LARGE SCALE DISTRIBUTED PARAMETER MODEL OF MAIN MAGNET SYSTEM AND FREQUENCY DECOMPOSITION ANALYSIS*

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Abstract

Large accelerator main magnet system consists of hundreds, even thousands, of dipole magnets. They are linked together under selected configurations to provide highly uniform dipole fields when powered. Distributed capacitance, insulation resistance, coil resistance, magnet inductance, and coupling inductance of upper and lower pancakes make each magnet a complex network. When all dipole magnets are chained together in a circle, they become a coupled pair of very high order complex ladder networks. In this study, a network of more than thousand inductive, capacitive or resistive elements are used to model an actual system. The circuit is a large-scale network. Its equivalent polynomial form has several hundred degrees. Analysis of this high order circuit and simulation of the response of any or all components is often computationally infeasible. We present methods to use frequency decomposition approach to effectively simulate and analyze magnet configuration and power supply topologies.

INTRODUCTION

The criticality of large main dipole magnet chain and its power supply system demands detailed analysis and understanding of its circuit behavior. This has been a difficult task for large accelerator facilities. Note that almost all analysis of accelerator main magnet supplies are performed either at system level with much simplified model or single magnet level. The issue is the complexity of the circuit combined with high order networks. We present an approach to analyze the system with frequency decomposition, which divides the task within the modern day computer capability. As an example, we present the analysis of Brookhaven's AGS main magnet system based on 12-pulse and 24-pulse configuration.

ANALYSIS APPROACH

Like many main dipole magnet and its power supply system the AGS main magnet system has 240 dipole magnets and two power supply systems. The first order approximation of the circuit assumes magnet as an inductor with resistive loss. This would offer a simple circuit. It can be studied with analytical method. In Figure 1, it shows a simplified AGS main dipole magnet power supply model.

The second order approximation takes into consideration the capacitance of magnet coil to ground and the leakage resistance of magnet as well as the coil resistance. The model of the magnet chain can be represented by a pair of transmission lines. When the coupling of the upper and lower magnet windings and the crossing connections of wiring are added into consideration the circuit model is highly complicated. Even a finite section (two or more sections) transmission line is a high order circuits. Usually the transfer function of an n-section transmission line corresponds to a rational function with 2nth-order polynomial as its denominator. Its complexity makes the numerical simulation a necessary approach of the main magnet circuit analysis.

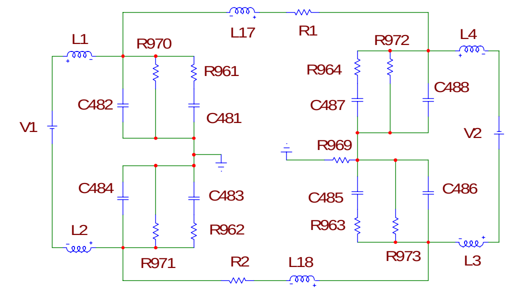

Figure 1: Simplified main diagram of AGS main magnet power supply

Shown in Figure 2 is a circuit model of the AGS main dipole magnet system with AC inputs. This model consists of 1871 components. The number of reactive components is in the range of a thousand.

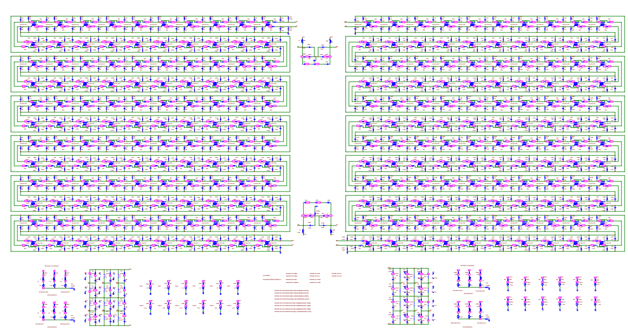

Figure 2: A simulation circuit of AGS main magnet power supply

Due to high order of the network, discontinuity caused by switching devices, and complexity of configuration, it challenges even latest version of programs and computers to carry out its circuit simulations in many ways. Therefore, researchers often choose to divide circuit into smaller sections or even single magnet for higher order circuit analysis, which would scarify information associated to magnet locations around accelerator ring and very high order phenomena.

Our approach will provide each and all magnet current and voltage responses to ac inputs at selected frequencies and their corresponding locations as well as very high order behavior of the network.

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SIMULATION RESULT

In this report, the Micro-Cap VI or VIII is used to simulate the circuit. The inputs are unity sinusoidal signals of the sub harmonic frequency from 60 Hz to 720 Hz, and 1440 Hz. The outputs are magnet currents and magnet voltages from coil to ground. The first and last magnets, the middle one, and the two located quarter length from either end are selected as sample magnets.

Since the main dipole magnets are fed from two places in the AGS ring, the wave propagation along the magnet chain can cause undesirable consequences.

The current waveforms and voltage waveforms of selected sub harmonic are simulated for comparison of 24-pulse and 12-pulse configuration. So far, all simulation results show that the current peak and voltage peak both occur during first few cycles. Therefore, the simulation results of the first 50 ms or 25 ms are used for comparison.

The actual magnet-coupling coefficient of upper and lower coils is not available and therefore assumed to be 80% for the purpose of study.

We can simulate any magnet current for study. Here, we selected the first, last, middle, quarter-length in the chain from either end to observe circuit behaviors. We used following symbols in simulation:

- 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

In Figure 3 and Figure 4, we show the current response to 60 Hz signal for 24-pulse and 12-pulse configuration.

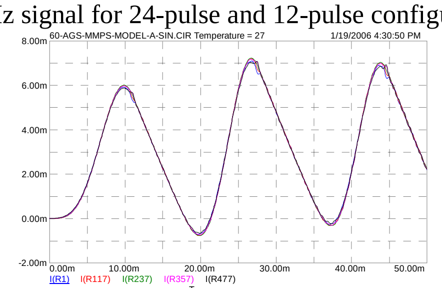

Figure 3: Simulated magnet current responses of 1V 60 Hz input under 24-pulse configuration and 80% coupling condition

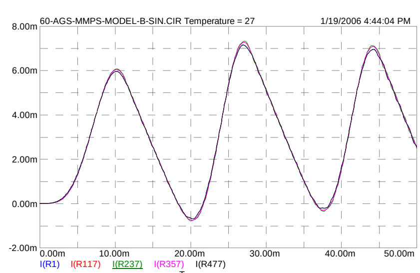

Figure 4: Simulated magnet current responses of 1V, 60 Hz input under 12-pulse configuration and 80% coupling condition

In above waveforms, magnet current response magnitudes are similar in both configurations.

In Figure 5 and Figure 6, we show the current response to 600 Hz signal for 24-pulse and 12-pulse configuration. Both current magnitudes are much smaller than at 60 Hz. In addition, the current response in 24-pulse configuration is much smaller than in 12-pulse configuration. These waveforms reveal magnet current differences verses time.

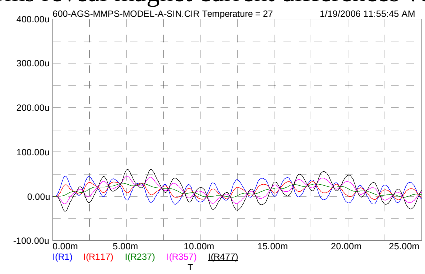

Figure 5: Simulated magnet current responses of 1V 600 Hz input under 24-pulse configuration and 80% coupling condition

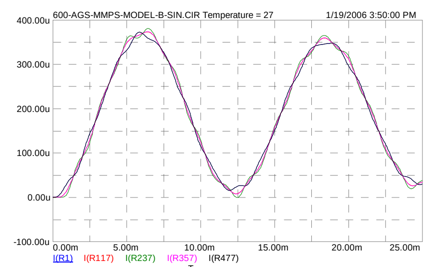

Figure 6: Simulated magnet current responses of 1V, 600 Hz input under 12-pulse configuration and 80% coupling condition

Similarly, we show simulated magnet voltage waveforms in Figure 7 to Figure 10. We used following symbols in simulation:

- ✓ 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

In Figure 7 and Figure 8, we show voltage responses to 240 Hz signal for 24-pulse and 12-pulse configuration. In Figure 9 and Figure 10 are same magnets with 540 Hz input. The magnitudes of magnet voltage response are similar with different patterns under both configurations.

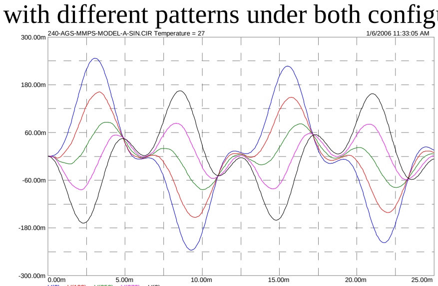

Figure 7: Simulated magnet voltage responses of 1V 240 Hz input under 24-pulse configuration and 80% coupling condition

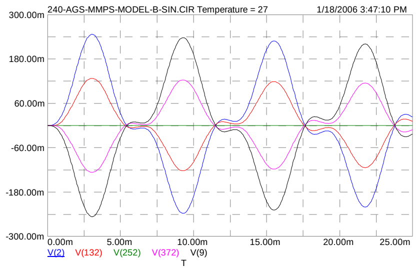

Figure 8: Simulated magnet voltage responses of 1V 240 Hz input under 12-pulse configuration and 80% coupling condition

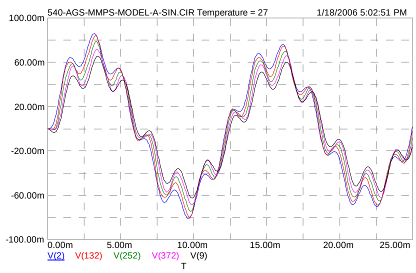

Figure 9: Simulated magnet voltage responses of 1V 540 Hz input under 24-pulse configuration and 80% coupling condition

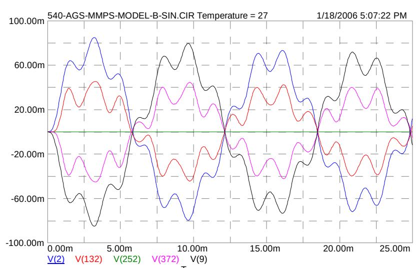

Figure 10: Simulated magnet voltage responses of 1V 540 Hz input under 12-pulse configuration and 80% coupling condition

COMPARISON OF AC HARMONIC TIME DOMAIN RESPONSE

The graph in Figure 11 compares the peak current response level of sampled magnet to the unity ac sinusoidal signal of harmonic frequency with 24-pulse configuration and 12-pulse configuration.

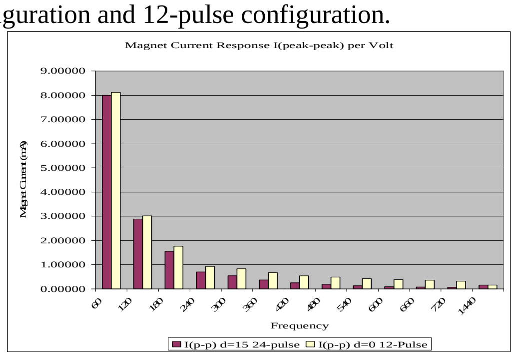

Figure 11: Comparison of simulated magnet current responses of 1V AC input under 24-pulse configuration and 80% coupling condition at harmonic frequencies

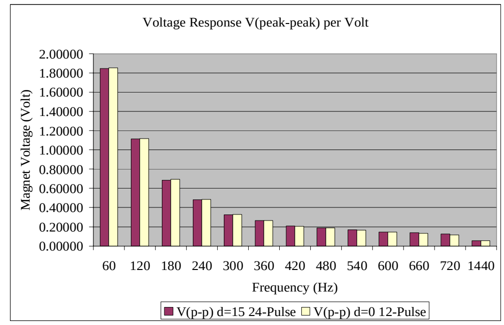

Figure 12: Comparison of simulated magnet voltage responses of 1V AC input under 24-pulse configuration and 80% coupling condition at harmonic frequencies

Similarly, the graph in Figure 12 compares the peak voltage response level of sampled magnet to the unity ac sinusoidal signal of harmonic frequency with 24-pulse configuration and 12-pulse configuration.

In summary, the current and voltage simulation results show lowered current response and similar voltage response of 24-pulse configuration than 12-pulse configuration to sub harmonics of the same amplitude. However, these are relative comparisons assuming unity input. The actual amplitude of each sub harmonic input in 24-pulse or 12-pulse configuration has yet to be determined. In this study, the 720 Hz is the main concern. In principle, the 24-pulse configuration will contain lower amplitude of 720Hz component, which is the main concern, than 12-pulse configuration.

The transmission line effect is observed in both configurations. However, it does not appear to be a dominant factor at lower harmonic frequencies. At higher harmonic frequencies, it becomes more important.

As shown in previous section, due to high transmission line impedance of dipole magnet chain, waveform reflections caused by transmission line effect are small comparing to oscillation amplitude during initial ramping. However, transmission effect can be more important at steady state and waveform reflections could cause magnet current tracking errors. Oscillation dominates the ramping region. Resistive damping may be used to reduce oscillation if necessary.

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