A HIGH BANDWIDTH BIPOLAR POWER SUPPLY FOR THE FAST CORRECTORS IN THE APS UPGRADE*

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Abstract

The APS Upgrade of a multi-bend achromat (MBA) storage ring requires fast bipolar power supplies for the fast correction magnets. The key requirement of the power supply includes a small-signal bandwidth of 10 kHz for the output current. This requirement presents a challenge to the design because of the high inductance of the magnet load and a low input DC voltage (40V). A prototype DC/DC power supply using a MOSFET H-bridge circuit with a 500kHz PWM control has been developed and tested successfully through the R&D program. The prototype achieved a 10-kHz bandwidth with less than 3-dB attenuation for a signal 0.5% of the maximum operating current of 15 amperes. This paper presents the designs of the power and control circuits, the component layout, and the test results.*

INTRODUCTION

At IPAC2015, we reported a switching-mode bipolar power supply to be used to achieve the required high bandwidth performance [1]. Since then, we have completed the schematic designs, manufactured the PCBs (printed-circuit board), and constructed a prototype power supply. The test showed that the 10-kHz bandwidth requirement had been achieved with a load of the similar resistance and inductance to the expected magnet.

POWER CIRCUIT

The circuit, shown in Figure 1, for the fast corrector power supply is a typical four-quadrant buck converter. The circuit consists of three sections – an input filter, L_1 and C_1; a standard H-bridge with four MOSFET switches, $Q_1 – Q_4$; and an output filter, L_{f1}, L_{f2}, C_f, C_d, and R_d.
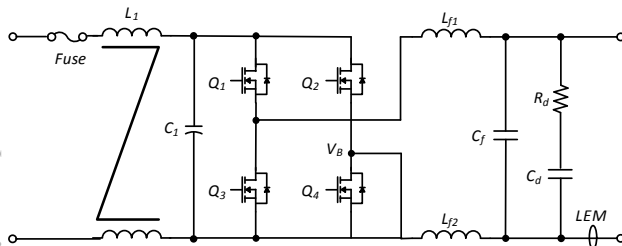

Figure 1: Power circuit.

The parameters of the components in the circuit are:

L_1: common mode, 0.5mH, C_1: 8000µF
$Q_1 – Q_4$: IRFB4610, 100V, 73A, 11mΩ

L_{f1}, L_{f2}: 10µH, C_f: 0.05µF, R_d:20Ω, C_d:0.2µH
LEM: LA 25-NP, 1000:1 current transfer ratio

The size of the input filter capacitor bank is based on the available space. This is to reduce ripple voltage and voltage fluctuations from the unregulated DC distribution that will be used in the final installation. MOSFET IRFB4620 is chosen as the switch for its low on-resistance of 11 mΩ. The output filter is a second order and damped filter. With the chosen parameters, the cut-off frequency of the filter is 160 kHz, which effectively removes the fast voltage spikes in the output without causing excessive delays and hence without affecting the speed of the power supply. A hall-effect current sensor, LEM LA 25-NP, is used to measure the current and provide the feedback signal for the current regulation.

LA 25-NP

SCHEMATIC DESIGNS

Triangular Waveform Generator

To generate the triangular waveforms for the PWM control, an 8-MHz oscillator, LTC6930CMS8-8.00 from Linear Technology, is configured to produce a 250-kHz clock signal. The clock signal then drives a MOSFET to charge and discharge an integrator through an AC coupling circuit to produce a symmetrical triangular waveform.
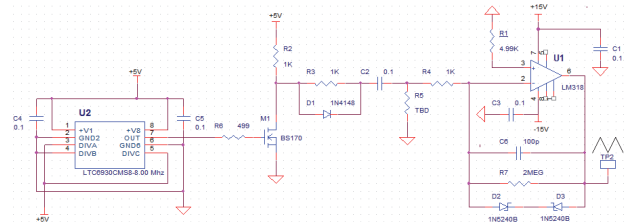

Figure 2: Triangular waveform generator.

In Figure 2, the value of R5 can be used to adjust the amplitude of the triangular waveform. When U2 is configured for 250kHz, R5 is not needed to produce a 10V amplitude.

Current Sensing and Conditioning Circuit

Figure 3 shows the current sensing and conditioning circuit. The signal from the LEM sensor drives a 200Ω burden resistor to produce a 3V signal at the full scale of 15A. This signal is filtered to reduce the unwanted ripple components and further scaled to an appropriate level before compared with the reference signal. The first stage of the circuit provides a precision gain of two with an

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instrumentation amplifier, INA105. The second stage is a second-order Sallen-Key 28.6kHz lowpass filter with a gain of 5/3.
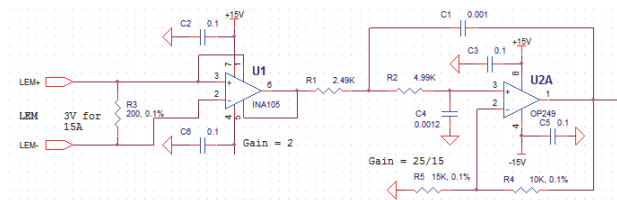

Figure 3: Current measurement and conditioning circuit.

The critical component in the filter circuit is the operational amplifier. In general, the amplifier needs to have a gain-bandwidth product (GBP) 100 times the cut-off frequency. Although OP249 has a typical GBP of 4.7 MHz, it still cannot sufficiently suppress very fast voltage spikes picked up by the circuit. A better amplifier needs to be selected or a better filter circuit needs to be designed in the future.

Regulator Circuit

The conditioned current signal is compared with the reference to produce an error signal at the output U5 in Figure 4. The error signal is sent to a proportional-and-integral (P-I) compensator followed by a lead compensator.
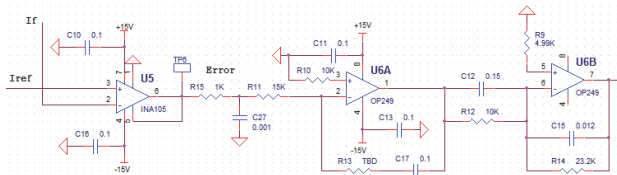

Figure 4: Regulator circuit.

R13 in the P-I compensator is used to adjust the regulator based on the load parameters. Several values from 50kΩ to 500kΩ have been tested. The final value will be chosen when the magnet becomes available.

MOSFET Gate Drive Circuit

Four MOSFETs in the H-bridge need to be electrically isolated from each other and from the PWM circuit. The isolation is achieved by using an isolated power supply for each gate drive circuit and using an optocoupler gate driver, Toshiba TLP152, to interface with the PWM circuit. An example of the gate drive circuit is shown in Figure 5.
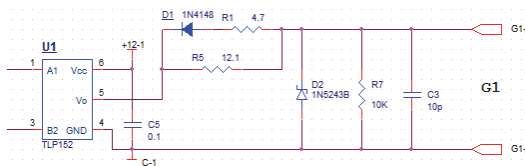

Figure 5: MOSFET gate drive circuit.

In Figure 5, R5 is the gate-on resistor and R1 is the gate-off resistor. A larger resistance is chosen for R5 to make the MOSFET turning-on slower than the turning-off. This is to prevent a possible destructive shoot-through condition between two MOSFETs connected in series between the positive rail and the negative rail of the DC bus, Q_1 and Q_3

in Figure 1 for example. The chosen resistor values combined with the MOSFET parasitic capacitances produce an approximately 40-ns delay between the turn-on and the turn-off gate signals.

MECHANICAL DESIGNS

Component Layout

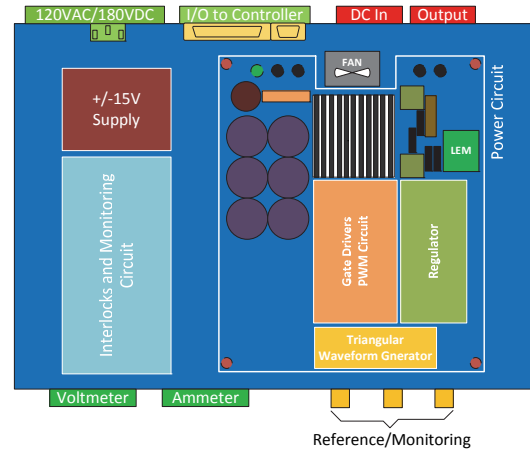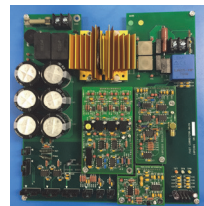Figure 6: Power supply component layout.

Figure 6 shows the layout of the components inside the power supply chassis. The major components are:

1) Power and control circuits
2) Interlock circuit
3) +/-15V AC/DC power supply for control circuit
4) Heatsink for the MOSFETs

Since it was anticipated that the designs would need to go through several iterations during the prototyping process, a modular design was used so that partial changes could be made without redesigning the whole circuit. The power circuit was designed as a mother or main board. Three control circuits were designed as daughter cards – a triangular waveform generator card, a regulator card, and a PMW and MOSFET gate driver card, to be mounted on the mother board.

An interlock circuit was designed to provide remote and local on/off controls and to protect the power circuit against conditions such as overcurrent, over temperatures of the major power components. The interlock circuit also monitors the magnet thermal conditions and turns off the power supply when the magnet temperature gets too high.

A 60W AC/DC power supply, TDK LAMBDA SCD601515, provides power to the control circuit.

To maintain the temperature of the MOSFETs within an appropriate range, the forced air cooling is used in combination with a heatsink, ATS-1106-C1-R0 by Advanced Thermal Solutions Inc.

All the power supply components are assembled inside a standard 1U chassis.
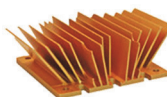
Figure 7: Assembled fast corrector power supply.

Figure 7 shows an assembled power supply and its front display. The power supply receives the reference signal via a BNC connector on the front panel. The reference signal and the output current can be monitored from the BNC connectors on the front panel. Two digital meters display the readings of the input or the output voltage and the reference or the output current, respectively. The selection of the display is controlled by two toggle switches.

The power entry and exit are mounted on the back panel of the chassis. The interfaces with the power supply controller are also on the back panel with two DB connectors.

TEST RESULTS

The prototype power supply has been tested with a 15-mH choke by Hammond Manufacturing since the fast corrector magnet was not available for the test. An external resistor was added to make the total resistance close to 0.2Ω as in the magnet design specification. A commercial AC/DC power supply was used to provide 40V DC input.

MOSFET Switching Waveforms

Figure 8 shows the MOSFET gating signals and the MOSFET Q_1 and Q_3 drain-to-source voltage waveforms during the transition between on and off. As can be seen, there is a 40ns delay between the gate signal for off and the gate signal for on. This delay ensures that the current in the switching-off MOSFET reduces substantially and the MOSFET recovers the voltage-withstanding capability before the other MOSFET is turned on, thus avoiding the shoot-through situation.
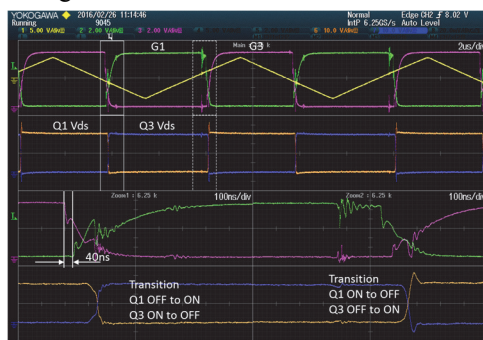

Figure 8: MOSFET switching waveforms.

Sinusoidal Waveforms

Figure 9 shows the measured current waveform for a 5-kHz sinusoidal reference with an amplitude of 1% of the full scale and with a zero DC component. The attenuation of the amplitude is minimal and the phase shift is about 18°. It can also be seen that the current goes thorough zero smoothly, which is a very important requirement of the power supply since the corrector current could be near zero for a particular beam orbit configuration.
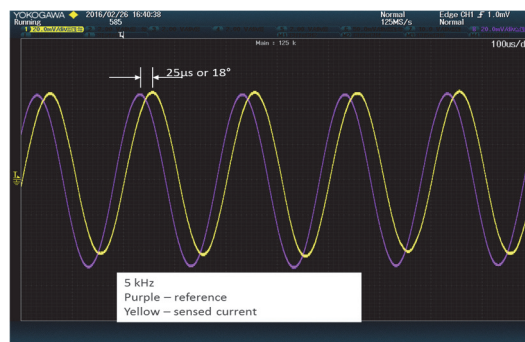

Figure 9: Sine waveform at 5 kHz.

Frequency Response

The frequency response of the power supply was measured with a Dynamic Signal Analyzer HP35670A. Since the input DC voltage was 40 volts, the peak-to-peak current was set to 0.5% of 15A to avoid distortions in the current waveform. As shown in Figure 10, at 1kHz, the amplitude attenuation was -0.407dB with a phase shift of -3.88°. At 10 kHz, the amplitude attenuation remained small, but the phase shift increased to -64.7°.
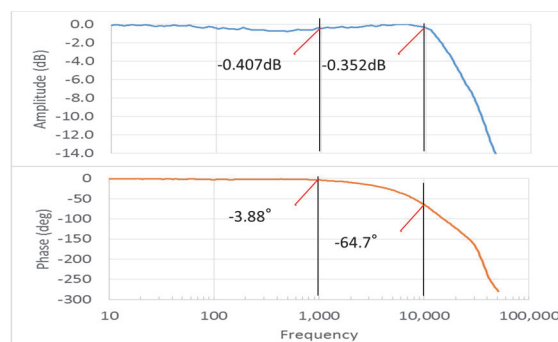

Figure 10: Frequency response measurement.

CONCLUSION

This paper presents the detailed designs of the fast corrector power supply for the APS Upgrade. The test results show that the prototype power supply has achieved the goal of 10kH bandwidth for a small signal of 0.5% of the full range. The current regulator will be optimized when the actual magnet becomes available. Many designed features in the prototype will be used in the final design. Further improvement will be focused on improving the stability in DC operation and reducing the electromagnetic interference generated by the switching circuit.

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," IPAC'2015, Richmond, VA, USA, 2015.