Hierarchical Modelling of Line Commutated Power Systems Used in Particle Accelerators Using Saber*

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Abstract

This paper discusses the use of hierarchical simulation models using the program Saber™ [1] for the prediction of magnet ripple currents generated by the power supply/output filter combination. Modeling of an entire power system connected to output filters and particle accelerator ring magnets will be presented. Special emphasis is made on the modeling of power source imbalances caused by transformer impedance imbalances and utility variances. The affect that these imbalances have on the harmonic content of ripple current is also investigated.

I. Introduction

In order to design power equipment for ring magnet systems it is necessary to know how subsystems interact with each other. This can get quite complicated when dealing with rings of hundreds of magnets, pulsed power supply systems and power supply output filters. In order to design a power supply output filter one must first know the ring load characteristics and the harmonic content under various load conditions of the power supply. Imbalances due to rectifier transformer winding error and ac utilities can also affect the harmonic content of the power supply output. In order to understand the interactions of these three systems hierarchical models were developed that addressed these systems and their imbalances.

II. The Accelerator Ring Model

The model of the accelerator ring is made up of hierarchal blocks that represent the magnets comprising the main ring. Within these block representations reside the circuit that models the magnets. A swept frequency ac analysis was then performed yielding the common mode and differential mode admittance responses of the ring or for an element within the ring. These responses were saved and then multiplied by the frequency spectrum derived from the power supply/output filter combination to yield a simulated current ripple (see figure 1).

III. The Power Supply Model

This model is the most complex of the three. In this model reside the various imbalances due to ac utilities and transformer winding errors as well as the models for the SCRs being used in the bridges, the snubber circuits, the gate firing circuit, and a simplified load. To accomplish this without creating a very large and complicated schematic, three levels of hierarchy were used. For a 24 pulse system the top level schematic consists of four, six pulse bridge power supplies connected in series to form a complete 24 pulse power supply connected to its load. Below each six pulse supply there is a model of a three phase transformer secondary including impedances, gate firing circuit and three phase bridge. Below this level are the elements that make up the transformer secondary and the schematic representations of the SCR models connected to snubber circuits. The final level of hierarchy contains the device model for the SCRs.

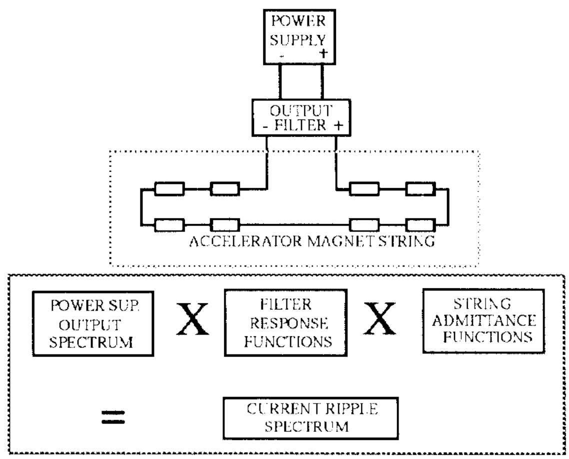

Figure 1.
Block Diagram for Obtaining Current Ripple

With the power supply model complete, common and differential mode simulations at the currents and voltages of interest were run. This resulted in a detailed Fourier voltage spectrum of the power supply output (see figures 2&3). Applying this spectrum to the load admittances yielded an expected ripple current spectrum. The frequency response of the output filter was then tailored to provide the desired ripple currents within the ring magnets.

IV. The Filter Model

The filter type used is a Praeg topology modified to incorporate L-C series traps (see figure 4). This model does not contain other levels of hierarchy. With the basic filter response requirements known, the filter design and simulation can be performed separately from the power supply and load. Once this design is complete the filter response can be verified by incorporating it with the power supply output spectrum and the ring magnet load response.

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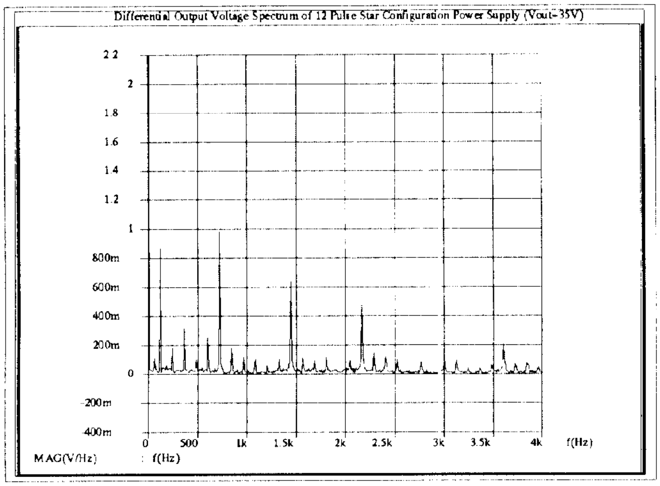

Figure 2.
12 Pulse Differential Power Supply Output Voltage Spectrum

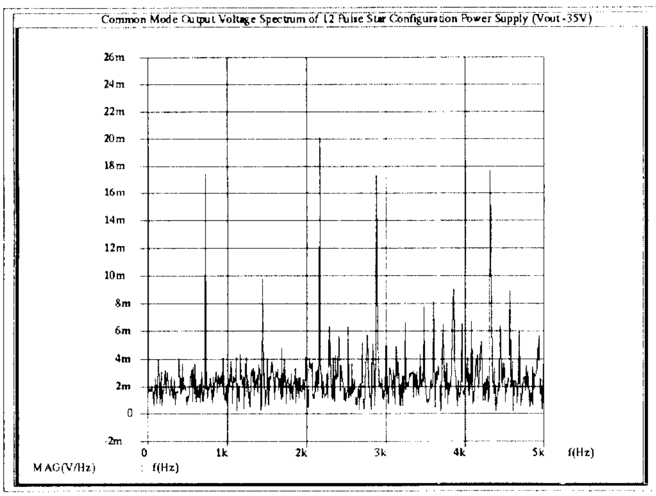

Figure 3.
12 Pulse Common Mode Power Supply Output Voltage Spectrum

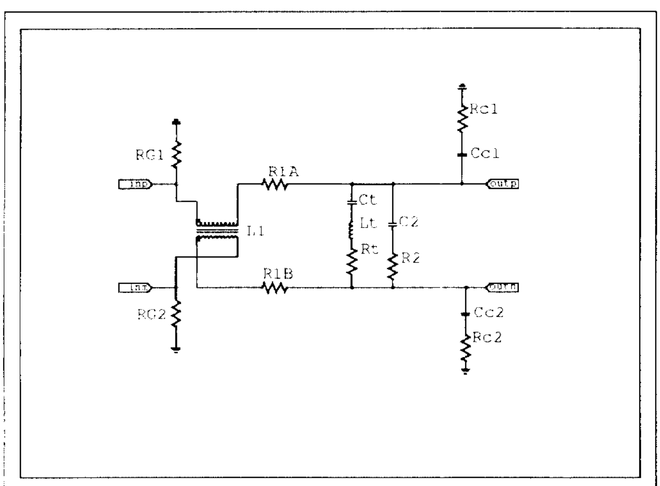

Figure 4.
Modified Praeg Filter Topology

V. Simulated Magnet Current Ripple

The results of the previous simulations were used to obtain a simulation of the ripple current spectrum existing in the ring magnet load. Within Saber, the waveform of the power supply output voltage spectrum is multiplied by the filter transfer function and the ring magnet load admittance. The resulting spectrum is that of the ripple current within the load. This ripple current depends on the admittance transfer function taken. It is also possible to reconstruct an approximate real time waveform of the ripple current. Current or voltage sources containing the correct amplitude and frequency of the ripple harmonics can be summed together. The resultant waveform is a simulated current ripple waveform (see figure 5).

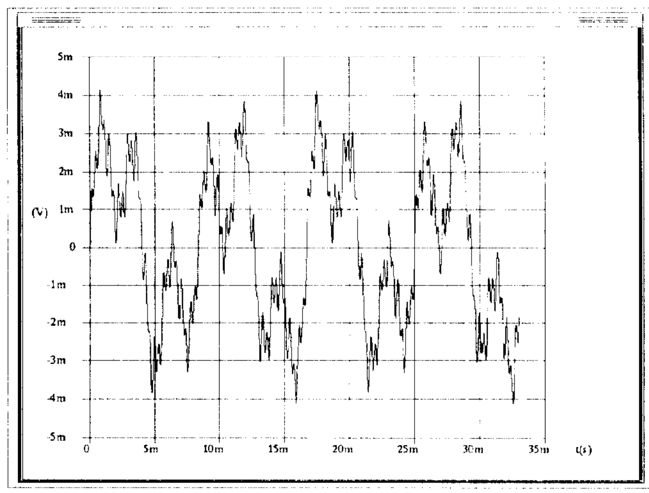

Figure 5.
Simulated Magnet Current Ripple
From 24 Pulse Power Supply

Arriving at current ripple can also be achieved by a different method. Instead of combining output spectra and load frequency responses, each of these models can be connected together to form an entire ring magnet power system. The ripple current is then measured within the ring magnet load at the desired location. Obtaining current ripple in this way, however, is about four to five times slower than the method previously described. The ripple waveforms obtained using both methods were very similar.

VI. Power Source Imbalances

There were two sources of power supply harmonics that were investigated. The first and most obvious source is due the number of pulses per line cycle produced by the power supply. The second is caused by imbalances in such things as transformer windings and ac utilities. The primary harmonics are well known and can be easily accounted for but the harmonics caused by utility power and transformer variances is not as apparent. These imbalances cause voltage and phase asymmetries that produce low frequency harmonics (i.e. sub-harmonics of the primary switching frequency). These harmonics may not be nearly as high in amplitude as the primary switching harmonics but because of their low frequency they are harder to filter out. This can be a problem if these low frequency harmonics occur at critical frequencies of interest. For a multi-kiloamp filter, the capacitance and inductance values can become quite high which adds to the expense of production and the size of the overall filter. Figures 6 and 7 show the output voltage spectrum of a balanced and imbalanced six pulse system respectively. The imbalances consisted of a 1% voltage and a 2% transformer impedance imbalance.

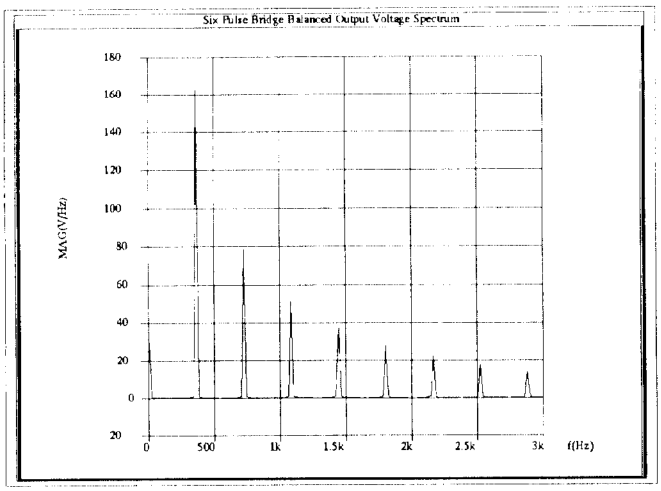

Figure 6.
Six Pulse Balanced Output Voltage Spectrum
(firing angle=85 deg.,I=1500A)

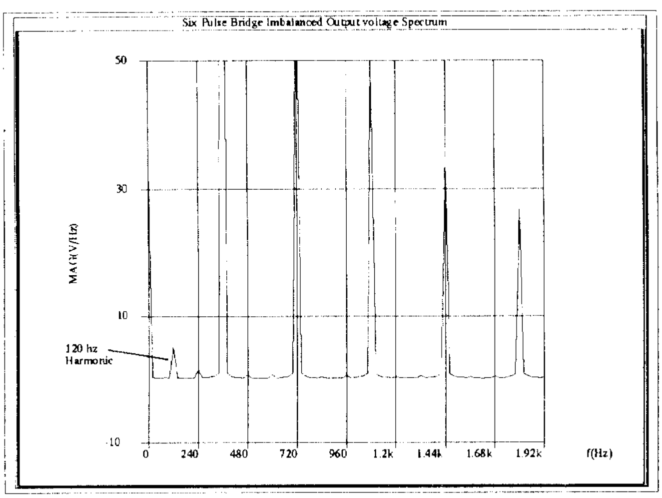

Figure 7.
Six Pulse Imbalanced Output Voltage Spectrum
(firing angle=85 deg.,I=1500A)

With these imbalances in the transformer secondary new harmonics are observed in figure 7. The harmonic at 120 hz is particularly large with smaller harmonics occurring at 60 hz intervals. For a system with more pulses per cycle and with series connected bridges the effects and harmonic production will be different depending on the asymmetries of the system. In the case presented three fold asymmetries are introduced in both the phase voltages and the line to neutral impedances. This is the cause of the predominant 120 hz harmonic. For a power supply with four of these bridges in series (i.e. a 24 pulse system) the possibility of two, three and four fold asymmetries exist.

Affects of current overlap can also be observed using this model. Overlap is not the result of any imbalance but can still cause a shift in harmonics that could prove troublesome.

VII. Conclusion

With Saber it is possible to model an entire ring magnet power supply system, either in its entirety or in separate parts whose responses are then combined. This allows the simulation and measurement of such parameters as common and differential mode magnet ripple current due to converter type, filter design, and transformer/ac utility imbalances. It is also possible to use the ripple spectrum created to reconstruct an approximate real time current waveform for examination of peak to peak ripple.

VIII. REFERENCES

[1] Saber^{TM} is a registered trademark of Analogy Inc.