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DISCLAIMER

ANALYSIS AND SIMULATION OF MAIN MAGNET TRANSMISSION LINE EFFECT*

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Abstract

A main magnet chain forms a pair of transmission lines. Pulse-reflection-caused voltage and current differentiation throughout the magnet chain can have adverse effect on main magnet field quality. This effect is associated with magnet system configuration, coupling efficiency, and parasitic parameters. A better understanding of this phenomenon will help us in new design and existing system upgrade. In this paper, we exam the transmission line effect due to different input functions as well as configuration, coupling, and other parameters.

INTRODUCTION

The parameter and configuration used in this study are based on Brookhaven's AGS, but the approach is applicable to similar systems. AGS has 240 dipole magnets. They are placed around AGS ring. AGS ring has 12 super periods, with 20 dipole magnets in each period. Each dipole magnet has four winding pancakes split into upper-two and lower-two, and two pancakes of each upper or half magnet are connected in series.

Four chain of 120 half magnets are arranged with each two chains in parallel and then two pairs in series. The electrical connection of magnets is in zigzag style, as shown in Figure 1.

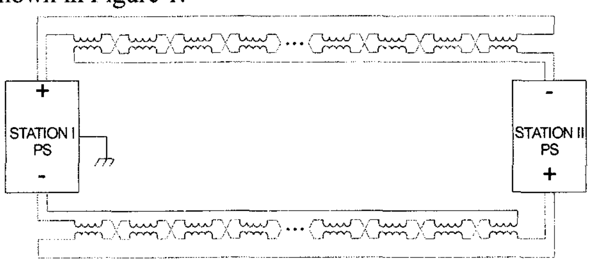

Figure 1: Simplified AGS main dipole magnet power supply diagram

The physics reason of this zigzag connection is to make sure the leakage currents, both capacitive and resistive, are balanced. In addition, the magnetic coupling of upper and lower magnet pancakes greatly helps to balance the current and field. There are two power supply systems, each with two banks. They feed magnet chain in two places in push-pull fashion.

MAGNET PARAMETERS AND UNCOUPLED MAGNET MODEL

We use L_{HC} to denote the inductance of a chain of 120 half magnet. Its measured equivalent inductance is 760 mH. Therefore, the half-cell magnet inductance, L_{HD}, is 6.33 mH.

Similarly, the measured magnet coil resistance is 270 mΩ. It gives an average value of half-cell coil resistance, R_{HCD}, of 2.25 mΩ.

Capacitance was measured on the number 242 magnet, which is a hot spare. The total capacitance of half magnet (upper half or lower half) C_{HD} is about 7.95 nF.

Magnet leakage resistance is measured in similar way of capacitance measurement. The total leakage resistance of half magnet (upper half or lower half) R_{HDL} is 1.125 Meg ohm.

From above measurement, we establish a half-cell dipole magnet model as illustrated in Figure 2. In this model, the coupling effect of upper and lower coils is not included.

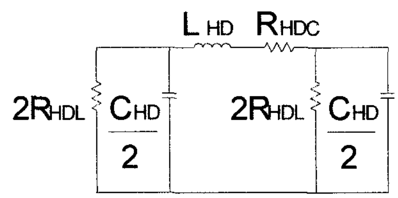

Figure 2: Half-cell dipole magnet model

AGS RING DIPOLE MAGNET TRANSMISSION LINE ANALYSIS

Based on the model of half-cell dipole magnet, we created a simplified circuit model of a single chain of 120 uncoupled half-cell magnets as shown in Figure 3.

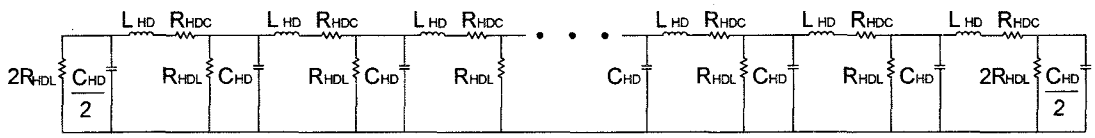

Figure 3: Single chain uncoupled half-cell magnet model

This circuit model depicts a typical finite section transmission line. It is a low loss transmission line. Since its series coil resistance is much smaller than its inductive reactance, and its parallel leakage resistance is much larger than its capacitive reactance, they can be ignored in impedance estimation. Therefore, the impedance, Z, of this transmission line is given by

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$$Z = \sqrt{\frac{L_{HD}}{C_{HD}}} = \sqrt{\frac{6.33\times10^{-3}}{7.95\times10^{-9}}} = 892.3\Omega \qquad (1)$$

The transmission time, T_{HD}, per half-cell magnet can be estimated as

$$\begin{aligned} T_{HD} &= \sqrt{L_{HD}\times C_{HD}} \\ &= \sqrt{6.33\times10^{-3}\times7.95\times10^{-9}} = 7.09\mu S \end{aligned} \qquad (2)$$

The transmission time of 30, 60, 90, or 120 half-cell magnet sections are listed in Table 1.

Table 1: Transmission time of selected section of half-cell magnet

symbol		quantity	
T_{30}	30 half-cell magnet	212.7	ms
T_{60}	60 half-cell magnet	425.4	ms
T_{90}	90 half-cell magnet	638.1	ms
T_{120}	120 half-cell magnet	850.8	ms

Note that the transmission delay of 120 half-cell magnet is 850.8 ms, which means a 220-degree phase shift at 720 Hz. The wave reflection affects magnet current and voltage uniformity. The magnitude of wave reflection is determined by excitation source and transmission line impedance. At higher impedance, the reflection is smaller. Therefore, reducing coil capacitance is important.

Time domain simulation:

The magnet chain is powered by two rectifier power sources with different polarity from both ends. At the power feeds of the magnet chain, low pass filters are used in between power source and the magnet chain.

The time domain simulation is focused on 720 Hz components. We compare two cases. One is the original configuration of P-bank with two 60 Hz 3 Phase rectifier transformers differ by 30 degree phase shift to generate a 12 pulse rectifier system. Another one is the proposed configuration of P-bank with two 60 Hz 3 Phase rectifier transformers differ by 15 degree phase shift to generate a 24 pulse rectifier system.

In the first case, 720 Hz component of the rectifier two is in phase with the rectifier one. Therefore, the 720 Hz current flowing through the magnet chain is driven by two rectifier sources 0.5 Vac each added together. In Figure 4 and Figure 5, transmission line effects are clearly visible on voltage waveforms, but oscillation amplitudes are higher. Transmission effect exists on magnet currents as well. In these simulations, we used following notations:

- I(L1) current of magnet number 1
- I(L30) current of magnet number 30
- I(L60) current of magnet number 60
- I(L90) current of magnet number 90
- I(L120) current of magnet 120
- V(L1) voltage across magnet number 1
- V(L2) voltage across magnet number 30
- V(252) voltage across magnet number 60
- V(372) voltage across magnet number 90
- V(9) voltage across of magnet 120

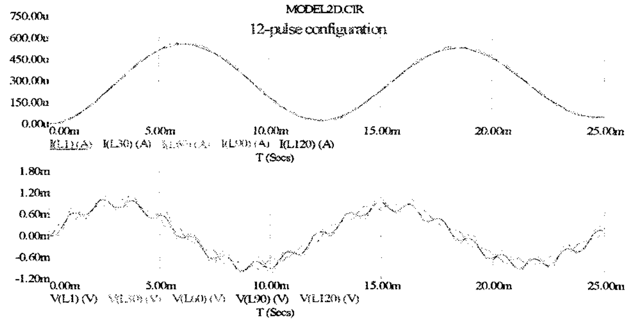

Figure 4: Magnet current and voltage waveforms of first 25 ms with 720 Hz input under 12-pulse configuration

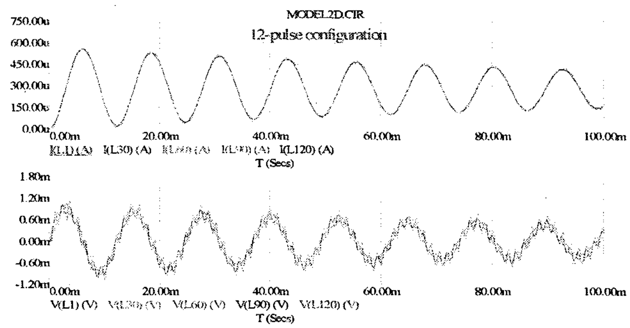

Figure 5: Magnet current and voltage waveforms of first 100 ms with 720 Hz input under 12-pulse configuration

While in the second case, 720 Hz component of the rectifier two is 180 degree out of phase with the rectifier one. In principle, the 720 Hz current shall not be present due to zero potential difference of two rectifier sources. However, the 720 Hz current will flow in the magnet chain due to transmission line effect. The mid-section of the magnet chain will act like a virtual opening. The 720 Hz current is basically determined by the source voltage and transmission line impedance of the magnet chain. In Figure 6 and Figure 7, transmission line effects are visible on both current and voltage waveforms.

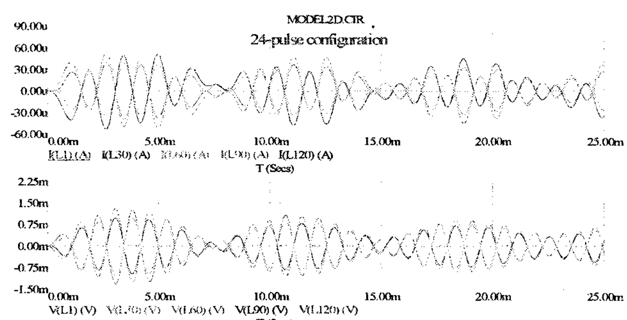

Figure 6: Magnet current and voltage waveforms of first 25 ms with 720 Hz input under 24-pulse configuration

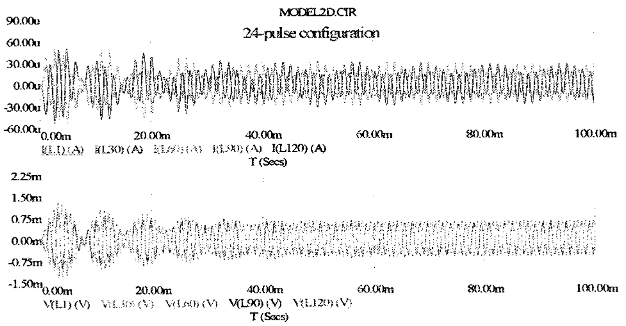

Figure 7: Magnet current and voltage waveforms of first 100 ms with 720 Hz input under 24-pulse configuration

Next, we simulate the AGS dipole magnet system response to pulsed excitations. The simulations, shown in Figure 8 and Figure 9, are performed with following conditions: 80% upper and lower magnet coupling, 240 magnets, two trapezoidal voltage pulses of 1.0 V each, 5m rise time, 60 ms flat top, 5ms fall time. We used following notations in Figure 8:

- I(R1) - current of magnet number 1
- I(R117) - current of magnet number 30
- I(R237) - current of magnet number 60
- I(R357) - current of magnet number 90
- I(R447) - current of magnet 120
- DELTAI1W30 - absolute value of current difference between magnet number 1 and magnet number 30
- DELTAI1W60 - absolute value of current difference between magnet number 1 and magnet number 60
- DELTAI1W90 - absolute value of current difference between magnet number 1 and magnet number 90
- DELTAI1W120 - absolute value of current difference between magnet number 1 and magnet number 120

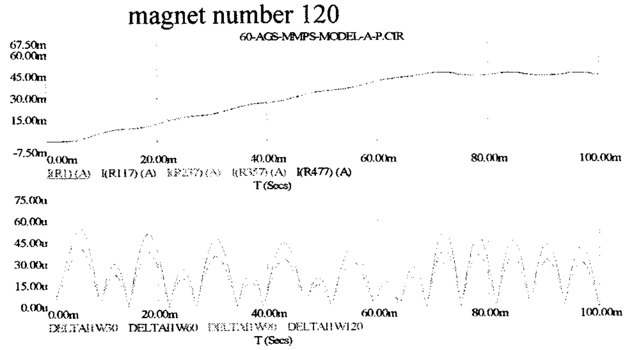

Figure 8: Magnet current waveforms and magnet current differences

Current tracking errors, as shown in above waveforms, are less than 0.2% of full current amplitude.

We now look at magnet voltage responses under same conditions. The notations are as follows:

- V(V1) - voltage of source V1
- V(2) - voltage of magnet number 1 to ground
- V(132) - voltage of magnet number 30 to ground
- V(252) - voltage of magnet number 60 to ground
- V(372) - voltage of magnet number 90 to ground
- V(9) - voltage current of magnet 120 to ground
- DELTAV1W30 - absolute value of voltage difference between magnet number 1 and magnet number 30
- DELTAV1W60 - absolute value of voltage difference between magnet number 1 and magnet number 60
- DELTAV1W90 - absolute value of voltage difference between magnet number 1 and magnet number 90
- DELTAV1W120 - absolute value of voltage difference between magnet number 1 and magnet number 120

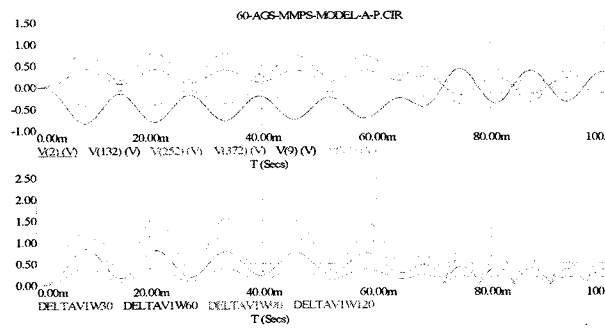

Figure 9: Magnet current waveforms and magnet current differences

The magnet voltage waveforms show that oscillation amplitudes are location dependent. The middle magnet is a virtually ground as it shall be in a push-pull configuration.

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