Electrical Characteristics of the SSC Low-Energy Booster Magnet System*

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Abstract

The purpose of this paper is to review the electrical design of the magnet system for the Superconducting Super Collider (SSC) Low-Energy Booster (LEB). The primary operating mode of the LEB is as a 10-Hz rapid-cycling proton synchrotron. In this mode, capacitor banks are used to make the entire magnet circuit resonant at 10 Hz. This resonant system thus eliminates the requirement of having to provide (and recover) a large amount of reactive power. The primary focus of this paper is to analyze the electrical properties of the magnet system. In addition to the 10–Hz mode, the magnet system is capable of operating as a 1-Hz ramped proton synchrotron, with flat "front porches" and "flattops" for injection and extraction. This mode is initiated through bypassing the choke–capacitor system and exciting the magnet system with a SCR power supply using predetermined waveforms. Both these operating modes (10 Hz and 1 Hz) are analyzed using SPICE (Version 3E).

I. INTRODUCTION

Because the energy gain during the acceleration cycle of the Superconducting Super Collider (SSC) Low-Energy Booster (LEB) is from 600 MeV to 12 GeV, the magnet current must swing through a factor of 10, from 400 A to 4000 A. Because capacitors cannot conduct dc current, the capacitors are placed in parallel with inductors (chokes) so that the magnet system can operate with a biased-sine-wave excitation. The primary focus of this paper is to analyze the electrical properties of this magnet power system.

The major components of the magnet power system include the 2-m dipole magnets, the quadrupole magnets, the chokes, the capacitors, and the power supplies. These can all be represented by electrical circuit models that have the same electrical behavior (both dc and ac) as the actual components. The electrical-equivalent circuit for the dipole is shown in Fig. 1.

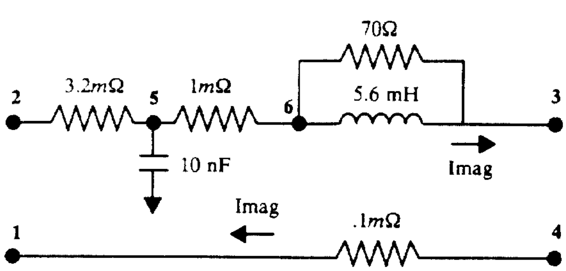

Figure 1. Equivalent circuit for a pair of 2–m LEB dipoles.

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II. SYSTEM LAYOUT AND COMPONENT VALUES

The overall electrical layout of the magnet system is shown in Fig. 2. The magnet system is divided into 12 approximately equal cells and separated by 12 choke-capacitor cells. The ring is powered by three power supplies and filters. The magnet bus turn-around point (not shown) is in magnet cell No. 12. The magnet bus wraps around on itself so as not to create a single-turn 180–m-diameter current loop. This strategy not only minimizes system inductance but also minimizes stray 10-Hz fields. (Also not shown is the resonance control loop, which attaches to the choke secondary windings.)

Ring magnet power is derived from three series-connected dc power supplies (2200 A) and three series-connected 10-Hz ac supplies (1800 A peak). The entire system is made resonant by tuning the capacitors. The resultant current excitation is a biased sine wave whose magnitude varies from a minimum of 400 A to a maximum of 4000 A.

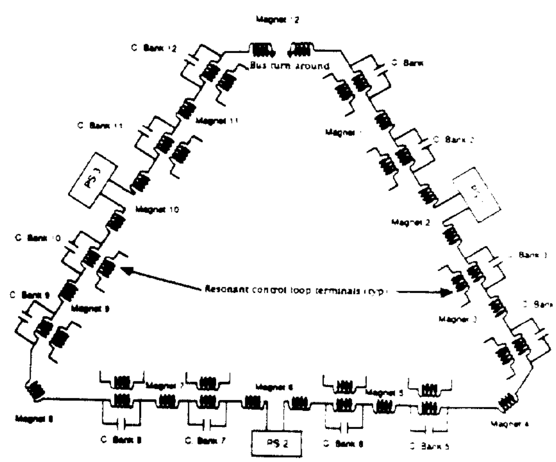

Figure 2. The overall LEB ring magnet system electrical layout.

The major electrical properties of the LEB magnet system include its total inductance (about 296 mH) and dc resistance (about 690 mΩ with the chokes). Thus, the peak stored energy in the LEB is about 2.7 MJ (2.4 MJ in the magnets and 0.3 MJ in the chokes at I_{MAG} = 4000 A). The general characteristics of the LEB magnet system can be seen in Table I.

General Characteristics	
Ring Circumference	570 meters
Injection energy	600 MeV
Extraction energy	12 GeV
Operating modes	10–Hz resonant, 1–Hz ramp cycle
Magnet injection current	400 A
Magnet extraction current	4000 A
Total ring inductance (magnets only)	296 mH
Total ring resistance (without chokes)	332 mΩ
Total ring resistance (with chokes)	692 mΩ
Dipole magnets	
Quantity	96
length	2 m
Peak field	1.3 T (approx.)
Maximum field ripple	± 100 ppm (est.)
Inductance	2.8 mH
dc resistance	2.1 mΩ
Capacitance to ground	5 nF (est.)
Quadrupole magnets	
Quantity	90
Inductance	0.3 mH
Maximum field ripple	±100 ppm (est.)
dc resistance	1.3 mΩ
Capacitance to ground	5 nF (est.)
Capacitors	
Quantity	12
Capacitance	16.61 mF
Max. Voltage	2900 V
Max. Power dissipated (ea.)	5 kW
Chokes	
Quantity	12
Inductance	40 mH
Max. ac current	1109 A
Max. dc current	2200 A
Capacitance to ground	50 nF (est.)

Table I. General characteristics of the LEB ring and magnet system.

Because the driving current of the ring is known [2200 + 1800*sin(wt) amps], it is possible to estimate the maximum choke current and the maximum capacitor voltage at 10 Hz. For the baseline design, it was decided that the inductance (L) of each choke should be 40-mH [1], which minimizes the estimated cost for 12 choke-capacitor circuits. The final choice for capacitance (C) was 16.61 mF. Thus, a resonant frequency equal to 6.17 Hz. The projected cost for the L and C components was based on an estimated fixed cost per Joule of energy storage capability in the chokes and capacitors.

The dc and ac electrical properties of the ring components were estimated using equivalent-circuit component values. The magnets and the chokes were modeled using a series resistance to represent the dc coil resistance and a resistance in parallel with the inductance to represent the eddy-current ac and hysteresis losses. The capacitors are expected to have ac losses not exceeding 5 kW each. Because the excitation current is known, it is possible to estimate both the dc and ac power requirements. The overall estimate is 3351 kW of dc power, plus an additional 1476 kW for the ac power component.

III. ANALYSIS OF THE OPERATING MODES

Analysis of the 10–Hz resonant Mode

Eight issues relating to the operation of LEB in the 10-Hz resonant mode were analyzed. These were magnet current in the frequency domain, magnet current in the time domain, the characteristics of the choke-capacitor circuit, unequal capacitance among the choke-capacitor cells, resonance control, transients caused by switching capacitors, power supply ripple, and effects of eddy currents in magnets.

All these topics cannot be thoroughly covered in this paper. However, a selected few will be discussed. (A complete discussion of the analysis is provided in a report submitted to the SSC Laboratory [2]).

Three simulations that examined the amplitude and phase (in relation to the excitation voltage) of magnet current in the frequency domain were used to determine the driving-point transconductance of the magnet system. One simulation spanned frequencies from 1 Hz to 100 Hz. The results of this simulation are illustrated in Fig. 3. The other simulations more closely examined the small-signal transconductance between 5 Hz and 10 Hz.

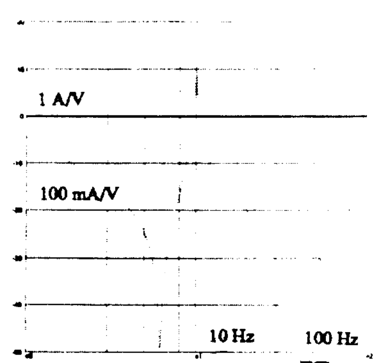

Figure 3. Simulated small–signal transconductance magnitude of the LEB.

Because the capacitors have a temperature coefficient and they will be housed in an unheated enclosure, the capacitance is expected to vary diurnally. To maintain resonance at 10 Hz, each capacitor bank includes discrete levels of switch-selectable capacitance that can be switched in or out remotely. There are three issues related to whether or not the ac and dc power can be present when the capacitors are switched into or out of the circuit. First, are there differential–mode current or voltage surges that can damage components when the power supplies are operating? Second, will there be current transients in the magnet system that can cause the beam to be lost? Third, are there common–mode surges that can lead to excessive voltage–to–ground transients?

To simulate the effects of switching a capacitor into the magnet string, the method of superposition was used. Here, an initial dc voltage of approximately 3000 V was placed on the 400-μF capacitor. When the switch is closed, the 400-μF capacitor discharges into the 16.6-mF capacitor through the snubbing circuit. Figure 4 shows the transient voltage across the capacitor bank as a function of time. The peak half–cycle voltage is 140 V and the frequency is 1 kHz while the other resonant frequency is 6.17Hz.

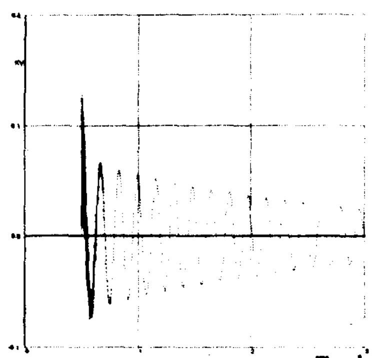

Figure 4. Transient voltage across capacitor bank as a function of time (3 second duration).

Analysis of the 1–Hz resonant Mode

In the 1-Hz operating mode, the choke-capacitor banks are removed from the magnet circuit and the three dc power supplies are ramped using a waveform generator to provide the correct voltage profile. Removal of the choke-capacitor banks is preferred to shorting them out because of the large expected shunt capacitance to ground in the choke-capacitor circuit that adversely impacts the rejection of power supply ripple voltage (especially common-mode).

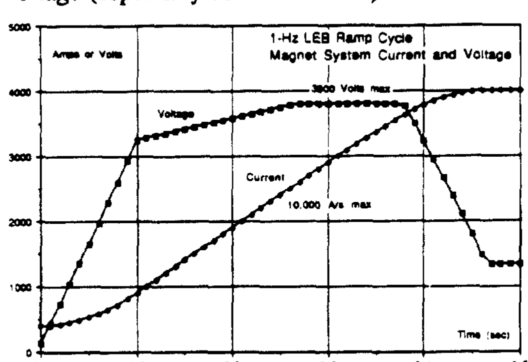

Figure 5. Sample ramp voltage and current profile.

The power–supply voltage and current waveform for 1–Hz ramping is limited by four constraints: maximum current ramp rate, maximum voltage ramp rate, injection and extraction parabolas, and maximum ring voltage. Figure 5 illustrates a sample ramp voltage and current profile that achieves a 470 ms acceleration cycle from 400 A to 4000 A with the current ramp rate equal to 10,000 A/s, voltage ramp rate equal to 32,000 V/s, injection and extraction parabolas equal to 100 kA/s^2, and ring voltage equal to 3800 V.

This ramp waveform is adequate to achieve a 1-s cycle time. Other ramp programs can be used to produce faster acceleration cycles. This ramp cycle is based on a ring resistance of 332 mΩ and inductance of 296 mH and requires only two 2000-V power supplies.

The dc voltage and 1440-Hz ripple voltage on a single power supply at injection will be 133 Vdc and 110 Vac peak, respectively, assuming the full-scale power supply output voltage is 1333 V (33% of 4000 V). The expected differential-mode driving-point transconductance for a single power supply with the choke-capacitor banks removed is about 1.3 mA per volt at 1440 Hz. Thus, the expected ripple current at 1440 Hz is 140 mA peak (360 ppm at 400 A). So some filtering is required. Eddy currents in magnets, beam tubes, etc., will provide some filtering of the magnetic-field ripple.

III. CONCLUSIONS

There are no critical issues in the design or operation of the magnet power supply system for the LEB. However, there are some issues that do need further consideration.

- The stray capacitance—specifically coil-to-ground (magnetic components) and shunt capacitance to case (capacitors)—should be estimated better. This stray capacitance leads to higher common-mode ripple and displacement currents in the magnets.
- The resonant frequency needs to be controlled to about 0.05 Hz (0.5%). The resonance control loop is inadequate for controlling the 10-Hz resonance. A power-factor monitor at the 10-Hz power supplies appears to be a better monitor for the resonant frequency.
- Because the LEB is a separted–function–synchrotron, the eddy-current time constants of the dipoles and quadrupoles should be matched in order to minimize tune shifts during acceleration. The source of the tune shift is a retardation of the magnetic fields due to eddy currents. The matching is best done by adding external bypass resistors across dipoles or quadrupoles. The magnets should be designed to allow for the attachment of external bypass resistors in order to control the magnetic field retardation.

IV. REFERENCES

[1] C. Jach, et. al. , "Energy Storage Inductor for the Low-Energy Booster Resonant Power System, " To be published in 1993 Proc. Particle Accelerator Conference.

[2] R.E. Shafer and A. Young, "Electrical Characteristics of the SSC Low-Energy Booster Magnet System, " Los Alamos National Laboratory document number LA-UR-92-3298-01.