ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF008

PRELIMINARY DESIGNS AND TEST RESULTS OF BIPOLAR POWER SUPPLIES FOR APS UPGRADE STORAGE RING*

Ju Wang, Gary Sprau, Iftikhar Abid, Robert Keane
Argonne National Laboratory, Argonne, IL 60439, USA

Abstract

After the development of prototype fast corrector power supplies (FCPS) for the APS upgrade (APS-U) [1, 2], we performed preliminary designs to incorporate findings from the prototypes, consolidate electronic circuits, and further improve the performance. Meanwhile, we also performed preliminary designs for the DC bipolar power supplies (DBPS) utilizing most of the designs for the fast corrector power supplies since they share many common requirement. This paper presents the changes and the improvement from the R&D prototypes and the test results.

INTRODUCTION

The APS-U requires 1243 bipolar power supplies for beam orbit corrections. Of 1243 power supplies, 322 are for fast corrector magnets and 961 are for slow correction or trim windings in multipole magnets. The following table lists the key specifications of the power supplies.

Table 1: Bipolar Power Supply Specifications

Parameters	FCPS	DBPS	Unit
Output current	±15	±15	A
Input voltage	40	40	V
Bandwidth (<1%)	10	N/A	kHz
Current accuracy	100	100	ppm*
Current stability	100	100	ppm*

* ppm – part per million of the maximum.

It can be seen from Table 1 that the only difference between FCPS and DBPS is the small signal bandwidth requirement. To achieve the required 10 kHz bandwidth, a prototype DC/DC converter utilizing a MOSFET H-bridge was developed through the R&D program. Figure 1 shows the measured frequency response for a current of 0.5% of 15 A into a prototype fast corrector magnet that has an inductance of 16 mH and a resistance of 0.3 Ω. At 10 kHz, the gain of the output current over the reference is at -0.352 dB, well within the -3 dB limit.

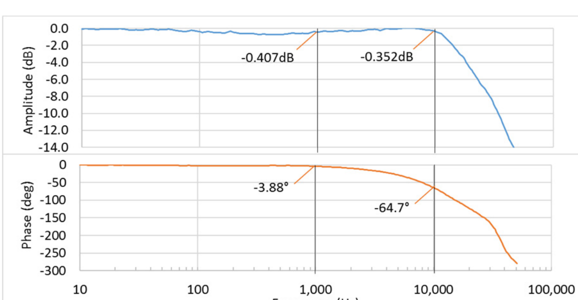

Figure 1: Frequency response of prototype FCPS.

* This work is supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under contract # DE-AC02-06CH11357.

POWER CIRCUIT

Based on the success of the R&D prototypes, we completed the preliminary designs with several changes to improve the performance and applied the same circuit and hardware designs with necessary parameter changes to the DC bipolar power supplies.

Figure 2 shows the power circuit of the preliminary design, which is very similar to the circuit of the R&D prototypes with changes to the input section, to the output section, and to the current sensing device.

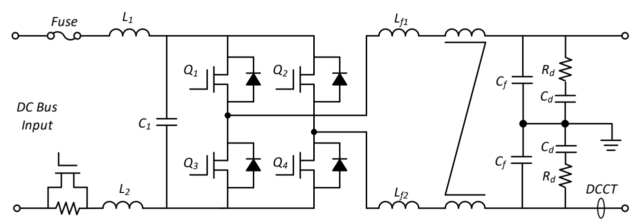

Figure 2: Power circuit.

Input Filter

In the input filter, two regular inductors replace the common-mode choke in input filter of the prototypes. The common mode choke worked well to reduce the common-mode ripple in the input DC voltage. It, however, helped little to reduce the more prominent AC harmonic components. It was also found that the common-mode choke did not limit the inrush current when the power supply was connected to a live DC bus, which will be the way to replace a failed power supply during operations. The regular differential inductors help both reducing input voltage ripples and limiting the inrush current.

Soft-start Circuit

As shown in Figure 2, a soft-start circuit, consisting of a resistor paralleled with a MOSFET switch, is added to the return path of the input. The soft-start circuit provides an overdamped condition when the power supply is first connected a live DC bus. The resistor is shunted out by the MOSFET switch after the capacitor bank is charged to the bus voltage.

Output Filter

In the output section, a common-mode choke is added to the output filter. The common-mode choke is transparent to the differential-mode voltage and does not affect the bandwidth of the circuit, which is extremely important to FCPS, but acts as a regular inductor to reduce the common-mode voltage ripple with respect to the earth ground.

Table 2 lists the filter parameters for the fast corrector power supplies and the DC bipolar power supplies. The

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF008

values of the inductors and the capacitors are chosen based on the availability of commercial hardware.

Table 2: Output Filter Parameters

Parameters	FCPS	DBPS	Unit
L_{f1}, L_{f2}	10	70	µH
C_f	0.1	0.56	µF
C_d	0.39	2.2	µF
R_d	10	10	Ω
Corner frequency	159.2	25.4	kHz
Common-mode choke	0.62	0.62	mH

Current Sensing Device

In the R&D prototypes, a hall-effect current sensor, LEM LA 25-NP, was used as the current sensor. In the preliminary design, it was decided to replace the LEM with a zero-flux DC current transducer (DCCT), CT-150-P-O by CAENels. The LEM worked well in terms of the frequency response. However, the DCCT provides better stability and accuracy for the current measurement and hence the better current regulation.

MOSFET Cooling

Another improvement in the preliminary design is the cooling of the MOSFET heatsink. In the R&D prototypes, a constant-speed, 38-mm fan was used for the heatsink cooling. In the preliminary design, the constant-speed fan is replaced with two variable-speed fans to improve the overall reliability. If one fan fails, the remaining fan can still provide the needed cooling with only a minor increase in the temperature of the MOSFET heatsink. The speed of the fans is continuously monitored. In case the speed of a fan becomes too low, it will be replaced during next weekly maintenance period. Figure 3 shows a constructed power circuit for a fast corrector power supply.

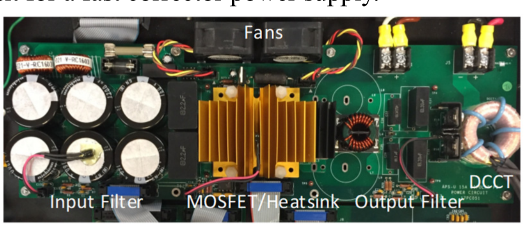

Figure 3: Constructed power circuit.

SCHEMATIC AND PCB DESIGNS

In the R&D prototypes, several control circuits such as the regulator circuit, the PWM generator, and the MOSFET gate driver were designed as modular printed circuit boards (PCB) and assembled on a baseboard to provide flexibility for revisions of each individual circuit. Since the circuits worked very well, the preliminary design integrates all the circuits on one PCB.

PWM Generator and Current Regulator

The DBPS shares the same PWM generator circuit with the FCPS. Since there is no need for fast responses, the PWM frequency for DBPS is reduced from 500 kHz to 250 kHz to reduce the MOSFET switching losses. The change of the PWM frequency is achieved easily with a simple on-board jumper configuration. With the reduced PWM frequency, the average temperature of the MOSFET heatsink is reduced by five degree Celsius.

The regulator circuit contains two parts: a second-order Sallen-Key lowpass filter and a proportional-and-integral (P-I) compensator followed by a lead compensator. The cut-off frequency of the lowpass filter is 28.6 kHz for the FCPS and 2.86 kHz for the DBPS. The parameters of the P-I and the lead compensators for the FCPS are unchanged from the prototypes while the parameters for the DBPS are to be determined since the parameters of the slow correctors and the trim windings are not finalized yet.

TEST RESULTS

Figure 4 shows a fully constructed fast corrector power supply from the preliminary design. It has three major components – a power circuit, a regulator and PWM driver circuit, and a monitor/interlock circuit. The DC bipolar power supply looks very similar with only differences in the sizes of the hardware components of the output filter.

Figure 4: FCPS from preliminary design.

Output Waveforms

Figure 5 shows the waveforms of the output current and voltage of an FCPS for a step reference function. The voltage waveforms show the switching voltage ripples are effectively reduced by the output filter in both the differential mode and the common mode.

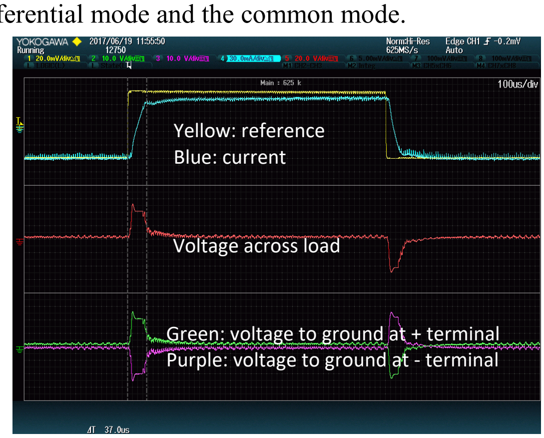

Figure 5: Output current and voltage waveforms.

Stability Measurement

Figure 6 shows the stability of the output current of a DBPS over a period of ten hours. It shows no noticeable change in the current when the room temperature increased more than one degree in the morning.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF008

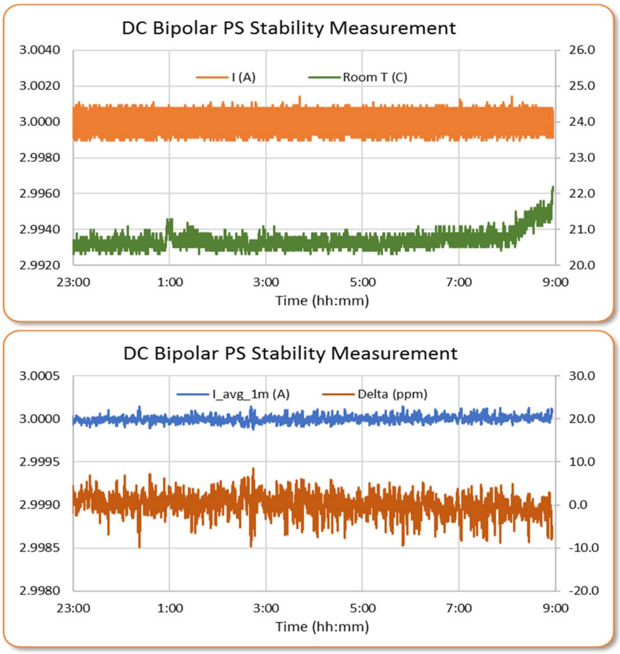

Figure 6: Measure current stability over 10 hours.

After the measurement noises are removed from the raw date by averaging over one minute, the result shows a stability better than ±10 ppm of 15 A, which is well within the 100-ppm specification.

MOSFET Heatsink Temperature

Figure 7 shows the MOSFET heatsink temperature of two types of the power supplies operating at 15 A under different ambient temperatures. When the ambient temperature increases from 25°C to 46°C, the heatsink temperature increases to 59°C for FCPS and 54°C for DBPS, respectively.

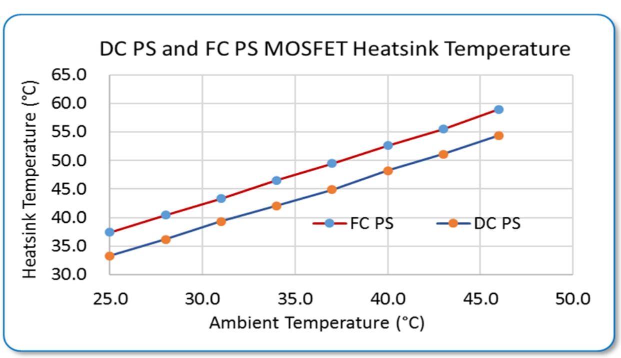

Figure 7: MOSFET heatsink temperature vs. ambient temperature at 15 A.

Based on the heatsink temperature and the measured power supply efficiency, the calculated average junction temperatures of the MOSFET devices are 44.5°C for DBPS and 57.1°C for FCPS, respectively, when they are operating at 15 A and at room temperature. These junction temperatures are well within the safe operation region of the MOSFET device.

Comparison of DCCT and LEM

Figure 8 shows the performance comparison of the DCCT and the LEM. With the DCCT, a simple linear fit can be applied to the current reference to improve the accuracy to within ±100 ppm over the whole range (green trace in the picture). With the LEM, the linear fit does not work because the nonlinearity of the LEM gain. A more complicated fitting algorithm would have to be used.

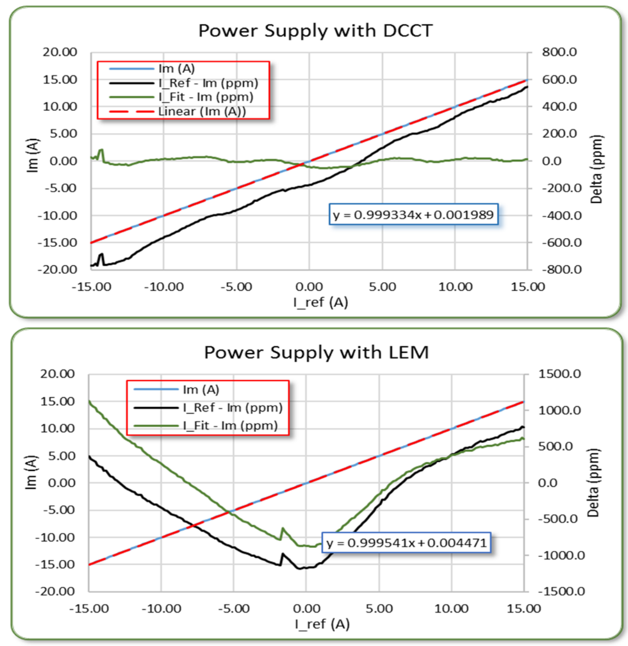

Figure 8: Comparison of DCCT and LEM.

CONCLUSION

Based on the prototype fast corrector power supplies developed in the R&D phase of APS-U, the preliminary designs have been performed on the power circuit and the control circuit of the fast corrector power supplies. Most of the designs are applied to the DC bipolar power supplies as well because of the common requirement between the two types. This paper presents the changes and improvement in the preliminary design and the test results as well.

ACKNOWLEDGEMENT

Authors would like to express sincere appreciation to T. Meier, J. Goetzen, and J. Vanis for their contributions to the construction of the PCBs and the power supply units.

REFERENCES

[1] B. Song and J. Wang, "Mathematical Modelling and Analysis of a Wide Bandwidth Bipolar Power Supply for the Fast Correctors in the APS Upgrade," in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, paper WEPTY004, pp. 3264-3266.

[2] J. Wang and G Sprau, "A High Bandwidth Bipolar Power Supply for the Fast Correctors in APS Upgrade", in *Proc. NAPAC'16*, Chicago, IL, USA, Oct. 2016, pp. 96-98, doi.org/10.18429/JACoW-NAPAC2016-MOPOB12.