TRANSIENT ANALYSIS OF THE AGS-BOOSTER RING DIPOLE AND QUADRUPOLE MAGNET SYSTEM[1]

W. Zhang, A.V. Soukas, and S.Y. Zhang

AGS Department, Brookhaven National Laboratory, Upton, NY 11973

ABSTRACT

A case study has been conducted for the quantitative analysis of the transmission line effects in the Brookhaven AGS Booster ring dipole and quadrupole magnet string. The Booster is a rapid cycling synchrotron (7.5 *Hz*) which is excited by multiphase rectifier power supplies. A computer model and a simulation program are developed to study the transient current response of the magnet string due to an applied step voltage. To damp out the staircase noise caused by wave reflection during the current ramp, external resistors will be added in parallel with each half dipole magnet and each quadrupole magnet. The system model and simulation values are based on the actual magnet parameters, the magnet power supply bus system, and the proposed current ramping rate. The system simulation approach can be applied to a larger system as well, and will be briefly discussed.

INTRODUCTION

In the AGS Booster main ring, there are 36 dipoles, 24 horizontal and 24 vertical focusing quadrupoles. The main coils of these magnets are connected in series and powered by multiphase rectifier power supplies. The requirements for the AGS Booster ring power supplies are quite varied. They must act as accurate low voltage supplies for beam injection; they must ramp rapidly up and down, in two distinctly different modes, for beam acceleration and cycle recovery; and also be capable of flat top operation for a period greater than two seconds for accumulation of polarized proton beams. It is known that magnet strings will behave like a varying impedance transmission lines, due to their distributed inductances and capacitances. This leads to the concern of pulse reflection noise problem during fast current ramping. The circuit models of the dipole and quadrupole magnets are shown in Figure 1. In these models, L_D, R_D, C_D are the dipole magnet inductance, resistance, or capacitance, respectively. And, L_Q, R_Q, C_Q are defined similarly for the quadrupole magnet. The parameters used in the simulation are summarized in table 1.

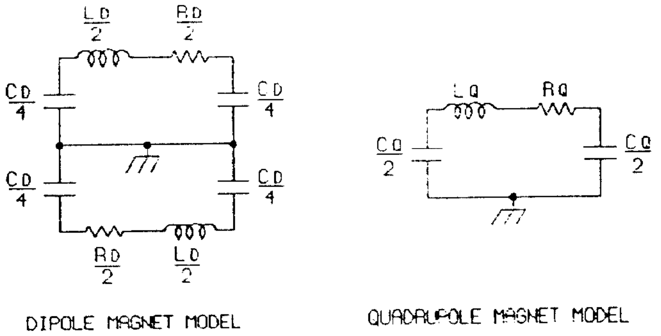

Figure 1. The dipole and quadrupole magnet models.

Table 1. Magnet Parameters

Magnet	Dipole	Quadrupole
Inductance	3.2 mh	0.35 mh
Resistance	1.5 mohm	0.9 mohm
Capacitance	10 nf	2 nf

A simplified schematic of magnet bus connection and power station arrangement is shown in Figure 2.

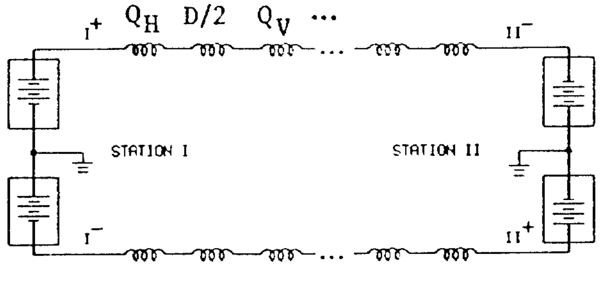

Figure 2. Simplified schematic of the AGS-Booster ring magnet power supply system.

---

[1] Work performed under the auspices of the U.S. Department of Energy.

0-7803-0135-8/91$01.00 ©IEEE

This arrangement virtually splits the circuit into two identical strings. One is from I^+ to II^-, and another is from II^+ to I^-. There are 12 identical sections in each string, a total of 24 sections in the ring. Figure 3 shows a typical section consisting of 2 quadrupole magnets and 3 top or bottom halves of dipole magnets. The computer simulations are based on the circuit model of one entire string powered by two supplies, one at each end, with the same voltage amplitude but opposite polarities.

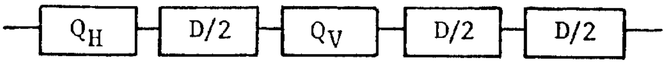

Figure 3. A typical section of the magnet string.

SIMULATION RESULTS

The transient current response due to an applied voltage step is the main interest in this study. In the AGS Booster operation, the magnet current must ramp up linearly from 600 *amperes* to 2500 *amperes* in 60 *ms*. This requires a voltage step about +/−1068 *volts* at each end.

Each magnet string is a balanced circuit about the center. Therefore, the center point is a virtual short of the transmission line, when the magnet string is powered by a pair of power supplies with equal amplitude and reversed polarity. The wave reflection time is twice the half way delay time of the transmission line. The initial magnitude of the staircase noise is about U/Z, where U is the voltage step, and Z is the average impedance of the transmission line.

To damp out the noise, first we added an external resistor in parallel with each half dipole magnet. As one might expect, the result shows that the smaller the external resistance, the faster the noise damping rate. However, the current sharing between the external resistor and the dipole magnet results in a current difference between the dipole and quadrupole magnets. For better tracking of the quadrupole and dipole fields in the Booster ring, it is necessary to put an external damping resistor in parallel with each quadrupole magnet as well as across the dipole magnet.

The damping resistor used with each half of the dipole magnet is 300 Ω, as suggested by M. Meth in [4], and a 50 Ω resistor is used for each quadrupole magnet. Figure 4 shows 6 current curves of quadrupole and dipole magnets located at the first, middle, and last section of the magnet string, for the first 2 *ms* after the excitation. Figure 5 (a) shows the absolute current difference, as a percentage, between quadrupole magnets and the design value, and (b) of the dipole magnets. It can be seen that the current differences reduce to below 0.01% in 600 μs. The average absolute current difference of dipole and quadrupole magnets to the design value is shown in Figure 6, where it decreases to less than 0.01% in about 200 μs. It may be noticed that this scheme now contains a high impedance resistive bypass with the main magnet string. Therefore, the nonlinearity of current ramping caused by parallel and series resistance should be taken into account. Figure 7 shows the dipole and quadrupole magnet current differences to the design value in percent. The peak difference is about 0.76%. A cure of this problem is to apply small trimming steps during current ramping, and current tracking to the command will not be a problem. Compared to the initial step, each trimming step must be fine enough, so that the reflection noise will not become noticeable.

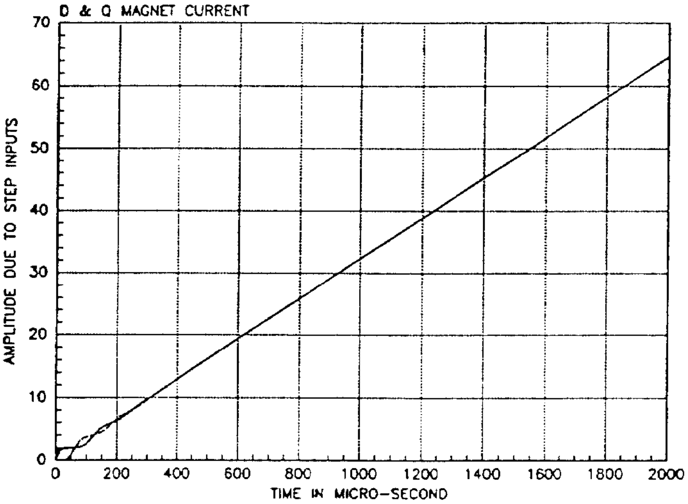

Figure 4. Current response of dipole and quadrupole magnets.

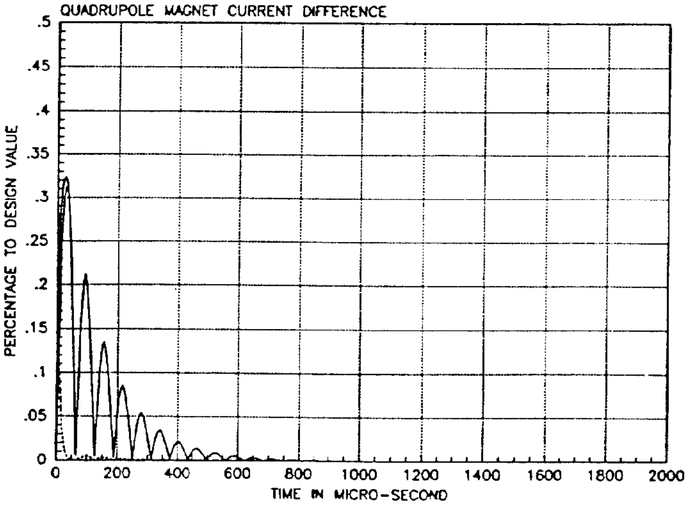

Figure 5 (a). The absolute current difference between quadrupole magnets.

SIMULATION APPROACH

The circuit model of the AGS Booster ring magnet string is a high order ladder network. For an N section L-C ladder network, the network matrix size is usually $2N\times2N$, which can easily go beyond the capability of the electronic simulation programs. To simulate the Booster ring magnet string, we formulate the network in state space form. The voltage across the capacitor and the current through the inductor are chosen as the state variables. Since most high order ladder network have all the distinctive eigenvalues, the simulation can be obtained by using an eigen-system analysis approach. Applying a similarity transformation to the state equation, the output can be converted to a summation of the exponential functions. In this simulation, time step iteration is not involved. The simulation accuracy depends on the circuit model and eigen-parameter computation. This method turns out to be effective and of better simulation accuracy. However, it is restricted that the network must be a linear system. This is an extension of the method we used to simulate our fast kicker systems. Some detailed information is given in reference [5]. The circuit is simulated in $MATRIX_X$[2]. We developed our own user code. Expanding the stack size of the program, this method can be applied to a larger system.

ACKNOWLEDGEMENT

The authors wish to thank Mr. Roger Katz and Mr. Richard Casella for their support in using the Apollo system, also Dr. M. Meth for useful discussions about the problem.

REFERENCES

[1] "Booster Design Manual," AGS Booster Project, Brookhaven National Laboratory, 1988.

[2] O. Calvo and G. Tool, "Analysis of Transmission Line Effects in the SSC Magnet System," Proc., 1987 PAC.

[3] O. Calvo, et al., "Magnet Current Regulation in the SSC," Proc., 1987 PAC.

[4] M. Meth, "Magnet Wave Propagation," AD Booster tech. note #136, BNL, 1989.

[5] W. Zhang, et al., "A PFN and Transmission Line Simulation Method for Energy Discharge Systems," IEEE Conf. Rec., 19th PMS, 1990.

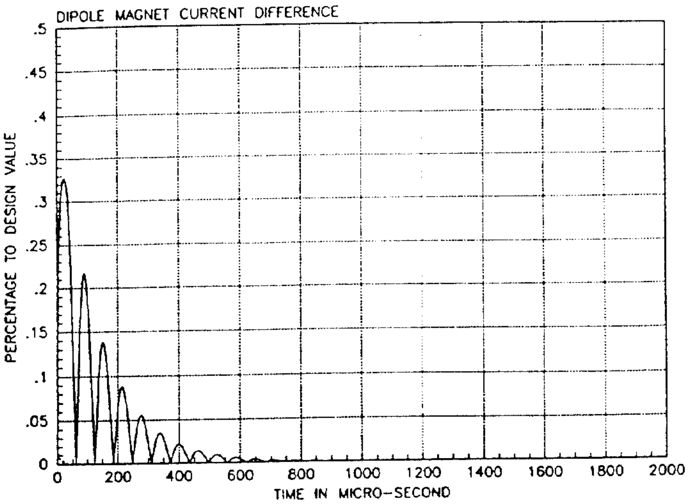

Figure 5 (b). The absolute current difference between dipole magnets.

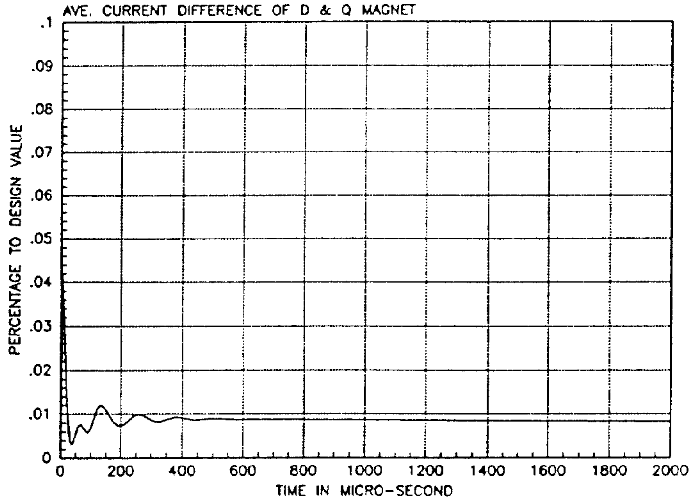

Figure 6. The average absolute current difference of quadrupole and dipole magnets.

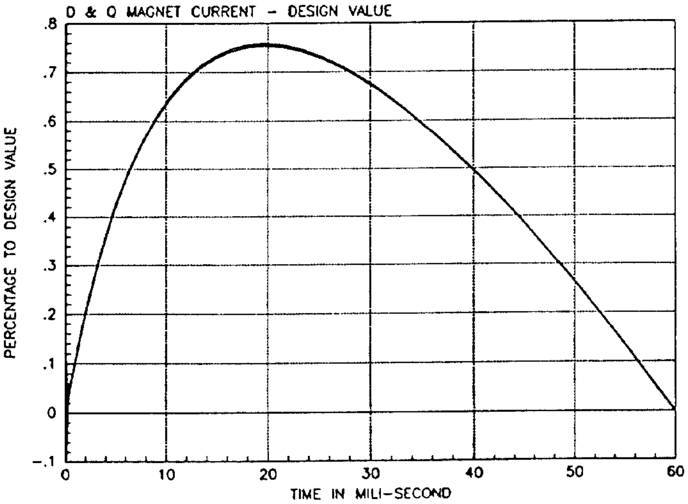

Figure 7. Current difference to the design value.

---

[2] $MATRIX_X$ is a trademark of Integrated Systems Inc., Santa Clara, CA 95054.