Low Energy Booster

Main Magnet Power Supply System

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Abstract

The Low Energy Booster (LEB) is a rapid cycling synchrotron to be built at the Superconducting Super Collider Laboratory in the injector complex. The Low Energy Booster will be ready for operation by late 1995.

The LEB is used to accelerate protons from an injection momentum of 1.2 GeV/c to an extraction momentum of 12 GeV/c. The machine is a separated function design with dipole and quadrupole magnets driven by a single power supply system. Tracking errors between dipoles and quadrupoles are corrected by corrector quadrupole magnets powered from independent power supplies.

The dipoles and quadrupoles are excited with a 10 Hz biased sine wave or 1 Hz linear ramp. Change of operating mode from 10 Hz to 1 Hz takes no more than 2 hours.

This paper describes the present design of the ring magnet power supply system.

I. INTRODUCTION

In the 10 Hz operating mode dipole and quadrupole magnets are excited with a biased sinusoidal current of the form:

$$i(t) = I_{dc} - I_{ac}\sin(2\pi ft) \qquad (1)$$

To avoid drawing a large reactive power from the ac source, it is necessary to use a circuit which is resonant at 10 Hz and in addition provides a path for the dc bias current. These requirements are satisfied by the distributed resonant circuit shown in Figure 1.

II. NETWORK

Figure 1 shows the power supply network. The two modes of operation are provided by this network. When operating in 10 Hz mode, the mode switches are open. When operating in 1 Hz mode, the mode switches are closed. Three locations of the power supplies agree with magnet lattice super-periodicity. This is advantageous in case of leakage current errors caused by voltage to ground distribution.

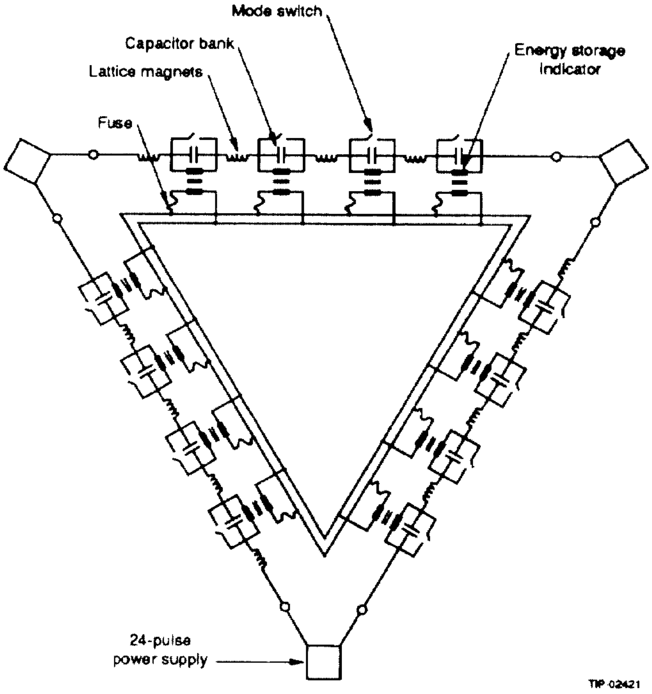

Figure 1. LEB Magnet Power Supply Network

Capacitor banks and energy storage inductors are outdoor devices. A capacitor bank consists of approximately 100 individually fused capacitor units. The bank is divided into two sections: fixed and remotely adjustable. On-load adjustments of capacitance are needed due to large temperature variations in relatively short time periods.

The mode switch is a manually operated knife switch and is a part of the capacitor bank.

The energy storage inductor uses flux aiding arrangements with distributed "air-gaps" in the legs of the core to allow for energy storage and to obtain linear inductance characteristics. The energy storage inductor is of FOA type and weighs approximately 50 tons.

III. 1 HZ MODE OF OPERATION

In the 1 Hz mode, the knife switches are closed. Figure 2 shows the magnet current waveform. In the 1 Hz operating mode the magnets are energized with a piece-wise linear current having approximately 0.3 second linear rise, 0.3 second linear

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fall. 0.1 second flat bottom, 0.1 second flat top. The remaining 0.2 seconds is reserved for connecting the linear segments via parabolas.

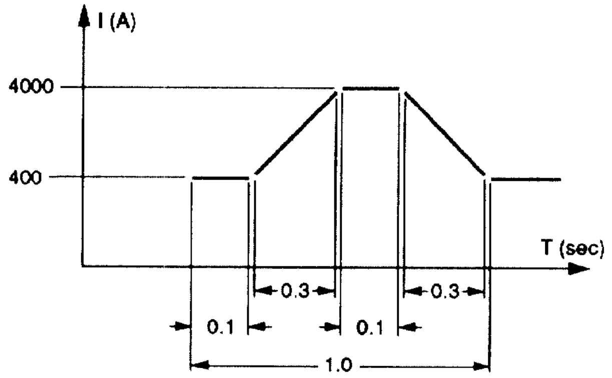

Figure 2. Magnet current waveform, 1 Hz operation.

The power supply parameters for 1 Hz mode are listed in Table 1.

Table 1. Power Supply Parameters, 1 Hz Mode

Magnet Load dc resistance	0.34 Ω
Magnet Load inductance	0.28 H
Peak current	4.00 kA
Minimum ramp/reset time	0.30 sec
Peak ring voltage required	4.72 kV
Number of power supplies	3
Current regulation	100 ppm

Table 2. Power Supply Parameters, 10 Hz Resonant Mode

Equivalent cell magnet dc resistance	26.0 mΩ
Energy Storage Inductor dc resistance	40.0 mΩ
Resonant cell total dc resistance	70.0 mΩ
Nominal dc current	2200 A
Ring dc nominal voltage (12 cells)	1850 V
Equivalent cell magnet ac resistance	38.0 mΩ
Energy storage inductor ac resistance	60.0 mΩ
Capacitor bank ac resistance	3.0 mΩ
Equivalent magnet inductance	23.3 mH
Energy storage inductor inductance	40.0 mH
Capacitor Bank capacitance	17.2 mF
Resonant cell impedance at 10 Hz	66.0 mΩ
Nominal peak ac current	1800 A
Ring ac nominal peak load voltage	1430 V
Total dc & ac nominal peak load voltage	3280 V
Current regulation	100 ppm

IV. 10 HZ MODE OF OPERATION

In the 10 Hz mode, the knife switches are open. The power supply system is required to produce current of the form (1). Figure 3 shows the magnet current waveform.

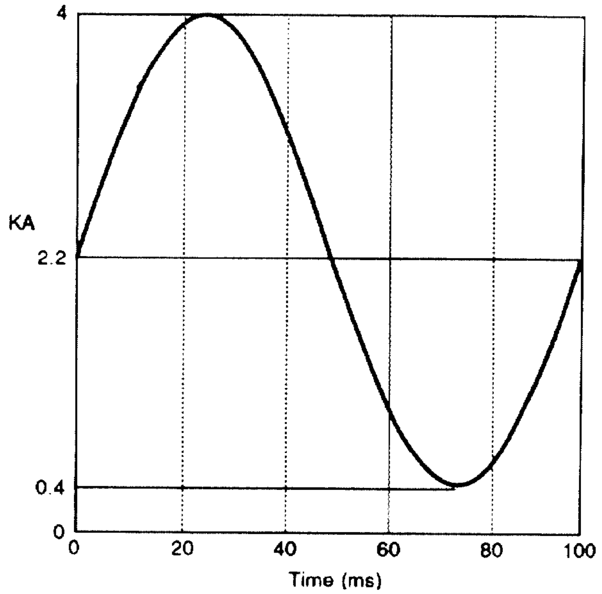

Figure 3. Magnet current waveform for 10 Hz.

The power supply parameters for 10 Hz resonant mode are listed in Table 2.

V. POWER SUPPLIES

Three 24-pulse power supplies (see Figure 1) are used to energize the magnets in both the 1 Hz and 10 Hz modes. Figure 4 shows the basic power supply circuitry.

Four extended delta-wye transformers with three-phase full-wave thyristor bridges operate off a 12.47 kV input line via phase-shifting transformer. The extended delta-wye transformer was chosen in order to keep the impedance of four rectifier bridges matched. Bypass thyristors across the input of a passive filter provide a path for a magnet discharge current. The 24-pulse power supply is rated 2040 V no-load voltage. The total ring voltage required to attain peak field in 10 Hz operating mode is 5100 V no-load voltage. This voltage was calculated, assuming a 20% error in estimating a load impedance and a 1% de-tuning of the resonant system. The total available no-load voltage is 6120 V, which gives the system high availability.

Thyristor assemblies are arranged in groups of three. The common cathode and common anode configurations are designed to cover phase thyristors. Also, the common cathode configuration is designed to cover bypass thyristors.

The passive filter is designed to have appropriate attenuation of 720 Hz ripple in case of working in 12-pulse mode. The passive filter is a second order, critically damped, low-pass filter with an additional trap tuned to 720 Hz. Its resonant frequency is approximately 100 Hz.

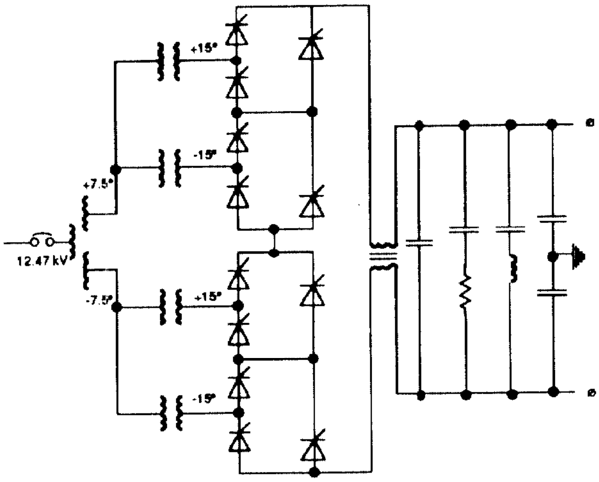

Figure 4. LEB Power Supply Diagram

VI. POWER SUPPLY REGULATORS

The regulation system consists of two major loops; an internal one controlling the output voltage of each power supply and an external one controlling the current in the magnets. Each power supply has its own voltage loop and output filter. The voltage loop is designed to have a high frequency response and its main function is to regulate the voltage applied to the magnets. It must follow a predetermined voltage reference related to the current reference, rejecting line voltage changes, offset errors and other voltage perturbations. Due to bandwidth limitations, the voltage loop only rejects voltage perturbations up to 120 Hz while the output filter rejects the ripple at 720 Hz and other higher frequencies perturbations. The same voltage loop is used for both operation modes but two different regulation loops are needed.

In the linear ramp current mode, the central computer provides the reference current waveform and the magnet current is regulated in a conventional manner. A PI cascade compensator was designed having a dc open-loop gain higher than 80 dB and providing a closed-loop stable operation with a low-pass bandwidth of about 30 Hz.

In 10 Hz biased sine wave mode, the central computer provides the maximum and minimum values of the 10 Hz sinusoidal current waveform. The total deviation on the maximum and minimum values of the magnet current, has to be less than 100 ppm of the actual current. A current regulation system with a high open-loop gain at 10 Hz is necessary for satisfying this regulation requirement. A conventional regulator, as used for the linear ramp, is not suitable for this application. The requirements of high open-loop gain at 10 Hz and adequate closed-loop stability cannot be simultaneously fulfilled by using conventional techniques.

The regulation problem has been solved by applying frequency conversion techniques. The designed current regulator presents an equivalent open-loop gain of 80 dB for 10 Hz sine wave while the closed-loop bandwidth is limited to 0.5 Hz. The schematic diagram of the current loop is shown in figure 5 where, L(s) represents the magnetic load and resonant cells, F(s) the voltage regulation loop and output filter and G(s), $C_{dc}(s)$ cascade current compensators.

The load behavior is different for d-c and a-c current components. For obtaining similar transient responses to dc and ac current changes, two independent compensated loops are used to regulate the 10 Hz ac current amplitude and the dc current mean value.

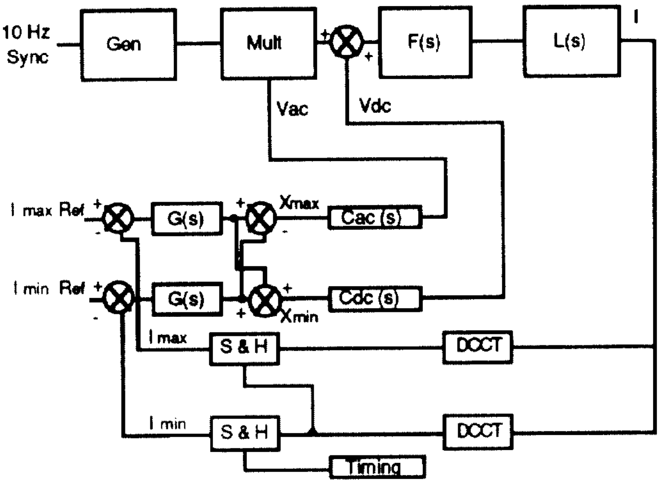

Fig 5. Current Regulation Block Diagram-10 Hz

The central computer provides a 10 Hz synchronization signal and the maximum and mimimum values of the 10 Hz sinusoidal current waveform ($I_{max\ ref}$ and $I_{min\ ref}$). In the regulation system, shown in figure 5, maximum and minimum values of the output current (I_{max} and I_{min}) are measured and compared with the reference values.

The maximum and mimimum output currents measurements are performed by using a precision zero-flux transductor, a 10 Hz timing circuit and two sample and hold circuits. Maximum and mimimum errors processed by the G(s) controller are added and subtracted for driving the dc controller and the ac controller respectively.

The 10 Hz sinusoidal generator is synchronized with the signal provided by the central computer. A multiplier excited by the ac controller regulates the 10 Hz ac current amplitude while the dc component is regulated by adding the dc controller's compensators designed in order to provide adequate stability and transient behavior.