Switchable 10 Hz/1 Hz LEB 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 separate 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:

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

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

Both modes of operation require the power supply system to produce a peak current of 3750 Amperes. The regulation requirement for both modes is 100 ppm of full scale.

II. MAGNETS

The ring magnet power supply system energizes 138 main magnets in the booster, 48 dipoles and 90 quadrupoles. There is 1 type of dipole and 5 types of quadrupoles (5 different lengths). The magnet excitation coils are copper conductors with a cooling hole in the center. Magnet parameters are listed in Table 1.

Table 1. LEB Magnet Parameters

Number of dipoles	48
Peak current	3750 A
Peak field	1.3 T
Dipole inductance	4.8 mH
Dipole dc resistance	4.2 mΩ
Dipole ac resistance at 10 Hz	7.3 mΩ
Number of quadrupoles	90
Quadrupole peak current	3750 A
Quadrupole peak pole tip field	0.8 T
Quadrupole mean length	0.6 m
Quadrupole mean inductance	0.3 mH
Quadrupole mean dc resistance	1.5 mΩ
Quadrupole mean ac resistance at 10 Hz	2.3 mΩ

Figure 1 shows the power supply network. The two modes of operation are provided by this network.

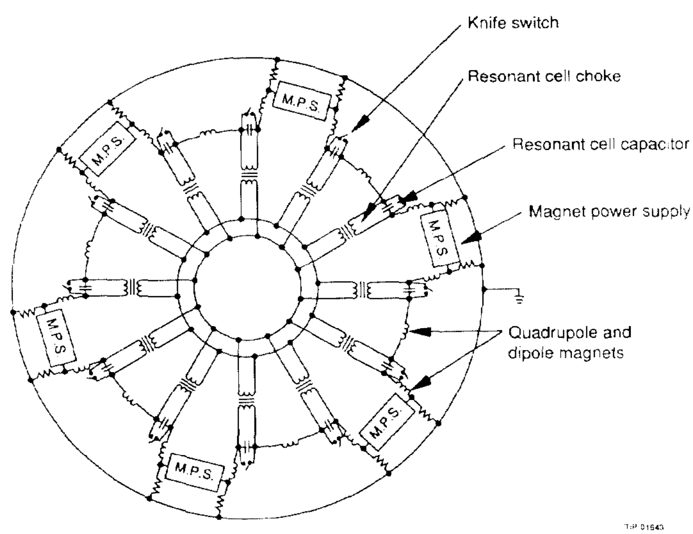

Figure 1. LEB Magnet Power Supply Network

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III. 1 Hz Mode of Operation

In the 1 Hz mode, the knife switches are closed. Figure 2 shows the magnet current waveform.

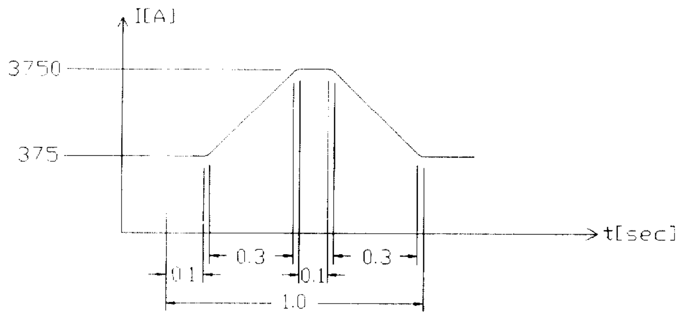

Figure 2. Magnet current waveform, 1 Hz mode of operation.

The power supply parameters for 1 Hz mode are listed in Table 2.

Table 2. Power Supply Parameters, 1 Hz Mode

Magnet load dc resistance	340 mΩ
Magnet load inductance	260 mH
Maximum output current	3750 A
Minimum ramp/reset time	0.3 sec
Maximum dI/dt	11.25 kA/sec
Maximum voltage required	4230 V
Number of distributed power supplies	6
Power supply peak voltage	700 V
Power supply peak current	3750 A
Power supply rms current	2270 V
Maximum operating voltage to ground	350 V
Current regulation	100 ppm of full scale

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.

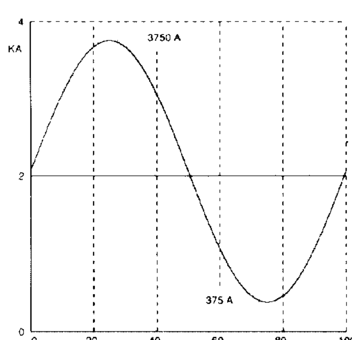

Figure 3. Magnet current waveform required for 10 Hz.

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. The power supply specifications for 10 Hz mode are listed in Table 3.

Table 3. Power Supply Parameters, 10 Hz Mode.

Total magnet inductance	260 mH
Number of resonant cells	12
Resonant choke inductance	35 mH
Number of chokes	12
Resonant capacitor capacitance	18.8 mF
Number of capacitor banks	12
Single cell parameters	
Resonant cell magnet load dc resistance	28.3 mΩ
Resonant cell choke dc resistance	15.0 mΩ
Resonant cell dc resistance	43.3 mΩ
Maximum magnet dc current, I_{dc}	1875 A
Dc voltage required	81 V
Resonant cell magnet load ac resistance	42.5 mΩ
Resonant cell choke ac resistance	22.5 mΩ
Resonant cell capacitor ac resistance	2.8 mΩ
Resonant cell magnet impedance	0.043 + j1.38 [Ω]
Resonant cell choke impedance	0.073 + j2.20 [Ω]
Resonant cell capacitor impedance	0.003 - j0.85 [Ω]
Resonant cell impedance	0.079 + j0.00 [Ω]
Peak magnet ac current, I_{ac}	1875 A
Ac voltage required	148 V
Total ring parameters	
Number of distributed power supplies	6
Power supply peak voltage	460 V
Power supply peak current	3750 A
Power supply rms current	2300 A
Total ring ac losses	1660 kW
Total ring dc losses	1830 kW
Total magnet stored energy	1850 kJ
Total choke stored energy	1950 kJ
Total capacitor stored energy	855 kJ
Total ring Q	32.4
Maximum operating peak voltage to ground	1420 V

V. Power Supplies

Six power supplies (M.P.S. in 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.

Two extended delta-wye transformers with three-phase full wave thyristor bridges operate off a 12.47 kV input line. The extended delta-wye transformer was chosen in order to achieve 6-phase, 12-pulse rectification and at the same time keep the impedance of both rectifier bridges matched. Bypass thyristors across the input of a passive filter provide a path for magnet discharge current. The passive filter is a second order damped low-pass filter. Its resonant frequency is approximately 100 Hz. The phase shift of the filter at 10 Hz is only -2°. The distortion of the filter output voltage has no noticeable effect on the magnet current because of the high Q of the 10 Hz resonant network. For 1 Hz operation, the output voltage is corrected in a fast voltage feedback circuit.

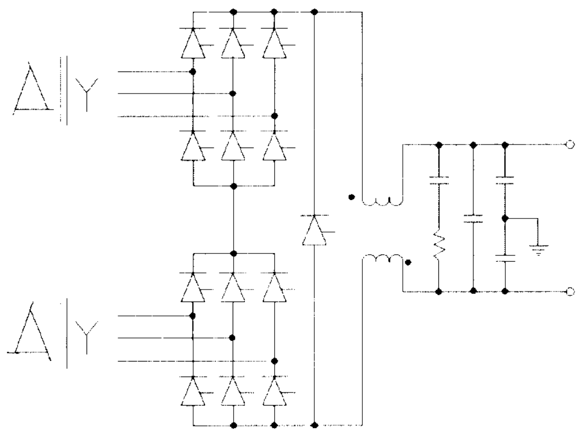

Figure 4. LEB power supply diagram.

VI. POWER SUPPLY REGULATORS

Two separate regulators are used to regulate the power supply voltage and current in two modes of operation.

The magnet current shown in Figure 2 and 3 must be repeated within 100 ppm of full scale. For the magnet current of Figure 3, the regulation is accomplished by a regulator which consists of a fast acting voltage loop controlled by the sum of two current loops. The voltage loop provides fast correction for line transients. Two components of magnet current, I_{ac} and I_{dc}, have their individual feedback loops. A precision zero-flux transductor is used to measure the magnet current. The two components are extracted from the transductor signal and compared with the two references. The current error signals are summed and used as the reference for the voltage feedback loop. The current loops' lagging corner frequencies are matched by adjusting the time constant of the feedback circuits around their error amplifiers. The current feedback loop open loop bandwidth is approximately 0.1 Hz.

For the magnet current of Figure 2 regulation is accomplished by a regulator which consists of two nested loops; a fast acting voltage loop for rejecting line transients and a slower current loop. The same precision zero-flux transductor is used to measure magnet current. The current feedback loop has an open loop bandwidth of approximately 40 Hz. It provides correction for the magnet load pole (0.2 Hz) and has a dc gain of approximately 80 dB.

VII. HARMONIC/POWER FACTOR CORRECTION

In order to achieve a power factor of 0.9 at the point of common coupling with the 12.47 kV distribution and total harmonic distortion of 5%, a harmonic filter is planned.

The filter is rated at 16 MVA and consists of a high pass stage, a band pass stage and a power factor stage. The high pass stage is tuned to 1300 Hz and the band pass stage is tuned to 720 Hz. The filter reactance at 60 Hz is capacitive and produces a capacitive reactive power of 11.1 Mvar needed for power factor correction. Figure 5 shows the arrangement of the major components of the harmonic filter.

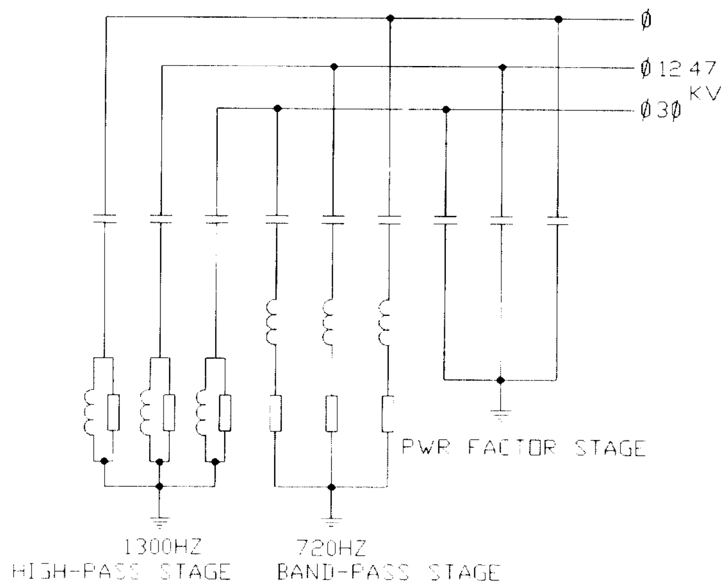

Figure 5. Harmonic filter diagram

VII. REFERENCES

R. Hettel, R. Averill, M. Baltay, S. Brennan, C. Harris, M. Horton, C. Jach, J. Sebek, J. Voss, "The 10 Hz Resonant Magnet Power Supply System for the SSRL 3 GeV Injector", *IEEE* Press, Proceedings of this conference.

K.W. Reiniger, "Power Supply System for the TRIUMF KEON Factory", Proceedings of this conference.

W. Bothe, P. Pillat, "Magnet Excitation Circuit for DESY II" *IEEE Transactions on Nuclear Science*, Vol. NS-32, No. 5, October 1985.

J. Ryk, "Gradient Magnet Power Supply for the Fermilab 8 GeV Proton Synchrotron", FERMILAB-PUB-74/85.

C.W. Brown, K.E. Owen, "Stabilization of the Magnet Power Supplies for the NINA Synchrotron", Proceedings of the International Conference on Magnet Technology, Oxford, 1967.