



Figure 2: Basic shunt regulator circuit. Each MOSFET has local feedback loop.

The shunt module uses the same Isothermal Controller Module (Highland Model M427) used by the CEBAF trim power supplies[2]. This module contains a manganin shunt, DAC, and reference amplifier integrated on a temperature controlled substrate. Regulation stability of .05% per 24 hours is achieved.

Forced air cooling was chosen to simplify the electrical isolation requirements and is achieved using airflow obtained from a blower fan mounted in the top of the rack in which the shunt cardcages are mounted.

The shunt module uses a Motorola MC68701C uP for remote communications, readback of internal levels, and alarm monitoring. The uP and readback circuitry was borrowed intact from the CEBAF trim boards[3]. Only a few lines of code needed to be changed to adapt it to the shunt usage, which shortened the project turn-around. A serial communications interface is used to communicate with the external control network via RS-485 protocol. The link operates full duplex at 76.8 Kbaud. Up to 32 shunts may share a common RS-485 link.

III. ELECTRICAL ISOLATION

Shunt modules present unique requirements for electrical isolation. Depending where on the magnet string the shunt is electrically connected, it may be required to "float" at up to 600 VDC above Earth Ground. Total electrical isolation from the remote programming source, from other other shunts in the cardcage, and from Earth Ground is required. This isolation is achieved by transformer-isolation of the supply circuits providing control power to the each module and by electrically isolating the modules from the chassis by use of insulated supports and a special connector mounted on G10 laminate.

Isolation for remote programming and readback information is achieved by opto-isolating the RS-485 communications link and three discrete digital control

lines. Initial attempts to use 5KV opto-isolators were unsuccessful, due their slow rise and fall time response characteristics. In order to operate the link at 76.8 Kbaud, use of fast opto-isolators (6N138s) was necessary. Since the 6N138s are rated at only 3KV breakdown, it was decided to doubly-isolate each signal, passing them through two tiers of opto-isolation. The common circuitry between these two tiers is connected to Earth Ground. Should a voltage surge cause an opto-coupler to break down, the fault current would be intercepted by Earth Ground and not applied across the second tier, possibly causing it to fail as well. As a precaution, all input/output circuits are highpotted to 3KV DC after initial assembly of the chassis to insure integrity of isolating circuitry. Connections to a module are via a multipin connector which is isolated from the adjacent module and from chassis ground by mounting it on an insulated bulkhead fabricated from G-10 laminate. To-date, the isolation scheme has worked well. No failures of these circuits to maintain electrical isolation have been reported.

IV. DETAILS OF MODULE CONSTRUCTION

The shunt module itself is constructed on an 10" x 17" finned aluminum extrusion, which serves as a heatsink. The power MOSFET transistors are mounted directly to the heatsink, using sockets to facilitate replacement. The heatsink itself serves as the +LOAD terminal, forming a common connection between the MOSFET cases.

All low level circuitry is contained on three removable circuit boards mounted to the non-finned side of the heatsink. The three boards are interconnected by a wiring harness and plug-in connectors. This facilitates repair-by replacement.

The power supply board contains a common rectifier-filter, from which is developed +24VDC, +15VDC, +5VDC, -15VDC, and -24VDC. Three-terminal linear regulators are used to develop each discrete voltage. The rectifier is fed with 28VAC from a step-down transformer located off the module in the rear apron of the card-cage chassis. This transformer has 5KV winding insulation.

The controller board contains the microprocessor, A-Ds, and analog signal conditioning circuitry. Two A-D converters are employed. A 16-bit converter is dedicated to readback of the output current. A 12-bit A-D is multiplexed to monitor output voltage, heatsink temperature, isothermal module temperature, and an auxiliary output current level.

The driver board contains the eight parallel driver stages and the isothermal module. The current sensing resistors connected to each MOSFET source are thermally coupled to the main heatsink using an aluminum bar in a manner similar to that of the power supply module. The common -LOAD buss employs a stamped copper buss bar, soldered perpendicular beneath the driver PCB.

V. DETAILS OF CARDCAGE CONSTRUCTION

The shunt modules are designed to slide into a cardcage-style chassis, making electrical connection by means of a connector mounted on the rear apron of the heatsink. Since the shunt is directly connected to a magnet string with potentials as high as 600 VDC above Earth Ground, safety considerations require that the module be totally enclosed in a chassis whose covers are interlocked to the dipole string power supply.

Unlike a conventional power supply, for the shunt module the hazardous source of power is the box power supply. At CEBAF, the shunt cardcages are often located in entirely different buildings than the box supplies. For this reason, it is necessary to completely interlock the shunt modules and cardcage to that box supply. Removable front and rear chassis covers are interlocked to the box supply to prevent personnel access to the shunt module while the magnet string is energized. Heatsink overtemperature or loss of more than two driver stage fuses will also trip off the box supply.

For safety purposes and ease of interlocking to the box supply, only shunts connected to a common magnet string are housed together in a common chassis. To suit the CEBAF applications, two cardcage packages were developed, a single-channel and a four-channel unit.

In the single-channel chassis, the shunt module slides in horizontally on insulated card guides. Because airflow through the rack is in a vertical sense, an integral linear squirrel-cage fan is employed to force air across the heatsink fins. An integral airflow sensor is interlocked to the box supply to remove power should this fan fail. In the four-channel unit, the modules mount vertically, and air flows directly over the heatsink fins from vents strategically located in the top and bottom chassis covers.

VI. INITIAL OPERATING RESULTS

From an operational standpoint, the shunts have worked as desired. No unusual or undesirable modes of operation have been experienced. A single module design has sufficed for all applications to date. Field repair of a failed module is accomplished by remove-and-replace, requiring only a few minutes to restore service to a faulted channel. Remote programming and readback, via the RS-485 link, has worked without problem-validating the strategy of using the same microprocessor circuitry and software as the time-proven trim cards[3].

There are presently 112 shunt regulators installed and operational at CEBAF. Typically, one module shunts one magnet, however there are eight applications where a module shunts two adjacent magnets in a string. There are

34 four-channel chassis and 11 single-channel chassis installed.

In the past three and one half months, we have accumulated a total of 150,000 module-hours of operation [4]. Six failures have been experienced. These failures were all traceable to workmanship errors in the initial manufacture (pinched wires, poor solder connections, etc.).

VI. REFERENCES

[1] E. Martin, et al., "Re Use of Common Elements of a Corrector Power Supply Design to Develop A Dissipative Shunt Regulator Design," E. Martin, et al., Conference Record of 1992 IEEE Nuclear Science Symposium, October 25-31, Vol. 1, p. 563-565.

[2] N. Dobeck, "Precision Power Supply Control Module," Conference Record of the 1991 IEEE Particle Accelerator Conference, May 6-9, Vol. 2, p. 935-937, IEEE91Ch3038-7.

[3] N. Dobeck, et al., "Precision 32 Channel Power Supply System," Proceedings of the 1990 Linear Accelerator Conference, September 10-14, p. 490-492, LANL LA-12004-C.

[4] W. Merz, et al., "Early Operations and Reliability Experience With the CEBAF DC Magnet Power Supplies," to be published in Proceedings of the 1995 IEEE Particle Accelerator Conference.