Analysis of Transmission Line Effects in the SSC Magnet System

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Abstract

The response of the SSC accelerator magnet string to transient excitation from the power supply is considered. Some criteria for the selection of the optimum damping resistors for the SSC magnets are discussed. The transient response of the load to power supply transients, including the effect of the power supply filter is analyzed. A comparative analysis is made of the differences between two possible configurations in the distribution of the magnets (with and without a return bus.)

Introduction

Superconducting magnet strings have electrical properties similar to signal transmission lines. Voltages from the power supply cause slow electrical waves to propagate along the string, resulting in a spatial variation of current in the magnets during the response time. These waves do not see a characteristic impedance termination, so reflections add to the original signal, causing a standing-wave pattern of current and voltage in the string. The eddy current losses in the magnets eventually damp this response, but in order to reduce the effect on the accelerator operation to an acceptable level, it is usually necessary to provide some external damping resistance.

Dipole Characteristics

Studies of the electrical characteristics of individual Energy Saver superconducting magnets indicate the circuit shown in Fig. 1 to be appropriate to analyze the transmission line characteristics of the magnets.[1] Since the inductance and eddy current resistance of the coil bus dominates the series impedance, the return bus and ground conductors can be considered to have no resistance or inductance.

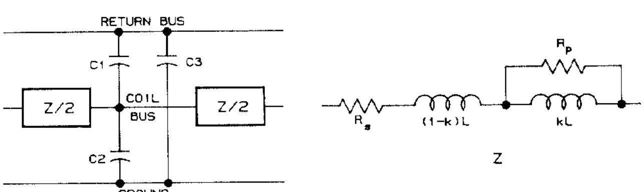

Fig. 1. Magnet Equivalent Circuit

In this model,

- L = coil inductance
- C_i = capacitance between conductors
- R_s = coil resistance (0 Ω if superconducting)
- R_p = eddy current loss resistance
- k = coupling coefficient between L and R_p.

For this analysis, a simpler variation of this circuit shown in Fig. 2 will be used. In Fig. 2, C is the capacitance from coil to ground. C_1 and C_3 of Fig. 1 are estimated to be less than 10% of C_2 and will therefore be ignored. From inductance measurements made on early prototypes leading to the present dipole design,[2]

$$L' = 3.146 \text{ mH/m}, \quad l = 16.6 \text{ m/dipole}$$
$$L = 52.2 \text{ mH/dipole.}$$

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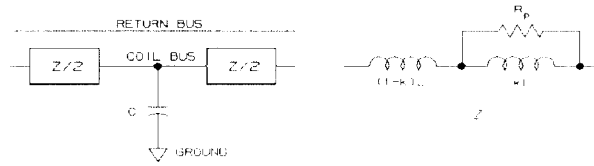

Fig. 2. Simplified Equivalent Circuit

An estimation of the capacitance per unit length based on measurements of the first 4.5 m SSC magnet model is[3]

$$C' = 4.2 \text{ nF/m}; \quad C = 70 \text{ nF/dipole.}$$

Estimation of Eddy Currents

The eddy current effects in the magnets are strongly dependent on the geometry of the magnets. For the Energy Saver magnets it was shown that the eddy current resistance could be expressed as[4]

$$R_p = kL/\tau$$

where k and τ are determined by the magnet geometry. Since better information is not available, the values of these parameters used for the Energy Saver magnet design will be used here to estimate the eddy current resistance for the SSC magnets. These values are

$$k = 0.6, \quad \tau = 650 \ \mu s.$$

Then,

$$R_p = kL/\tau = (0.6)*(52.2 \text{ mH})/(650 \ \mu s) = 48 \ \Omega.$$

Determination of Transmission Line Parameters

With the circuit component values known, we can proceed to characterize the nature of the circuit formed by a string of dipoles. Design considerations have determined that the power supplies will be situated in the center of the dipole string; the transmission line model is shown in Fig. 3 and Fig. 4(a).

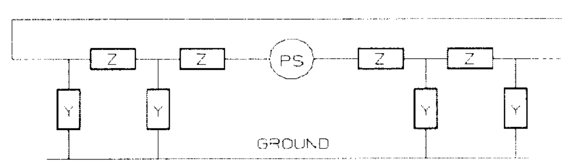

Fig. 3. Transmission Line Model of Magnet String

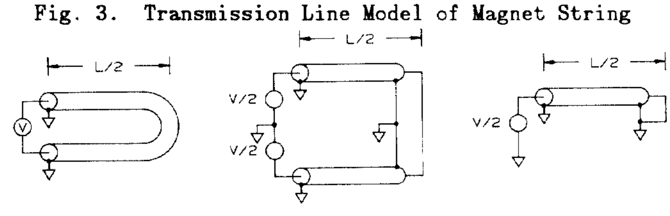

Fig. 4. Simplified Transmission Line Model

For purposes of this study, a sector is assumed to contain 80 half-cells of 5 dipoles each, or 400 dipoles total. The contribution of quadrupoles to be connected on the same bus will be ignored as small compared to the dipole contribution. As the line is a homogeneous circuit, the bisection theorem applies, and the load can be split in two symmetrical subcircuits, each 200 dipoles in length as shown in

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Fig. 4(b). Considering the power supply as a pure differential one, the voltage at the end of the subcircuits will be constant and hence, can be considered as ground. Then the analysis can be done considering only one half of the transmission line excited with one half of the power supply and shorted at the end as shown in Fig. 4(c). To obtain the overall response, the superposition theorem can be used.

In order to simplify the analytic process to characterize the magnet string as a transmission line, the impedance Z shown in Fig. 2 can be transformed as shown below in Fig. 5.

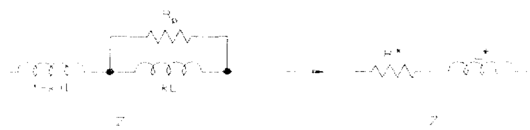

Fig. 5. Series Impedance Transformation

$$Z = R^* + j\omega L^*$$

$$R^* = \frac{kL\tau\omega^2}{1+\omega^2\tau^2}, \quad L^* = (1-k)L + \frac{kL}{1+\omega^2\tau^2}, \quad \tau = \frac{kL}{R_p}$$

Solution of the differential equations of the transmission line lead to the approximate relationships for the characteristic impedance, propagation velocity and attenuation length:

$$Z_0 \simeq \sqrt{L^*/C}\ , \qquad v_p \simeq \sqrt{1/L^*C}$$

$$\lambda \simeq \frac{2Z_0}{R^*(\omega)} \text{ magnets to } 1/e.$$

Standing waves will exist at frequencies:

$$f_n = nv_p/N$$

and

$$Q_n = \omega_n L^*(\omega_n)/R^*(\omega_n)$$

where:

n = odd or even number half integer
N = number of magnets in the total string.

Application to SSC Magnets

Using the simplified equations and the SSC parameters we obtain:

Z_0 = 861 Ω, v_p = 16565 dipoles/s

f = 41.4 Hz, Q = 10.2

where f and Q are for the half-wave resonance.

An SCR power supply usually has ripple output at power line harmonic frequencies, with the 120 Hz component often predominant because of power line unbalance and difficulty in filtering at this frequency. Hence it is important to know the value of the attenuation length and the quality factor Q at this frequency.

L^*(120 Hz) = 46.1 mH/dipole, R^*(120 Hz) = 9.33 Ω
$\lambda_{120\ \text{Hz}}$ = 175 dipoles to 1/e
$Q_{120\ \text{Hz}}$ = 3.7

To decrease the effect of power supply ripple and to obtain a desirable transient response to voltage steps from the power supply, an external damping resistor will be placed in parallel with a half cell or cell of magnets. As in the Energy Saver, the value will be determined by minimizing the attenuation length at a specific frequency of interest.[5]

Selection of the Optimum Damping Resistor

The transmission line properties of the magnet string were calculated as a function of the damping resistor, R_d. The results for 41.4 Hz (half-wave resonance, curve A) and 120 Hz (curve B) are shown in the graph of Fig. 6. For 41.4 Hz, the attenuation length has a minimum value for a resistance of 8.25 Ω, and for 120 Hz, the attenuation length has a minimum value for a resistance of 25.5 Ω per dipole.

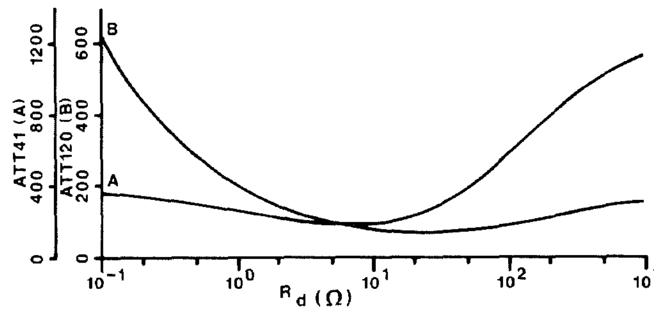

Fig. 6. Attenuation Length (λ) vs. Damping Resistance

In order to analyze the sensitivity of the value of the damping resistor to the eddy current resistance R_p, a case was calculated considering this resistance to be infinite (no loss). The 120 Hz optimum value for the damping resistor in this case is 22.4 Ω, which indicates that the eddy current model chosen does not greatly affect the selection of R_d. The low resistance of the optimum R_d attenuates the sensitivity to changes in R_p.

The optimum value is probably in the range of 8 - 25 Ω. For a ramping condition as indicated in the SSC Reference Design Study, a voltage of 100 V from the power supply leads to total sector power dissipations of 1 - 3 W and shunt currents of 10 - 30 mA for the two values of damping resistance studied above.

Computer Simulation of the Magnet String Response

In order to provide further insight into the behavior of the magnet string, a SPICE model of approximately one sector of magnets containing 16 subcircuits of 25 dipoles each has been generated.[6] A magnet equivalent circuit based on Fig. 2, including an eddy current resistance was used.

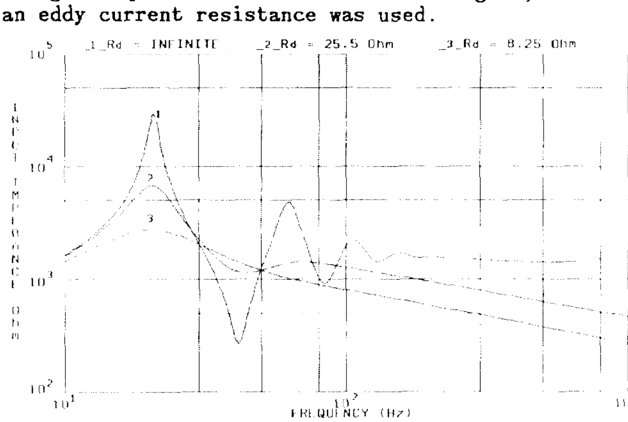

Fig. 7. Input Impedance of Magnet String

An ac analysis was conducted for the magnet string with no damping resistor and each of the two damping resistor values discussed above. The input impedance plots for these cases shown in Fig. 7 show the lowest frequency resonances of the magnet string model and how they are affected by the damping resistance. The half-wave 41.4 Hz resonance calculated for the simplified transmission line model is verified in the impedance plot of Fig. 7.

To study the system response to voltage transients from the power supply, a differential perturbation of the voltage of approximately 10% full output with rise and fall times appropriate for a 12-pulse SCR controlled power supply was used. Transients of this nature should be expected in a real system of this type.

Cases were studied for no damping and for the two values of damping resistance. Since we do not know what actual coil and bus configuration is to be used, we analyzed two variations:

1.) A global return bus system in which all inductance is on the bus connected to the power supply terminals with a stabilized return bus outside the magnetic field running the total length of the sector. Results for this case using the two values of damping resistance are shown in Fig. 8 and Fig. 9. (Transients with no external damping exceed twice the amplitudes indicated in Fig. 8.) The individual curves show the instantaneous current at locations along the magnet string moving from the power supply toward the far end.

2.) A "split-bus" system in which half of the inductance is on each of two busses (with alternations of coils and return busses as in the Energy Saver) assuming that the effective current contributing to the magnetic field is the sum of the currents in the two busses.

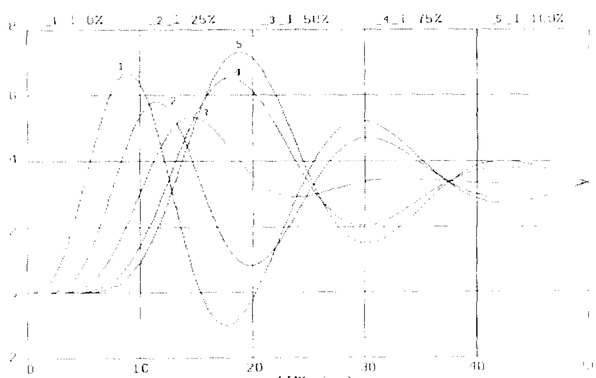

Fig. 8. Transient Response, Return Bus Model, 25.5 Ω

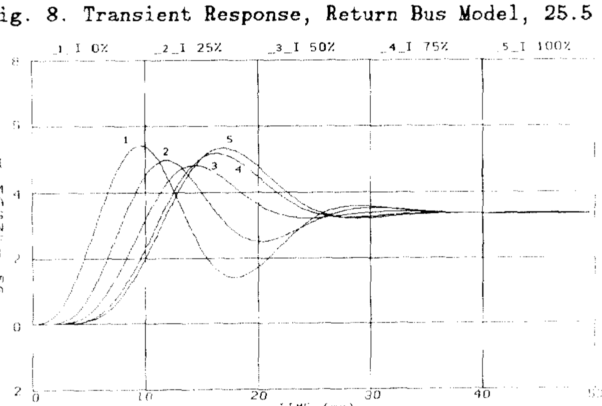

Fig. 9. Transient Response, Return Bus Model, 8.25 Ω

The split-bus case shows an interesting compensation effect, i.e., the sum of the magnet currents in the two busses varies less with distance from the power supply as shown by the differences between Fig. 9 and Fig. 10. How practical this effect is depends on whether the effect on the beam can be integrated over several magnets with their coils distributed between the two busses.

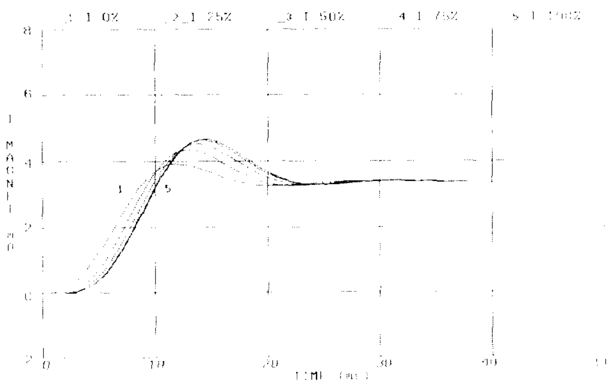

Fig. 10. Transient Response, Split Bus Model, 8.25 Ω

Conclusions

This analysis of the transmission line behavior of the SSC magnet string does not indicate any serious problems to be expected in the system electrical behavior. It does indicate however that external damping resistors should be added to the magnet string to reduce the effect of power supply ripple and to reduce the magnetic field spatial distortions due to power supply transients. The value of resistance used is not critical and with the ramping voltages expected in the SSC, the power dissipation in these resistors is negligible. The power rating of the resistors may be determined from other considerations such as the voltage due to dumping the energy from the system during a quench.

A significant difference in transmission line behavior of the magnet system has been noted dependent on the distribution of the magnet coil windings on the two busses passing around the ring. Splitting the coil windings on two busses appears to have a beneficial effect on the electrical behavior of the circuit.

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1. R. Shafer, "Transmission Line Characteristics of Energy Doubler Dipole Strings", FNAL UPC-37, January, 1979

2. G. Cottingham, "Quadruple Diode Quench Protection for SSC Reference Design "D" Magnets", SSC-MD-97

3. G. Cottingham, Private Communication, November, 1985

4. R. Shafer, "Eddy Currents, Dispersion Relations, and Transient Effects in Superconducting Magnets", FNAL TM-991, September, 1980

5. R. Shafer, "Transmission Line Properties of Long Strings of Superconducting Magnets", FNAL TM-997, September, 1980

6. O. Calvo, G. Tool, "Initial Estimate of Transmission Line Effects in SSC Design D Magnets", FNAL TM-1360, December, 1985