CEBAF Beam Transport Magnet Power Supply Control System*

M. O'Sullivan, N. Dobeck, R. Flood, J. Perry
Continuous Electron Beam Accelerator Facility
12000 Jefferson Avenue
Newport News, VA. 23606

Abstract

The CEBAF beam transport magnet power supplies must satisfy tight repeatability, stability and availability constraints under relatively severe environmental conditions. The control system described allows these constraints to be satisfied in a straight forward fashion by permitting the embedding of all sensitive signals and components in the power supply itself and using a serial interface between the CAMAC based control system and the power supply controller interface.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility is designed to give nuclear physics researchers the opportunity to develop a greater understanding of the quark and its role within the nucleus. To obtain a large amount of high quality data, the beam will be continuous with high energy, high current and excellent beam quality. The accelerator topology chosen for CEBAF is the recirculating linear accelerator with the beam making up to five passes through the two linear accelerator sections. This scheme presents a greater challenge in designing the beam transport and control system but greatly reduces the cost of expensive superconducting accelerator hardware. The more than 1800 low power corrector and focusing magnets require 100 ppm (of full scale) current stability and repeatability while the large dipole strings used in the recirculating arc sections require 10 ppm performance. Beam transport simulations [1] show that current variations much larger than these will make it difficult to maintain control of the beam.

Three different groups of magnet power supplies have been defined to meet the above requirements. Over 1800 CEBAF-designed "trim regulators" are required for the low power corrector and focusing magnets. These regulators are required to provide 100 ppm performance at up to 200 W of power. About 45 commercially available 10 ppm "arc power supplies" are required for the dipole strings and septum magnets used in the recirculating arc sections of the accelerator. These free-standing magnet power supplies range in power from 13.5 kW to 152 kW. In addition, approximately 75 CEBAF-designed "shunt regulators" are required to divert a percentage of the string current from selected magnets in the arc section dipole strings. These regulators are required to provide 100 ppm performance at up to 200 W of power dissipation. All the magnet loads for these three groups of power supplies require dc operation only.

DESIGN CONSIDERATIONS

CEBAF is shaped in an oval nearly a mile around. The power supplies are thus widely distributed and housed in service buildings which are subject to estimated typical ambient temperatures of between 0° C and 40° C throughout the year. Ambient temperature swings of more than 20° C in an eight-hour period are not unusual in this coastal area. Furthermore, humidity levels during the summer are usually over 80% relative humidity, and frequently exceed 90%.

The CEBAF accelerator control system is called TACL (Thaumaturgic Automatic Control Logic) [2]. At present, it interfaces efficiently only with CAMAC-based physical interface devices. We therefore had to build an interface that is compatible with CAMAC.

The first CEBAF design was for the trim regulators. We considered controlling the trim regulators with standard CAMAC-based analog control references connected to the power supplies via shielded twisted pair conductors. This would have allowed the possibility of using commercially available CAMAC-based digital to analog converters and custom power supplies using straightforward analog control inputs. This approach was dropped because of difficulties in maintaining low noise and drift performance with widely distributed power supplies. The use of more dispersed intelligent analog controller nodes, which would reside very close to the power supplies, was also considered but rejected because this scheme was not enough of an improvement over the CAMAC analog controller modules. The magnet power supply control system finally selected neatly solves the usual interface problems by embedding all the critical components into the power supply itself and communicating with the CAMAC based main control system through a serial data link.

To solve the problem of electrical interference and thermal stability, we localized all the precision analog control circuitry at the power supply itself by putting the circuitry on a small aluminum block using surface mount technology electronics. This made grounding and shielding straightforward and simple. The problem of environmental control was also eased by this miniaturization. Incorporated onto this analog block is a temperature control circuit which regulates the temperature of the block and its circuitry well above any expected ambient temperature. The circuit and packaging were developed by

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Highland Technology, Inc. This precision control circuit that we refer to as the "analog block" [3] is now the basis for all CEBAF-designed power supplies. The basic magnet power supply (MPS) control topology for CEBAF designs is shown in Figure 1.

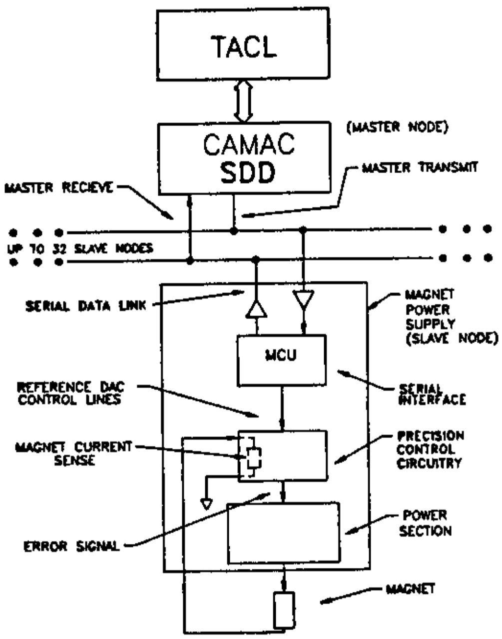

Figure 1. Basic MPS Control Topology

We implemented the interface to TACL by defining a CAMAC-based serial data distributor module and embedding a microcontroller in each power supply which allows the serial data distributor to communicate over a multidrop serial data link and control the reference DAC of the precision analog circuitry. The interface is flexible enough that all beam transport power supplies from the 200 W trim regulators to the 152 kW arc power supplies utilize the same basic communications hardware and one of two protocols.

CONTROL SYSTEM ARCHITECTURE

Analog Block

In designing the trim regulators for the many corrector and focusing magnets, the key component was determined to be the current sensor. Zero-flux transductors were rejected because the cost and package size were too large for our application. Hall effect devices were rejected due to temperature stability and noise considerations. Commercially available stable resistors made of low temperature coefficient alloys like manganin were considered, but with typical temperature coefficients of about 10 ppm/° C, they would have to be temperature regulated in order to keep within the error budget. The method chosen was to use a manganin shunt resistor bonded to a temperature regulated "analog block."

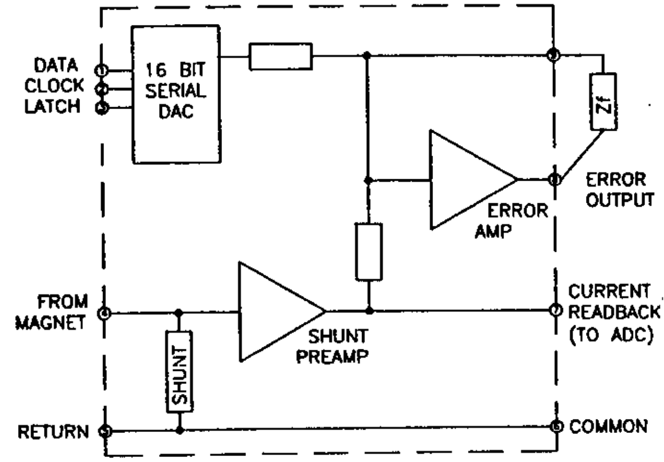

Figure 2. Analog Block Schematic

The analog block schematic is shown in Figure 2. The main components of the analog block are the manganin shunt resistor, a preamplifier, an error amplifier, a 16-bit reference DAC, the heater section and support electronics. The reference DAC is controlled directly by the microcontroller using a simple software driver routine. The output of the shunt preamplifier is available at the module connector and is monitored using an ADC. The module temperature and heater current signals are also provided at the connector for monitoring. The feedback compensation elements of the error amplifier are external to the module to allow for easy alteration of control loop dynamics. The analog block physical layout is shown in Figure 3. The shunt resistor and the heater element are bonded to a solid aluminum block along with a surface mount printed circuit board to which the remainder of the components are mounted. The module has a phenolic cover with overall

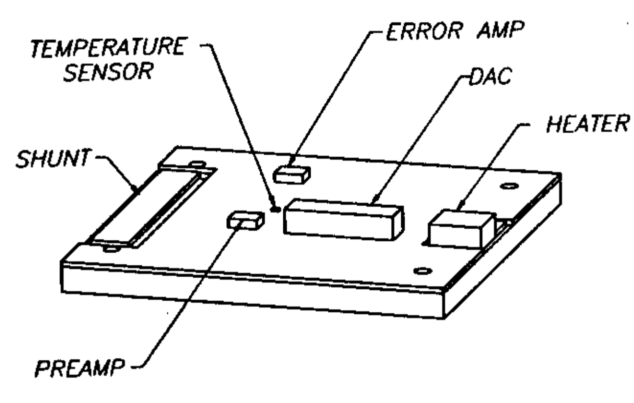

Figure 3. Analog Block Physical Layout

dimensions of 3 × 3 × 0.75 inches. All the critical components and signals are thus contained in a tightly controlled thermal environment. The analog block is attached to the regulator board with four mounting screws and a single row electrical connector. The module temperature regulates at 68° C, requires supply voltages of +24 and −24 volts and dissipates about 5 W under normal operating conditions.

This controller was developed primarily for use in the trim system but the versatility of the module allowed CEBAF to also use it as the standard key controller element in the shunt regular design. The analog block can be used with high current power supplies by replacing the shunt preamplifier output signal with the output signal from an external current shunt or transductor.

Serial Data Distributor

The serial data distributor (SDD) is a CAMAC-based master node in a multidrop serial data link and can control and monitor up to 32 slave nodes. As shown in Figure 4, the basic hardware blocks of the SDD are the microcontroller, CAMAC function and address decoding logic, dual port memory (DPM) for 24-bit CAMAC dataway access, system memory and communications hardware. Each of the CAMAC read and write function codes (along with their subaddresses) are mapped to each of the 32 slave data sets through unique DPM locations such that each individual byte of slave data can be specified by a CAMAC function code and subaddress. The remaining function codes do not use the read or write lines. Hardware reset, self test and "test the LAM bit" are implemented with three of these function codes. The remainder of these function codes generate unique interrupt vectors for future expanded use of the module.

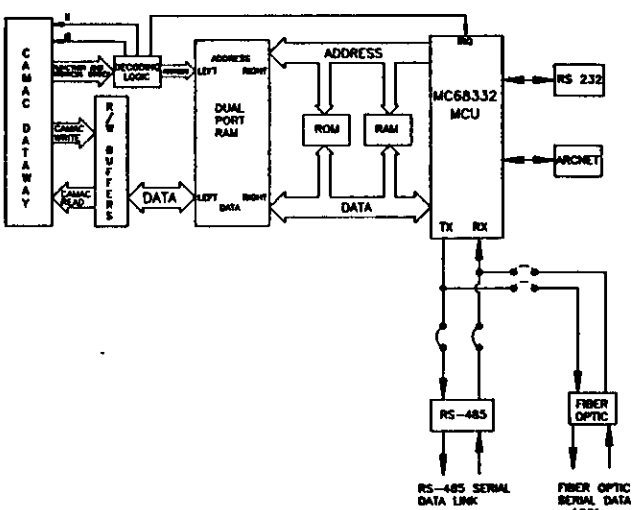

Figure 4. Serial Data Distributor Block Diagram

CAMAC writes digital control and setpoint data to the DPM and reads digital status and readback data from the DPM. The SDD has two main tasks. The first is to service CAMAC requests. The second is to route the digital control and setpoint data to each slave and pool the digital status and readback data from each slave over a full duplex serial data link. These two tasks are carried out asynchronously with respect to each other but with top priority given to CAMAC requests.

The SDD can be configured to use either RS-485 or a fiber optic port for the serial data link hardware. The module also has an ARCNET interface and an RS-232 port with plans for the ARCNET interface to be used for auxiliary, distributed communications within the power supply system. The RS-232 port is used as a debug monitor.

Protocols

The trim and shunt regulators use a simple polling communications protocol while the arc power supplies use a simple command driven protocol. The SDD can be configured for either protocol so that all power supplies can be controlled with the same hardware by the accelerator control system as shown in Figure 5.

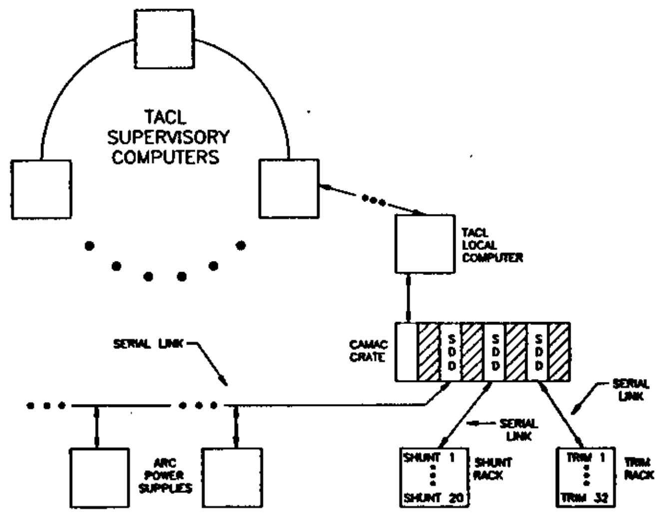

Figure 5. CEBAF Beam Transport MPS Control System

In the polling protocol mode, the SDD sequentially polls up to 32 slave nodes at a rate of better than 20 Hz. If there is a communications error or a slave does not respond properly when addressed, the SDD relays this information to the accelerator control system. Each SDD polling message consists of a polling address, a control byte, a 16-bit current setpoint and a checksum. After address detection, the addressed slave returns a response message in full duplex with the remainder of the SDD polling message. Each response message consists of the slave's address, a status byte, a 16-bit current readback (or alternate data) and a checksum. The polling protocol was originally developed for the trim regulators and will also be used for the shunt regulators.

In the command protocol mode, the SDD will communicate by transmitting characters in ASCII code followed by a carriage return. Power supply responses are in ASCII code terminated with a line feed and a carriage return. The command protocol is the standard remote communications protocol [4] for the commercially available arc power supplies purchased by CEBAF.

POWER SUPPLY GROUPS

Trim System

The first major group of magnet power supplies are the 200 W trim regulators [5] used with the corrector and focusing magnets. There are more than 1800 of these trim regulator boards and they are packaged in standard seven foot relay racks which hold up to 32 units each. Figure 6 shows the block diagram for an individual trim rack. All units in the rack are controlled and monitored by a single SDD via a full duplex multidrop serial data link operating

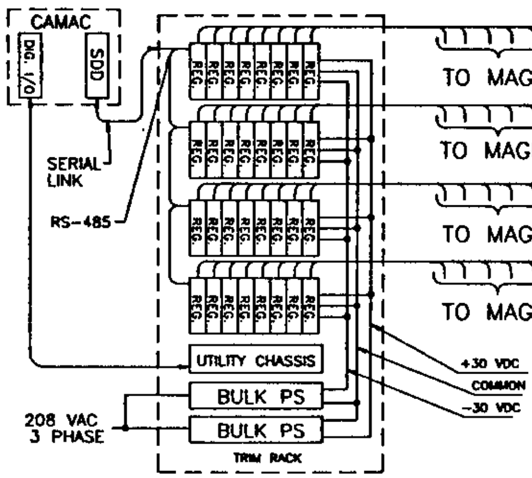

Figure 6. Trim System Block Diagram

at 76.8 kbps. A separate CAMAC digital I/O module is used to monitor and control the environment of the rack itself. Common bulk power supplies provide pre-regulated power to each of the regulator boards. The bulk power supplies are commercially available, 10 kW high frequency switchers. Each trim regulator is capable of providing a bipolar output of up to 10 A at 20 V.

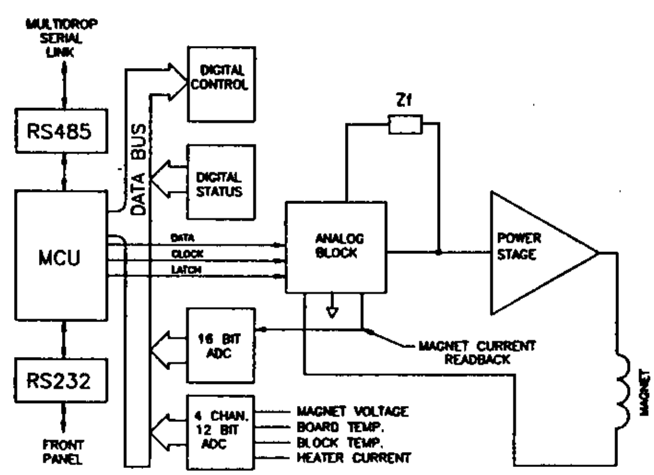

Figure 7. Trim Regulator Block Diagram

The trim regulator block diagram is shown in Figure 7. Each trim regulator board has an embedded microcontroller which handles the serial data link communications as well as data acquisition, monitoring and diagnostics. Each board has a standard RS-485 transmitter and receiver for connection to the multidrop serial data link. Each trim board is also equipped with an auxiliary RS-232 port operating at 9600 baud for local control. The critical components in the output current feedback control loop are located on the temperature-regulated analog block discussed earlier. This self-contained precision current control module is mounted to the trim regulator circuit board as a removable subassembly. Each trim board is equipped with a 16-bit ADC for monitoring the output magnet current sensed by the analog block. In addition, a four channel 12-bit ADC was designed into the board for alternate monitoring and diagnostic measurements. It is presently being used to monitor the magnet voltage, board temperature, analog block temperature and the analog block heater current. The microcontroller uses no external memory and is equipped with 192 bytes of RAM and 4K bytes of EPROM. The firmware is written in assembly language and presently occupies about 50% of the EPROM. All communications with the serial data link is done using vectored interrupts and the remainder of the microcontroller's time is spent continuously looping through the main program asynchronously from the serial link operation.

The main program processes valid incoming polling messages, updates the output current setpoint DAC on the analog block, updates the digital control latch, reads the digital status latch, reads the output current readback ADC, reads the four channel diagnostic ADC, calculates the magnet resistance, compares diagnostic readings to error thresholds, sets error flags and builds reply messages. As discussed in the polling protocol description, the output current readback in the slave response message can be replaced with alternate diagnostic data if requested with the output current readback being the default. For each trim regulator board, the diagnostic data available upon request is magnet voltage, analog block temperature, board temperature, analog block heater current, magnet current setpoint and firmware version. In addition, each trim board encodes the digital status byte with error flags. Since the digital status byte is always returned as part of the reply message, error conditions are constantly monitored by the accelerator control system. The information provided in the returned digital status byte is magnet current readback overrange, magnet overheat, bad polling message received, spurious interrupt to microcontroller, board overheat, analog block overheat, power supply not ready and request to go local.

A request to go local is generated when a connection is made to the RS-232 port. Permission to go local can be granted by setting the proper bit in the digital command byte sent to the trim board in the polling message. The microcontroller goes into local mode only when it has generated a local request and permission is granted by the TACL control system. It otherwise defaults to the remote mode. The trim board responds identically in both modes. Software has been written for a laptop computer that allows access to all features and diagnostics of a fully populated trim rack by connecting to the RS-485 link in lieu of a SDD. The same software can be used to exercise an individual trim board via the RS-232 port without affecting the operation of the other trim boards in the system.

Arc Power Supplies

The second major group of power supplies are those required to provide current regulation for the arc section dipole strings and septum magnets. There are five strings in the east arc section and four strings in the west arc section. Figure 8 shows the first pass of the east arc section. The "BOX PS" and "DOGLEG PS" shown are members of the arc power supply group. The box power supply drives the main dipole string and the dogleg power supply drives a three dipole chicane which is used to alter the beam path length. There are about 45 of these commercially available 10 ppm power supplies ranging in power from 13.5 kW to 152 kW. These power supplies are relatively large, unipolar, free standing, water cooled units.

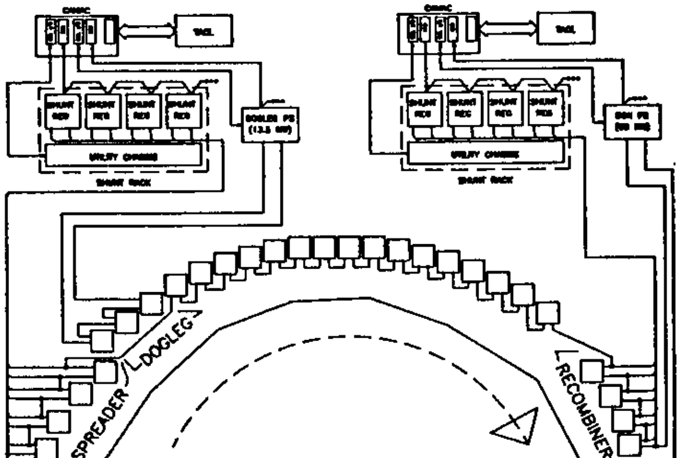

Figure 8. East Arc Pass 1E

Initially it was not known who the vendor would be so the power supply specifications called out a very simple, generic parallel interface which could easily be furnished by any power supply manufacturer. The intent was to install the serial link hardware and software when the units arrived at CEBAF. After the contract was let, it was determined that the vendor's existing serial interface could be used because the SDD could be programmed to use the command driven protocol of these commercial supplies. Although they look very different from the trim regulators, these power supplies can similarly be considered as intelligent current regulator nodes on a multidrop serial data link. In addition to the serial link interface, each power supply is connected to a CAMAC digital I/O module in order to provide limited redundancy for basic monitor and control functions so that a unit can be shut down even if the serial link fails.

Shunt System

The third major group of magnet current regulators are the 200 W shunt regulators used to divert a percentage of the string current from selected magnets in the arc section dipole strings as shown in Figure 8. There are more than 75 of these regulator boards which are packaged in standard seven foot relay racks holding up to 20 units per rack. All units in the rack are controlled and monitored by a single SDD via a full duplex multidrop serial data link operating at 76.8 kbps. A separate CAMAC digital I/O module is used to monitor and control the environment of the rack itself.

A key requirement for the shunt regulators is that they must electrically "float" at the voltage of whatever magnet they are placed across. Other than the increased electrical isolation requirement, the shunt system uses essentially the same serial link hardware and polling protocol as the trim system. Since the shunt regulators are not required to furnish current but to divert it, the power section is quite different from the trim regulator power stage. However, the same analog block is used as the precision current controller, but with a different value shunt resistor.

SUMMARY

Three different groups of magnet power supplies have been defined to meet the requirements of the CEBAF beam transport system. A versatile, standard control system has been designed to meet exacting accelerator needs. A high performance, low cost controller has been developed for use with power supplies of many sizes and applications by packaging all the critical components and signals in a small, temperature regulated module. This controller is now the basis for all CEBAF-designed magnet power supplies for the beam transport system. A standard serial interface to the CAMAC-based accelerator control system has also been defined and is flexible enough that all beam transport magnet power supplies can be controlled and monitored in basically the same manner. The CEBAF beam transport magnet power supply control system is designed to be general enough that it can be modified and expanded as needs dictate. As the beam transport system goes into operation, the use of the system will be expanded to more extensive fault monitoring and diagnostics which will have a favorable impact on power supply availability.

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