteristic equation of the control loop and compared to the result of the PSIM simulator [3]. Differences between two methods were in the order of range and the PI control loop worked very well. Then, the closed-loop control system for the PPS is given Figure 3.

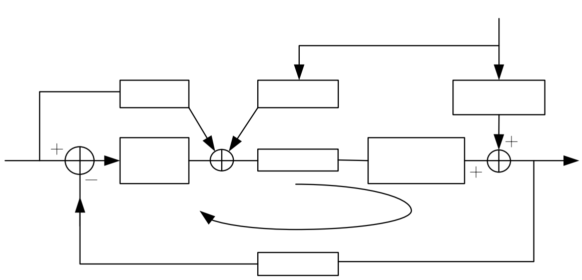

Figure 3: Block diagram of complete current loop system.

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

$$i_{out}(s) = i_{ref}(s)\left(\frac{G_C G_{id}}{1+T_C} + \frac{K_{FF} G_{id}}{1+T_C}\right) + v_g(s)\left(\frac{G_{iv}}{1+T_C} + G_v \frac{G_{id}}{1+T_C}\right)$$

while current loop gain, Tc is $Tc(s) = Gc(s) \bullet Gid(s) \bullet H(s)$.

The Bode plot was drawn with *Kp*=10 and *Ki* = 30 using the MATLAB in Figure 4. The shape of Bode plot was seen simple at a glance, but it really was a little more complicated one with complete output filter circuits. The sensed link voltage was used to modify the duty cycle. The updated duty cycle is expressed as $d_{update}(k) = d(k) + G_v \Delta d(k)$, where $\Delta d(k) = (V_{ref} - v_{in}(k))/V_{ref}$ and G_v is the feed-forward gain.

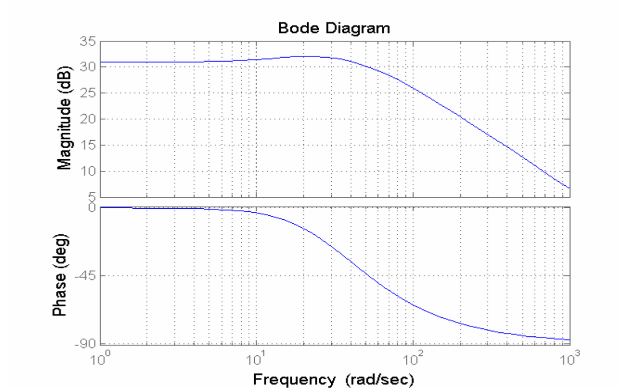

Figure 4: Bode plot of the given closed-loop control system.

CONTROL HARDWARE CONFIGURATION

The eight Enhanced Pulse Width Modulation (EPWM) signals are generated by the DSP. Four PWM signals of eights are generated with PWM control registers with updated PWM duty ratio according to the current direction, while the others are all off.

Four IGBTs in the first column in Fig.1, used as phase reference zero and the other in second column had phase shift of 180 Degree. Since PSP mode, the input voltage is subdivided into two pulse trains, the duty cycle of each IGBT is one half of the converter duty cycle.

After output current has been digitized ten times by two ADCs between control loops, the ADC values were added and averaged by divided by twenties to smooth the sensed load current value to keep the power system good control stability.

The rising or falling time of the current waveform depends on the time constant of the load magnet and DC input voltage. At the end of the rising mode of current or visa verse, the control loop should keep the load current constant for certain duration of 20ms for example, where PI control value was different from that of prior one. Thus, feed-forward compensation was necessarily required to archive fast output responses with changed control circumstances. The output current was increased in the fastest rate with applying the link voltage to the magnet without any PWM control for about 20 ms, 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.

ADC procedure and EPWM duty control are serviced by the each real time interrupt routine. And Timer Interrupt of the DSP was used for control loop. Both key scan and the LCD display were carried out at the base routine not to disturb the PWM interrupt.

The control program is composed using the CCS2000 from Texas Instrument. The object code of control program was simply loaded to developed home-made board through the JTAG.

EXPERIMENT RESULTS

A PPS has been implemented using the DSP, eights IGBTs and the other electric componenets. The quadrupole magnet of the PLS storage ring was used as a magnet load which inductance is 21 mH and resistance 25 mΩ. Figure 5 shows the phase-shifted voltage of each IGBTs. In this Figure, the Ch3 and Ch4 are forward voltages of PWM 1 and PWM 2. And the Ch1 and Ch2 are return voltages of PWM 1 and PWM 2 respectively, where we can see that PWM 1 and 2 are added. The Figure 6 shows the test results of PPS. This figure shows the output stair current. A measured magnet current is stair waveform, 2.5 Hz frequencies and ± 200A for 160 V of DC link voltages. Transient time between each stair is about 23 ms and flattop is 27 ms which are a little different from each stage because of time constant of magnet. Another experimental result is bipolar SMPS operation. The output current is ± 350 A at 160 V of DC link voltage. At this mode, the current stability is less than 80 ppm. The PSP mode was well worked. The current difference between parallel arms is less than 1 A at full current output. The surface temperature of output filter core rose to about 60 °C, but IGBT modules and rectifier diodes were under the 40 °C cooled by water.

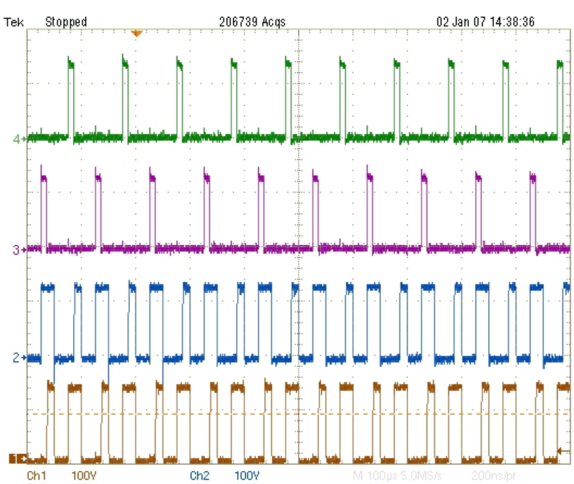

Figure 5: IGBT PWM voltage (Ch1: PWM-1 return, Ch2: PWM-2 return, Ch3: PWM-1 forward, Ch4: PWM-2 forward).

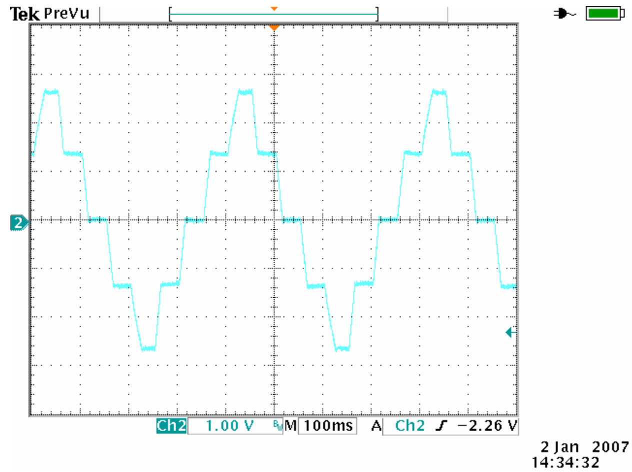

Figure 6: Actual load current of magnet (± 200A).

CONCLUSION

This paper deals with DSP-controlled PSP SMPS for accelerator magnet. This PPS is fully controlled by a DSP. From the experimental results with assembled power supply, output load current is well agreed with programmed arbitrary current waveform. In bipolar mode, the power supply output is ± 350 A with 160 V DC-link voltage. There was about 1 A difference between parallel arms at ± 350 A current output. The core temperature of output filter was about 60 °C, but IGBT modules and rectifier diodes were under the 40 °C cooled by water. The stability of this PPS is less than 80 ppm. It will be improve to 50 ppm in near future.

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[3] www.powersim.com POWERSIM, Powersim Inc. Andover, MA