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MAGNET POWER SUPPLY SYSTEM FOR THE ISABELLE* HALF-CELL PROTOTYPE†

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

SUMMARY

Due to stringent requirements on the spatial harmonic content of ISABELLE's magnetic field, the magnet power supplies for the half-cell prototype must be dynamically accurate and stable to within 0.01% of their full-scale rating. Depending on the application, the full-scale current of various units comprising the system ranges from ± 50 A to 4000 A. The system, as constructed is fully controllable and programmable either manually or with a control computer.

INTRODUCTION

The ISABELLE half-cell is a prototype of a segment of the ISABELLE machine. It has been constructed to permit detailed evaluation of the proposed major components of the accelerator when operating as a system. The half-cell consists mainly of three full-scale superconducting accelerator magnets, the associated cryogenic plant, magnet power supplies, vacuum system, and control/monitoring computer hardware. Two of the magnets are 4.45 m long dipoles with a design field of 3.9 T at a nominal current of 3200 A, and the third is a 1.5 m long quadrupole with a field gradient of 52 T/m at the same current. All magnets have a circular aperture 8.0 cm in diameter. The design and test results on these magnets are described in references 1 and 2.

Each of the ISABELLE magnets is constructed with a main high current winding and a number of smaller field correction windings. In the half-cell, these windings are connected and energized as shown schematically in Fig. 1. The main field windings of the

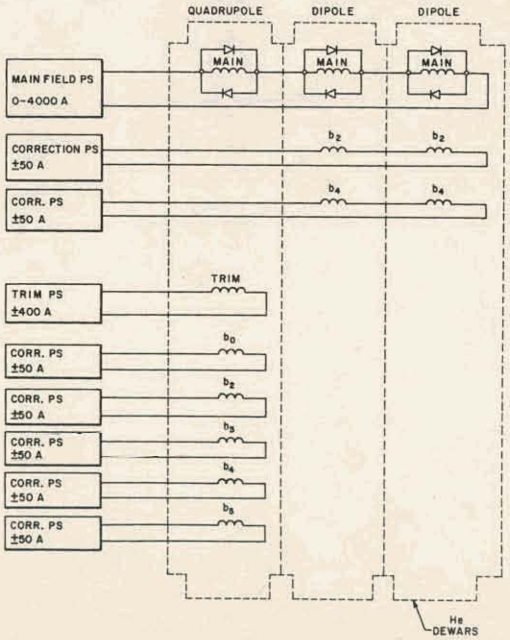

Fig. 1. Magnet and power supply connections.

*ISABELLE - a proposed 200 GeV × 200 GeV Intersecting Storage Accelerator utilizing superconducting magnets.

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magnets are energized in series with a 15 V, 4000 A programmable power supply. The series connection ensures that, to a first approximation, the magnetic field in the quadrupole tracks the field in the dipoles. In the machine, these fields will have to track in order to maintain constant focusing properties with increasing beam energy. The trim coil on the quadrupole, powered by an independent ± 400 A programmable power supply, is provided to permit a relative adjustment of the quadrupole field strength. In terms of machine operation, the quadrupole trim windings will be used to vary the tune of the machine.

The correction windings, energized by independent ± 50 A programmable power supplies, are designed to suppress the harmonic distortion in the field. The distortion is generated as a result of eddy currents, saturation of the iron core, imperfections in the construction and positioning of the windings, etc. In general, for a dipole magnet, the vertical component of the field in the median plane can be expressed in terms of the dipole field, B_o, and normalized higher order multipoles, b_n, as

$$B_y(x) = B_o[\ 1 + \sum_{n=1}^{\infty} b_n(B_o, dB_o/dt)x^n\ ]\ , \quad (1)$$

where x is the horizontal distance from the magnet center line. The magnitude of the multipoles is dependent, generally in a nonlinear fashion, on both the magnitude and the time rate-of-change of the dipole field (a typical variation of b_n vs B_o is shown in Fig. 2). Thus, to reduce the field distortion to acceptable levels, the currents in the correction windings, i_n, n = 1, 2... must be programmed to track B_o.

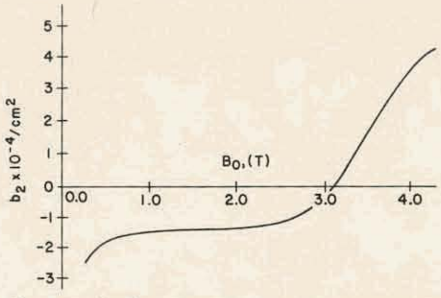

Fig. 2. Typical variation of b_2 term with dipole field strength.

In ISABELLE, the magnetic field must be accurately controlled during all phases of the magnet excitation cycle, except inversion (see Fig. 3). As a result, the magnet power supplies must be dynamically accurate and stable to within 0.01% of their full-scale ratings.

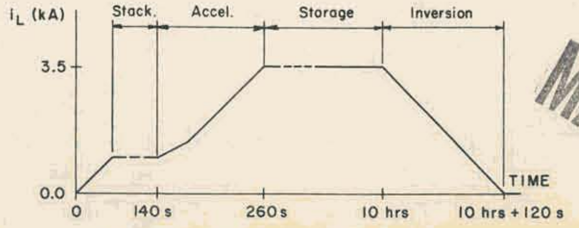

Fig. 3. A typical magnet excitation cycle.

MASTER

DISCLAIMER

The half-cell magnet power supply system, as constructed, is fully controllable and programmable either manually or with a control computer. A functional block diagram of the system is shown in Fig. 4. In the system, each power supply is remotely programmed by its own digital function generator. A digital-to-analog converter, driven by a function generator, is incorporated into each regulator chassis. The operation of the function generators is controlled by the digital computer via a serial data control system, Datacon 2, developed at BNL.[3,4]

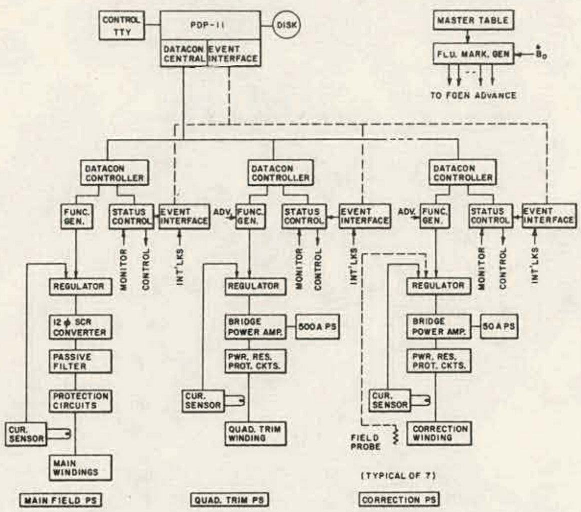

Fig. 4. Block diagram of magnet PS system and control.

In the case of a field correction power supply, the size of the function generator memory and the resolution of the D/A converter depend on the tolerance to which the current must be regulated and on the slope of the $i_n(B_o, dB_o/dt)$ curve.[5] In the present design, each correction power supply function generator has 2 kilowords of solid-state memory. The resolution of the converters ranges from 10 to 14 bits depending on the particular system accuracy.

This paper describes the parameters and design of the programmable power supplies used to power the half-cell magnets. The computer control aspects of the system are discussed in reference 6.

SYSTEM DESCRIPTION

In the design of the power supply system, the following general rules were observed in order to standardize parts and to ensure a high degree of system reliability:

1) Each power supply is electrically isolated from each other (transformers, optical couplers, etc.).

2) Power supply regulation is accomplished by means of local feedback loops, and in no way depends on the control computer.

3) Each system is protected by internal fault interlocks and does not depend on the computer for first line protection against faults.

4) All status control and monitoring circuits, and all regulators are, respectfully, of the same basic design and are fully implemented with solid state components.

The specifications and description of the three types of power supplies developed for the system are given below.

Main Field PS

The load parameters and design specifications of the main field power supply are summarized in Table I.

Table I. Parameters of the Main Field PS

Load	-	R = 1 mΩ, L = 0.16 H
Load Current, i_L	-	0-3500 A
Stored Energy at Full Field	-	0.8 MJ
$(di_L/dt)_{max}$	-	33.3 A/sec
Current Regulation (dc-0.003Hz)	-	0.01% of FS
Stability (24 h)	-	0.01 %
Settability	-	± 50 ppm
Repeatability	-	± 50 ppm
Settling Time for a 2 A Step	-	60 msec
Temp. Range	-	20^oC to 40^o C
Line Voltage Variation	-	± 5 %

This power supply consists of a 12-phase bidirectional thyristor converter, a passive filter, a current sensor and a high gain regulator. A functional block diagram of the system appears in Fig. 4. The thyristor bridge is located on the secondary of the voltage step-down power transformer to permit the extraction of energy from the magnet (in the invert mode). The passive RLC filter is critically damped and has a cut-off frequency of about 200 Hz. With the filter, the magnet current ripple at the fundamental ripple frequency is reduced to about 1 ppm of full-scale. The control signal for the thyristor firing circuits is generated by a regulator which compares the signal from the current sensor with the reference signal from the main field function generator.

The regulator contains a 16 bit D/A converter, a summing amplifier and compensation circuits necessary for the stabilization of the power supply. The system operates basically as a Type 0 servomechanism with a dc loop gain of 100 dB, an effective frequency roll-off of about -9 dB/octave, and a unity-gain bandwidth of 10 Hz.

Table I shows that the stored energy in the half-cell magnets at full field is about 0.8 MJ. The present magnet design with forced helium gas cooling permits the dissipation of the stored energy within the magnet in the case of a magnet quench. Protection diodes are included across each main winding to bypass the current around a quenched magnet as well as to provide a recovery path for the magnet current in case of other types of malfunction.

Correction PS

The performance requirements of the correction power supplies are listed in Table II. A correction power supply consists basically of a transistorized bridge power amplifier with a self-contained 20 V, 50 A power supply, a bipolar current sensor and a regulator. Depending on the winding, the load inductance is anywhere between 15 mH and 60 mH. In general, the magnitude of the voltage induced in a correction winding from the main and other correction windings is negligibly small.

The correction windings are powered via series power resistors to improve system response time. The system dc loop gain is in the order of 100 dB and the unity-gain bandwidth is greater than 200 Hz.

Table II. Parameters of the Correction PS

Load	-	R = 200 mΩ, L = 15-60 mH
Load Current, i_C	-	± 50 A
$(di_C/dt)_{max}$	-	15 A/sec
Current Regulation(dc-0.06 Hz)	-	0.01% or 0.1% of FS
Stability	-	0.01% or 0.1% of FS
Settability	-	± 50 ppm or ± 500 ppm
Repeatability	-	± 50 ppm or ± 500 ppm
Temp. Range	-	20°C to 40° C
Line Voltage Variation	-	± 5 %

As indicated in Table II, the tolerance on the power supply regulation may be either 0.1% or 0.01% depending on the correction winding to be powered. The two regulation requirements are met with a single power supply design which uses a 14 bit D/A converter and a transductor for the higher precision system and a 10 bit converter and a current shunt for the 0.1% system.

Quadrupole Trim PS

In functional terms, the quadrupole trim power supply is identical to the 0.01% correction PS. The basic physical difference between the two is in the current rating of the output bridge and of the current sensor. The bridge circuit, which contains some 160 power transistors, is constructed on water-cooled aluminum heat sinks and is energized with a 20 V, 400 A regulated power supply. The inductance of the trim winding is approximately 5 mH and the normal maximum induced voltage from the main winding is less than 0.2 V.

Table III. Parameters of the Quadrupole Trim PS

Load	-	R = 12 mΩ, L = 5 mH
Load Current, i_Q	-	± 400 A
$(di_Q/dt)_{max}$	-	200 A/sec
Current Regulation (dc-0.06 Hz)	-	0.01% of FS
Stability (24 h)	-	0.01% of FS
Settability	-	± 50 ppm
Repeatability	-	± 50 ppm
Temp. Range	-	20°C ro 40° C
Line Voltage Variation	-	± 5 %

OPERATIONAL EXPERIENCE

The magnet power supply system, as described, has been constructed and interconnected with the half-cell computer control equipment. A number of power supply units have been tested with inductive test loads in both the manual and the computer control modes. Test results on stability and speed of response indicate that all systems perform according to specifications. System tests, including the actual half-cell magnets are scheduled to begin in early April of 1977.

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