Reuse of Common Elements of a Corrector Power Supply Design to Develop a Dissipative Shunt Regulator Design*

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Abstract

The progress in development of a shunt regulator for the conventional recirculation arc magnets in the CEBAF superconducting recirculating accelerator is described. The shunt is capable of diverting up to 20 amperes around an individual magnet which is connected in a magnet string energized at a nominal 220 amperes. The regulation stability goal for the shunted current is 50 PPM. The regulator uses a digital link for both programming and readback of output current. Electrical isolation is achieved by optocoupling the serial communications link. The circuitry for this regulator was adapted from an existing CEBAF design for corrector magnet power supplies. The reuse of common elements from the corrector supply, especially the isothermal regulator module and the onboard microprocessor, significantly shortened the development time for the shunt regulator.

I. INTRODUCTION

For reasons of economy and to facilitate beam tracking at various energies, the CEBAF accelerator electrically connects up to 40 bending dipole magnets in the recirculating arc into a series string, all magnets sharing the same string current. Some individual adjustment, however, is desired on a few of the magnets at the entrance and exit to the accelerator arc. The shunt regulator configuration was chosen for this task. Each shunt regulator consists of an adjustable solid-state dissipative element. The shunt regulator is placed in parallel with the desired magnet element, allowing an adjustable amount of the string current to be diverted around that magnet. The initial goal was to allow up to 5% of the string current to be diverted. The current through the element is regulated by means of a conventional linear servo loop feeding back from a manganin sensing resistor.

A significant design problem was to provide the necessary electrical isolation between the control inputs and regulator output. Each magnet in the string will be operating at a different potential, some differing by as much as 660 VDC. Allowing for an adequate safety margin, a goal of 3 kVDC isolation between input and output circuitry was chosen.

Another problem arising from the high common mode voltages present on the regulator circuitry is the matter of "servicability". It would be hazardous to work on the shunt regulators *in situ* with these voltages present. It was decided to package the regulator as a plug-in module,

which could readily be removed and replaced, then serviced on a bench fixture.

A practical solution was found in the reuse of many of the common circuit elements and software available from the design of the existing corrector magnet power supplies. These units are bipolar power supplies capable of +10 ampere output. Some 1800 of these supplies are used in the main accelerator ring and the design is well proven. The circuit design is considered "modular" in that various functions, such as serial communications, output current monitoring, etc. are in separate, readily identifiable circuit blocks. In particular, the regulator and current shunt are built as a self-contained isothermal module.

The rapidity with which the shunt regulator project was accomplished demonstrates the advantages of designing magnet power supplies in a modular fashion. Given a well-debugged set of "building blocks", they may quickly be arranged to achieve power supplies or power regulators for a wide variety of applications.

II. DESIGN GOALS FOR SHUNT REGULATION

The basic shunt regulator consists of a controllable power MOSFET dissipative element which can divert current around a magnet without altering the total current in the magnet string (see Figure 1). A local current sensing resistor provides feedback to control the magnitude of the diverted current.

Fig. 1 Shunt regulator allows trimming current through one magnet in a series string.

The maximum current which can be diverted is a function of the resistance of the shunted current path as compared to the magnet resistance. The shunted path resistance consists of the sum of the resistances of the feeder cables, current sensor, and dissipative element in the full "ON" condition. It had been decided that the shunt regulators must be located in the service buildings at grade

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level above the accelerator tunnel, rather than in the tunnel itself, immediately adjacent to the magnets. This was in consideration of accessibility for service, availability of space, power, and communications, and to avoid radiation damage. Studies showed that, for the CEBAF application, the maximum anticipated shunt path resistance would be on the order of 0.45 ohms. For a typical magnet resistance of 0.050–0.080 ohms this would allow for maximum diversions in the range of 10% to 15% of total magnet current.

The current stability of the entire magnet string is regulated to within 10 PPM. Assuming a 10% diversion, the stability of the shunt current regulation must be better than 100 PPM in order not to degrade the 10 PPM stability of current flowing through the magnet.

The highest voltage (with respect to ground) to be encountered on the magnet string is 660 volts steady state. Inductive transients generated during turn-off could increase this value. It was decided that, in order to provide a satisfactory margin of safety, the shunt regulators must be designed with an electrical isolation of 3 KVDC to any grounded point, or to external communication lines, status lines, and AC power mains.

Another design goal was to package the regulator as a compact module which could be readily isolated from ground and fully enclosed for personnel safety. Packaging the regulator as a plug-in module, which could easily be removed and serviced on a bench fixture, would avoid the necessity of service personnel troubleshooting the regulator while it is connected to potentially lethal voltages. Finally, air-cooling was employed to eliminate potential stray electrical leakage via water paths.

The design concept which evolved was for a shunt regulator circuit capable of up to 200 watts dissipation, which could be "floated" at the magnet's potential. All necessary control inputs and monitoring outputs would be via a serial communications link which would be optically coupled to achieve the necessary high voltage isolation. The small amount of power needed for control functions would be obtained from a well-insulated step down transformer.

III. REUSE OF CORRECTOR POWER SUPPLY ELEMENTS

CEBAF already had in existence a well-developed design for a 200 watt bipolar power supply, used with small beam steering corrector magnets [1], [2]. This supply had most of the elements which were required by the shunt regulator: an on-board microprocessor which allowed two way communications via an RS485 serial link; a current regulator module which included a temperature-stabilized current sensing resistor and reference DAC; a 16 bit A-D converter for precision monitoring of the output current; and a 12 bit multi-channel A-D for monitoring of auxiliary signal levels, such as magnet voltage.

The comparison between the block diagrams of the corrector power supply and the shunt power supply is shown in Figure 2:

Fig. 2 Comparison of corrector magnet power supply and shunt regulator block diagrams showing the similarity between the two.

The circuitry for the CPU, 16 bit A-D, 12 bit A-D and discrete status monitor was borrowed intact from the corrector power supply. This allowed the reuse of the existing software code with only minor modifications such as modifying port assignments and scaling factors.

The current regulator was a purchased assembly manufactured by Highland Technology, Inc. (Model M427). It is a compact (3" x 3") module which combines reference DAC, comparison (error) amplifier and current sensing resistor onto a common, temperature-stabilized (isothermal) substrate [3]. Maximum current capability is 20 amperes. The 8 hour current stability is better than 50 PPM. This isothermal module is a key element in the design, allowing the regulator to achieve good regulation stability while occupying a very small space.

The entire regulator assembly was realized as four circuit boards: output driver, digital controller, regulator module, and power supply. Using standoffs, these boards were mounted directly to a large aluminum finned heatsink (8.75" x 17" x 1.25"). Rails and a low-insertion force connector were added to the heatsink to make it a plug-in module which would be slid into a card cage backplane.

A rack-mounting card cage was developed which would hold four of these plug-in regulator modules. Electrical isolation of the module from ground was achieved by fabricating phenolic card-guides on which the module rails could slide. The four mating connector receptacles were mounted on a phenolic bulkhead panel. This eliminated the need for connectors with 3 kV pin-to-case breakdown rating.

An opto-isolation board for each module was mounted on the rear of the bulkhead panel. The RS485 data link and several discrete status signals pass through this board. Dual-stage opto-coupling is employed for each signal. The first rank of couplers translate the signals to circuitry which is referenced to earth ground. The second rank of couplers re-translates the signals to circuitry which is referenced to the ground of the remote rack in which the data signals terminate. The concept is that any voltage breakdown which might occur across the first rank of opto-couplers will be intercepted by earth ground and not passed on to the data link, where other modules connected

to the RS485 could be damaged.

Finally, the regulator card cage is equipped with safety covers which are interlocked to the magnet string power supply. This protects personnel against inadvertent contact with high potentials.

IV. INITIAL RESULTS WITH THE PROTOTYPE UNIT

At the time this paper is being written, we are awaiting several PCBs from the vendor, so it has not been possible to test the final design. However, to prove the concept, the circuit was prototyped using pieces of the existing corrector power supply board driving a breadboarded output MOSFET output stage.

The magnet current was established at 100 amperes and the regulator current established at 20 amperes (80 amperes through the shunted magnet). Stability measurements were attempted using two Danfysik Model 860R current transducers, the output of which was monitored by HP 3458A digital voltmeters. The setup is shown in Figure 3.

Fig. 3 Setup for testing prototype shunt regulator. Two transducers allow measurement of diverted current stability.

The results showed that the shunted current could be digitally controlled over the desired range from zero to 20 amperes. Current regulation was well behaved with no oscillations and minimum overshoot. Magnet current remained stable within 12-14 PPM for a 24 hour period as measured by the current transducers and confirmed by NMR measurements of the actual magnetic field. A failure of the second current transducer during the experiment

caused the stability measurements for the current through the regulator itself to be invalid.

No dynamic instability was observed. The shunted current setpoint could be changed at will, without appearing to disturb the current through the main magnet string, and vice versa.

V. SUMMARY

- An electronic shunt regulator has been demonstrated which is capable of shunting up to 20 amperes around an individual magnet connected in a series string with other magnets. Stability of the shunted current is better than 50 PPM for an 8 hour period.
- The regulator is packaged as a plug-in module approximately 8.75" high x 17" deep. Four such regulator modules are housed in a card cage which occupies 10 1/2" panel height in a standard 19" relay rack.
- The control and monitoring link is entirely digital in nature, using serial communications via an RS485 link. Up to 32 modules can be operated on a single multi-drop link.
- By use of an opto-isolated RS485 communications link, each shunt regulator is electrically "floating" with respect to ground. The four units in a common card cage can serve magnets which are operating at substantially different potentials. Electrical isolation of 3 kVDC is achieved.
- The design is modular in concept and packaging. Reuse of circuit modules from an existing power supply design greatly shortened the time and expense required to realize working hardware.

VI. REFERENCES

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