

ISABELLE MAGNET POWER SUPPLY SYSTEM PERFORMANCE ANALYSIS*

R.J. Edwards
 Brookhaven National Laboratory
 Upton, New York 11973

Abstract

The power supply system that will energize the superconducting magnets in the ISABELLE 400 x 400 GeV accelerator must supply various voltages and currents. The voltages for the correction winding range from ten to one hundred twenty-five volts unipolar and bipolar with current rating of 50 to 300 amperes. The main field winding requires voltages from 90V (at flattop) to 600V during maximum ramp rate or acceleration cycle. The power supplies are programmable over their full range of output current with a reproducibility error varying from ± 10 ppm to ± 400 ppm of full scale. Included within the reproducibility error are the long and short term stability requirements of the power supplies. The purpose of this paper is to define some of the design goals and outline the approach taken in reaching these goals.

Introduction

The ISABELLE accelerator consists of two identical hexagonal shaped rings positioned to intersect with each other at six crossing regions. Bending magnets are used to bend the trajectories of the circulating beams into closed loops. An rf system is used in the accumulation of beam current and an accelerating rf system accelerates protons up to 400 GeV. The beams are stored for periods up to 48 hours, providing proton-proton collisions during the entire period.

The accelerator's magnetic field must be controlled accurately and with extreme precision during all phases of the excitation cycle. ISABELLE has many correction coils that are required to shape the working line, correcting non-saturation effects, control of the v-values, and controlling the orbit parameters at the crossing regions. One of the primary considerations that establishes the tolerances of the correction power supplies (CPS) is the change in the v-value due to small changes in the output current of the supplies. The tolerances used for the fluctuations in the v-value with time is < 0.001 .

The main magnet power supply (MMPS) tolerance is based on the required stability during injection and at flattop, and also the reproducibility during the ramp or acceleration cycle. The power supply accuracy for both MMPS and CPS, is defined as the ability to set the current to a particular value and maintain that value over time. Included in the power supply accuracy specification is the reproducibility or ability to return to any previous current setting. The current ripple is also an important factor in the power supply specification because of the possibility of beam growth due to ripple plus non-linearities in the magnetic fields. Table 1 and 2 summarizes the parameters of the main magnet power supplies and the correction power supplies.

Magnet Power Supplies Overview

Each power supply is remotely programmed by the control computer through the power supply's built-in microprocessor-based digital function generator. Power supply regulation is accomplished by means of local feed-back loops, and in no way depends on the control computer. The power supplies are protected by internal

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Table 1. Main magnet power supply system specification.

| Parameter | Specification |
|------------------------------|----------------------|
| output voltage (peak) | 0 to 600VDC |
| output voltage (steady rate) | 0 to 100VDC |
| output current | 0 to 5000ADC |
| current regulation | 0.001% of full scale |
| ripple | 0.5 mA Rms |
| load inductance | 50 Henries |
| circuit resistance | 0.02 ohms |
| system time constant | 2500 seconds |
| current ramp rate | 10 A/sec max |
| reproducibility | 15 PPM of full scale |
| temp. range | 20°C to 40°C |

Table 2. Correction power supply specification.

| Parameter | Specification |
|-------------------|--|
| output voltage* | 0 to +10V,+75V,+125V |
| output current* | 0 to $\pm 50A, \pm 100, \pm 200A, \pm 300A$ |
| ripple | 0.3mA rms |
| load inductance | 12 mh to 7.5 H |
| current ramp rate | 200 A/sec. max |
| reproducibility* | ± 10 ppm up to ± 400 ppm of full scale |
| Temp. range | 20°C to 40°C |

*Depends on correction winding.

fault interlocks and does not depend on the computer to acknowledge or recognize any faults for its protection. Built-in status and fault monitoring circuits are used to alert the central computer of each power supply's status in real time.

Main Magnet Power Supply System

The MMPS¹ system consist of two power converters that contain the following: a) 12-phase bidirectional thyristor converter, b) passive ripple filter, c) active ripple filter, d) current sensor, e) high gain regulator, and f) microprocessor-based controller. A functional block diagram appears in Fig. 2.

The thyristor bridge is located on the secondary of the input power transformer to permit the extraction of energy from the magnet load (in the invert mode of operation). The two converters are connected in parallel so that during acceleration or inversion (deceleration) only the high voltage (ramp) supply is operating, providing the output voltage (E_m) required for the magnets. (See Fig. 1).

$$E_m = L_m \frac{di_m}{dt} + i_m R = 50H (10A/sec) +$$

$$4500 A (0.02) = 590V \quad (1)$$

where: L_m = inductance of the superconducting magnet.
 i_m = magnet current.

After the desired current is reached, the high voltage converter is phased back and the low voltage (flattop) converter is phased forward, maintaining the magnet current constant and supplying the voltage drop

across the DC bus connecting the supply to the superconducting magnet.

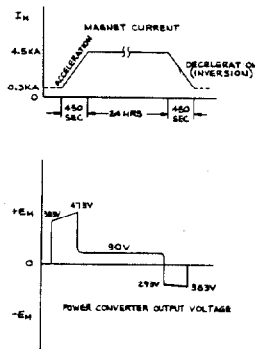


Fig. 1. Magnet excitation curves.

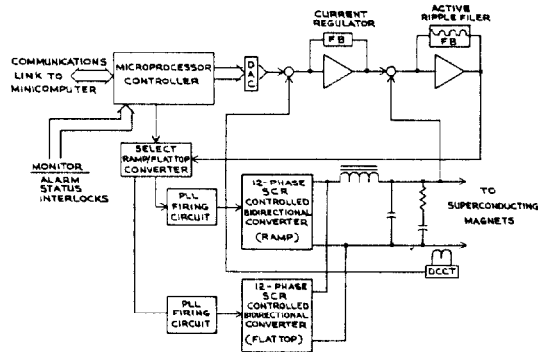


Fig. 2. Power converter functional block diagram.

The voltage (E_m) across the superconducting magnets is now close to zero volts and the IR drop in the DC bus is:

$$E_m = IR = 4500 \text{ A } (0.02) = 90 \text{ VDC} \quad (2)$$

The 12-phase low voltage (flat top) converter input circuit is designed so that it will be operating close to full conduction for minimum output voltage ripple.

Thyristor Firing Circuit

The firing circuits used in each power converter are two 3 phase, 6 pulse, phase-lock loop (PLL) packages. The PLL firing circuit offers several advantages over the more conventional type of firing circuit, and comprises three sections: a) phase sense and synchronization, b) pulse timing, and c) output drive. The two most common approaches used for gate firing circuits are mag-amp integration and zero crossing detectors. The use of a mag-amp produces very high immunity to noise due to its natural integration characteristics. Its drawbacks are size, cost and response time. Often, it introduces another time constant that must be compensated for in a closed-loop system, thereby decreasing the overall system response. Zero detection circuits are relatively inexpensive, with several linear IC's available with built in zero crossing detection. The most serious problem associated with this type of circuit is the susceptibility to noise, harmonics and line spikes generated from other equipment tied to the same power lines. The PLL circuit uses a single phase input, zero crossing detector and waveform synthesizer to generate the outputs for a 6 phase firing circuit. The PLL is locked to six times the line frequency and contains the necessary logic to sort out the individual phases. Because the waveforms are synthesized, it is possible

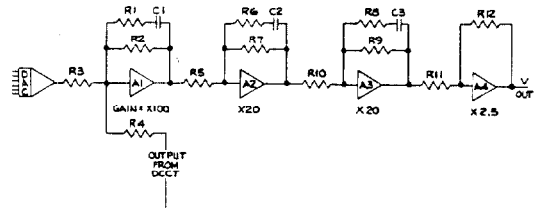


Fig. 3. Summing amplifier simplified schematic.

to use heavy filtering in the zero crossing detector and then compensate for the constant phase shift digitally. Implementing this technique using CMOS gives immunity to large amounts of line perturbations and noise. The output drive circuit used contains a pulse transformer providing a high current pulse at the leading edge and a "back porch" to supply sustaining current to the gate. The output pulse occurs at a repetition rate of about 20 kHz.

Passive LCR Filter

The passive LCR filter must provide sufficient ripple attenuation or undesired current ripple will appear in the superconducting magnet load. To reduce the ripple to an acceptable level an LCR power filter used. The design cutoff frequency of the filter is 167Hz. Harmonics above 720Hz are attenuated, however, frequencies below about 200Hz are not filtered. Attenuation at these latter frequencies is provided by an active filter in the flat top supplies.

Current Regulating Loop

The current regulating loop circuitry (see Fig. 3) is the same for all the magnet power supplies except for the digital-to-analog converter (DAC). The DAC selection is based on the resolution and overall accuracy requirements of a given power supply. The power supply system errors are caused by various components in the regulating loop such as the current sensing device, the summing amplifier and summing resistors, and the reference DAC. The worst case errors (full scale) are shown below for a power supply using an 18 BIT DAC.

System gain: $E/r = 10^{-5} = 10 \text{ PPM}$

| | |
|-------------------|---------------------------------------|
| Direct current | 50 PPM (absolute accuracy) |
| Current sensing | 1 PPM/°C temperature coefficient |
| Device: | 1 PPM/month stability |
| | 5 PPM linearity |
| Summing amplifier | 10 PPM (absolute accuracy) |
| and summing | 3 PPM/°C temperature |
| resistors: | coefficient & tracking |
| Reference DAC: | 2 PPM linearity |
| (18 BIT) | 4 PPM/°C temperature coefficient |
| | 14 PPM/10 ³ hour stability |

The total system full scale errors for the MMPS summarized as follows:

| | |
|--------------------------|----------|
| Absolute accuracy: | 72 PPM |
| Reproducibility: | 15 PPM |
| Stability: | 10 PPM |
| Temperature coefficient: | 8 PPM/°C |

The system static error specification of 0.001% of full scale requires a total open loop gain of 100,000 or 100db. Four amplifiers are used to provide this gain. Referring to Fig. 3 the first stage is set

for a gain of 100 (40db), the following two stages are for a gain of 20 (26db) each and the last stages set for a gain of 2.5 (8db). Figure 4 shows a gain frequency response curve of the amplifier. Pole-zero "dovetailing" is used to provide the necessary frequency compensation.

The dominant pole p_1 , is determined by the system time constant (the inductance of the superconducting magnets and the resistance of the interconnecting cables). Other poles and zeros introduced are shown in Fig. 4.

The dynamic characteristics of the regulating loop satisfies the slewing rate requirements as follows:

$$S = 2\pi f V_p \quad (3)$$

where S = slew rate

f = small signal bandwidth

V_p = maximum output voltage of amplifier

The maximum current ramp rate of the power converter is determined by:

$$\Delta T = \frac{L \Delta I}{V} = \frac{50H \times 4500A}{600V} = 375S \quad (4)$$

where L = inductance of superconducting magnets

I = maximum magnet current

V = maximum output voltage of power converter

The maximum slew rate is then:

$$\frac{\Delta V}{\Delta T} = \frac{5V}{375S} = 0.01 \text{ V/S} \quad (5)$$

To calculate the small signal bandwidth required for minimum dynamic error, equation (6) is used.

$$f = \frac{S}{2\pi V_p} = \frac{0.01 \text{ V/S}}{2\pi(5V)} = 4.25 \times 10^{-4} \text{ Hz} \quad (6)$$

Since the small signal bandwidth occurs before the dominate pole p_1 , is introduced, the dynamic error is negligible.

Active Voltage Ripple Filter

An active voltage ripple attenuator is used to reduce low frequency ripple since it is not practical to handle these frequencies in other filtering elements. The low frequency (dc to 360Hz) ripple information obtained from the flattop power converter is processed and fed back to the voltage controlled thyristor firing circuits, thus closing a feed back loop.

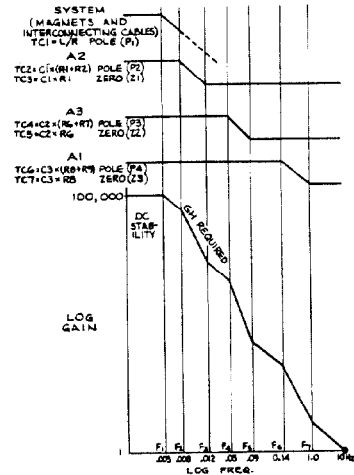


Fig. 4. Log-log plot of GH and pole, zero placement.

High Current Sensing Device

The current sensing device in the current loop is a DC current transducer referred to as the transductor or DCCT. The transductor is used to measure large direct currents of the order of thousands of amperes. The use of shunts to monitor these large currents would generate excessive power in the shunts and would not provide electrical isolation. Hence, even though shunts have been built with a stability that exceeds 0.001% and a pass band from dc to tens of kHz, transductors are commonly used because they dissipate negligible power, have output voltages greater than 10V and provide isolation from the power supply.

The devices used in the ISABELLE magnet power supplies have the following performance specifications:

| | |
|------------------------------|-----------------------|
| Output voltage at full scale | = 10 V |
| Small signal bandwidth | = 10 kHz |
| Linearity | = 5 ppm |
| Offset error vs temp. | = 1 ppm of F.S./°C |
| Slew rate | = 25 V/ms |
| Offset error vs time | = 1 ppm of F.S./month |
| Isolation | = up to 10 kV rms |

References

1. R. Edwards, "Optimizing The Design Of Very High Power, High Performance Converters", proceeding of POWERCON 7, March 1980.