

POWER SUPPLY CONCEPTUAL DESIGN AND R&D FOR THE APS UPGRADE*

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Abstract

The multi-bend achromat (MBA) storage ring of the APS Upgrade (APS-U) requires more than 2200 power supplies with either unipolar or bipolar DC output currents. The power supply performance requirements are much more stringent than what can be achieved with commonly available and off-the-shelf commercial power supplies. The power supply output currents must be calibrated to the given specifications and confirmed with independent and accurate measurement. The bipolar power supplies for the fast correction magnets are required to have a wide bandwidth of 10 kHz. There are also new requirements for the power supply controls and communications that are much more demanding than those in the existing APS power supply systems. This paper reports on the conceptual designs of the power supply systems and the R&D programs that have been developed to find solutions to the technical challenges.

INTRODUCTION

The APS Upgrade with an MBA storage ring [1] requires power supplies with a stability better than 10 parts per million (ppm) of the full scale for the dipole, quadrupole, and sextupole magnets. This stability requirement is an order of magnitude more stringent than the original requirement of the existing power supplies, and a factor of two or more than what has been achieved today. The proposed real-time feedback (RTFB) beam orbit correction system has a designed bandwidth of 1 kHz, which requires the power supplies for the fast correctors to have a -3dB and small signal bandwidth at 10 kHz or higher in order to minimize the power supply's impact on the RTFB system. In addition to more demanding power supply performance requirements, there are other requirements to better facilitate the machine operations and the power supply fault identification. Those requirements include independent magnet current measurement, fast control and communication interfaces, and intensive data acquisition to monitor power supply operation status and conditions.

To meet these requirements, the conceptual designs and R&D programs are underway to investigate and evaluate commercial power supply options and to develop technical solutions.

UNIPOLAR DC POWER SUPPLY SYSTEM

The MBA storage ring needs 1000 unipolar power

supplies with the output current up to 230 A, which is designated as DCU-230 in the conceptual design. The DCU-230 system is based on a 10 ppm stability-class commercial DC-to-DC power supply with modifications to satisfy the APS needs. The modifications are mostly in the input and output stages of the power supplies in order to utilize the existing APS DC distribution system.

Figure 1 shows a conceptual design of the unipolar power supply system. The system includes a commercial power supply, an external DCCT (DC current transducer) with a high precision measurement circuit for independent performance verification and calibration, and a power supply controller to provide the control and communication interfaces.

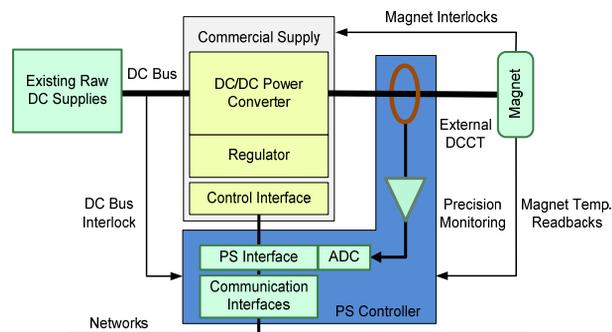


Figure 1: Unipolar power supply system.

Two different commercial power supply approaches have been evaluated through the R&D program. The first approach uses a 200A Danfysik 9100 power supply, which is a current-regulated power supply with a stability specification of 10 ppm. The second approach uses an external current regulator by BiRa Systems and SLAC to regulate a 250A TDK-Lambda Genesys power supply operating in the voltage mode. The evaluation results show that both approaches can meet the stability requirement. During a 7-day and 100A test, both approaches achieved a stability better than 0.5 ppm RMS and better than 5 ppm peak-to-peak. The two approaches were also tested for 24-hour runs with the output currents at 50 A, 100 A, and 200 A, respectively. The largest current deviation during the 24-hour runs is 0.7 ppm RMS and 4 ppm peak-to-peak.

In addition to DCU-230, there is also a requirement of two AC-to-DC power supplies for the L-bend, M1 and M2, dipole magnets. The maximum output currents are 880 A and 500 A, respectively, with the output voltage up to 450 volts. These sorts of power supplies – with a few ppm current stability – are available commercially.

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BIPOLAR POWER SUPPLY SYSTEM

There are 1240 bipolar power supplies in the MBA storage ring. Those power supplies can be divided into two families, slow and fast, according to the power supply output bandwidth. The slow bipolar power supplies are used for 760 trim or correction coils in the main magnets and 160 skew quadrupole magnet coils. The fast bipolar power supplies are used for 320 fast correction magnets. The general requirement for the bipolar power supplies are 40 volts DC at the input and ± 15 amperes at the output. In the conceptual designs, the power supplies are named as DCB-15 and FBC-15 for the slow and the fast, respectively.

Slow Bipolar Power Supplies

The conceptual design for the slow bipolar power supply system is very similar to the design for the unipolar power system. Commercial DC-to-DC power supplies will be used to provide the required magnet currents. Just as in the unipolar power supply system, external current sensing devices will be used to independently verify the output currents and provide calibration capabilities.

Fast Bipolar Power Supplies

The 10-kHz bandwidth requirement makes the fast bipolar power supply unique. There are no commercial products available that will meet the requirement. A suitable power supply circuit and a fast control loop are being developed through the R&D program. The conceptual design uses a standard four-quadrant (4-Q) switching-mode DC-to-DC power converter, switching at 200 kHz. The circuit modeling and simulation showed that a proportional-and-integral (P-I) control loop plus a phase-lead compensator can provide the required bandwidth with the 40V DC bus as the input if the product of the magnet impedance at 10 kHz and the AC signal amplitude is less than the DC bus voltage [2].

If the product is greater than the bus voltage, this design will not be able to achieve the required bandwidth. In this case, either the input DC voltage needs to be increased or a different power supply circuit is needed. A potential candidate is a hybrid circuit that combines a standard 4-Q switching-mode circuit with a linear power amplifier-based AC circuit. The 4-Q switching-mode circuit provides the DC current and the AC circuit provides the high bandwidth AC component. A high frequency step-up transformer is used to combine two circuits together and boost the voltage from the AC circuit to overcome the magnet impedance. Figure 2 shows a general block diagram for the combined DC and AC circuits.

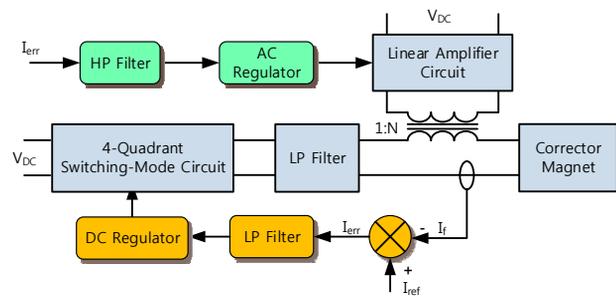


Figure 2: Block diagram of a hybrid AC and DC circuit.

POWER SUPPLY CONTROLLERS

There are two designs of the power supply controllers, one for the unipolar DC power supplies and one for the bipolar DC power supplies. The controllers for the bipolar power supplies are used for both the slow and the fast bipolar power supplies.

Controller for Unipolar Power Supplies

Each cabinet for the unipolar power supplies will have a unipolar power supply controller. The controller provides communication interfaces to the accelerator controls network, the bulk data network, and the synchronized data acquisition (DAQ) system for up to six power supplies inside the cabinet. The interface between the commercial power supplies and the controller is required to accommodate a set point change rate up to 10 Hz with a latency less than 10 ms. Additionally, the controller is required to provide signal processing and diagnostic capabilities to monitor the performances of the power supplies.

The unipolar power supply controller will utilize a System on Chip (SoC) Field Programmable Gate Array (FPGA) that combines an FPGA fabric with an embedded microprocessor system. An EPICS IOC will run on the embedded microprocessor whereas signal processing and real-time functions will be performed in the FPGA fabric.

The current measured by the precision measurement circuit and other important power supply operation parameters will be streamed back – synchronized with the global RTFB clock at 22.6 kHz – through a dedicated interface to the DAQ system for global time-correlation with other accelerator events. A memory buffer stores the current waveforms for at least one second. The waveforms can be read back with timestamps for post-mortem analysis when triggered by an internal event such as a glitch in the power supply output current or an external event such as a beam motion or beam loss.

Controller for Bipolar Power Supplies

Bipolar power supply controllers have many functions and features that are the same as those of the unipolar power supply controllers. Some of the designs such as the SoC FPGA, the ADC circuit, and the data acquisition and processing can be shared between the two controllers.

One of the unique requirements of the unipolar power supply controller is a fast interface to the RTFB system. The interface must be capable of receiving the set points

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for the fast bipolar power supplies from the double sector controller of the RTFB system at a frequency of 22.6 kHz. The communication speed requirement is such that the end-to-end latency in the communication link has to be less than 10 μ s.

A bipolar power supply controller will have ten channels of 18/20 bit DACs (digital-to-analog converter) to convert the set points to the analog references for ten power supplies. It will also have ten channels of 18/20 bit ADCs (analog-to-digital converter) for the measurement from the external current transducers. A number of digital I/O (input and output) channels will be required to handle the power supply status and magnet interlocks. The conceptual design of the controller is shown in Figure 3.

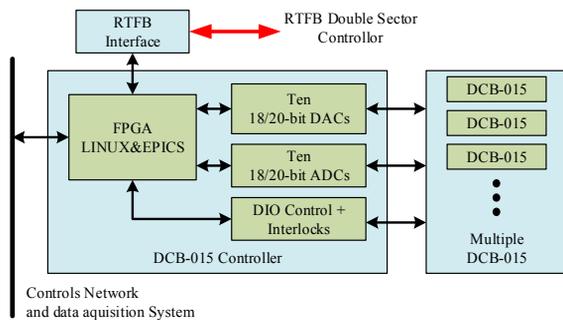


Figure 3: Bipolar PS controller with RTFB interface.

PRECISION CURRENT MEASUREMENT

The output currents of both the bipolar power supplies and the unipolar power supplies require independent measurement. The precision of the measurement needs to be 18 bits or better for the unipolar power supplies while the precision requirement for the bipolar power supplies may be 10 times or more relaxed. A common precision ADC circuit will be designed for both types of the power supplies although the bipolar power supplies may not need a very high precision measurement and a less precise current sensing device may be used. The ADC circuit conceptual design is shown in Figure 4.

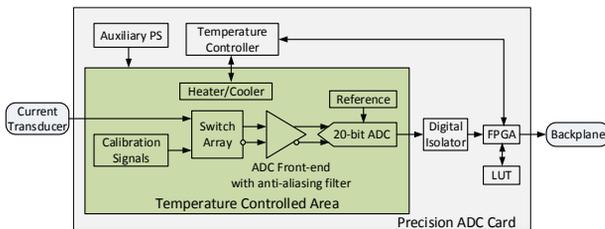


Figure 4: Block diagram of the precision ADC circuit.

In the design, a fast 20-bit ADC will be used to digitize the analog signal that is conditioned by the ADC front-end circuit and the anti-aliasing filter. The important components that may affect the measurement stability due to the ambient temperature variations will be placed in a temperature controlled area. An FPGA will provide data acquisition, temperature control, and data transfer to the power supply controller over the backplane. The calibration signals can be routed to the ADC for self-calibration purpose via a source selection switch array.

This feature allows a periodical self-calibration of the offset and the gain errors. A look-up table (LUT) contains a correction table that can be periodically updated during the self-calibration. The auxiliary power supply is a low-noise and galvanically isolated zero-current switching-mode power converter. The digital isolator isolates the ADC from the other electronics within the crate.

COMMUNICATION STRUCTURE

The proposed conceptual design of the power supply communication structure in a double sector has four communication links for different controls and communication purposes. Link 1 and Link 2 are used for the power supply operations and the slow monitoring while Link 3 and Link 4 are used for the fast monitoring and diagnostics.

Link 1 interfaces with the EPICS-based controls network. It delivers the DC set points to the unipolar power supplies. It handles the power supply logistics such as ON and OFF commands and interlocks or fault resets. It reads back the monitored stationary signals such as the interlock conditions, the magnet temperatures, and other power supply statuses. The set points for the slow bipolar power supplies and the fast corrector power supplies may also be sent through this link in certain operation or power supply maintenance modes.

Link 2 is for delivering the bipolar power supply set points, including the set points for both the slow and the fast bipolar power supplies. It connects the bipolar power supply controller to the double sector controller chassis of the RTFB system.

Link 3 is the interface for the synchronized data read back. Through this link, the power supply output current and other important data can be streamed back synchronously with the global RTFB clock at a frequency of 22.6 kHz.

Link 4 connects the power supply controllers to the bulk data network. The captured power supply waveforms will be sent through this link.

CONCLUSION

The APS Upgrade requires a large number of power supplies. The performance requirements of the 10-ppm current stability for the unipolar power supplies, the 10-kHz bandwidth for the fast bipolar power supplies, the independent precision current measurements, and the high speed communication interfaces present many technical challenges. To meet the requirements, the power supply conceptual designs and the R&D activities are underway to evaluate commercial power supplies with different technical approaches and options, and to develop solutions to the key technical challenges. To date, the R&D for the unipolar power supplies have shown that the commercial power supplies from Danfysik with built-in current regulator and from TDK-Lambda with external current regulator by BiRa/SLAC techniques can in fact achieve the required stability.

REFERENCES

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