Frequency-Domain Analysis of Resonant-Type Ring Magnet Power Supplies

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Abstract

For fast-cycling synchrotrons, resonant-type ring magnet power supplies are commonly used to provide a dc-biased ac excitation for the ring magnets. Up to the present, this power supply system has been analyzed using simplified analytical approximation, namely assuming the resonant frequency of the ring magnet network is fixed and equal to the accelerator frequency. This paper presents a frequency-domain analysis technique for a more accurate analysis of resonant-type ring magnet power supplies. This approach identifies that, with the variation of the resonant frequency, the operating conditions of the power supply change quite dramatically because of the high Q value of the resonant network. The analytical results are verified, using both experimental results and simulation results.

I. Introduction

For fast-cycling synchrotrons such as TRIUMF KAON Factory Booster Ring, resonant-type magnet power supplies are commonly used. The operating conditions of this power supply configuration have been analyzed by Fox[1], with simplifying assumptions. Assuming the resonant frequency of the ring magnet network is fixed and equal to the accelerator frequency, all the voltage and current waveforms can be described by a set of ideal analytical expressions. To the best of our knowledge, these operating conditions have never been related to the parameters of the resonant network and their variation, including the variation of the resonant frequency.

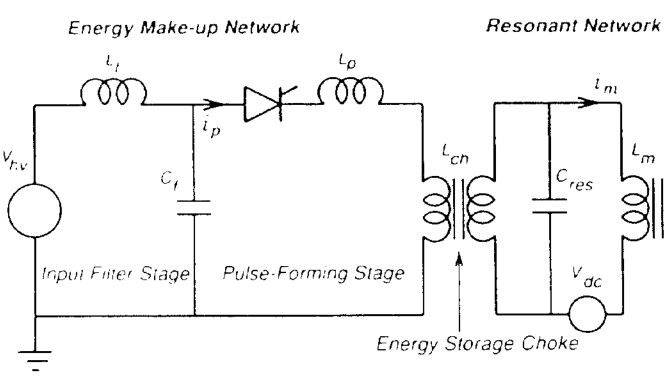

Figure 1: Resonant-Type Magnet Power Supply

On the other hand, Reiniger[2] has reported his experimental findings on the effects of resonant frequency drift on the operating conditions of the ring magnet power supply. With the variation of the resonant frequency, the operating conditions of the power supply change quite dramatically because of the high Q value of the resonant network.

This paper presents the frequency-domain analysis of resonant-type ring magnet power supplies, using frequency spectrum of energy make-up currents and ac transfer characteristics of the resonant network. With this approach, effects of resonant frequency variation can be identified and a more accurate analysis of the magnet power supply is possible. Reiniger's experimental results are confirmed using analytical results and simulation results.

II. Modelling of Resonant-Type Magnet Power Supply

The resonant-type magnet power supply is illustrated in Fig. 1. The resonant network provides a sinusoidally-varying magnet current, while the energy make-up network maintains a constant ac excitation of the ring magnets by injecting make-up energy into the resonant network via a pulse-forming network.

The fundamental frequency of the pulse currents, ω_a, is determined by the repetiton rate of the SCR firing and is set by the acceleration frequency. This frequency is also the fundamental frequency of the magnet current, but is not necessarily same as the resonant frequency, ω_o, of the resonant network.

The waveshape and the ringing frequency of the pulse currents are determined by circuit parameters of the pulse-forming network, including the filter capacitor, C_f, and the pulse inductor, L_p. Since the pulse currents are formed using the resonance of these circuit parameters and the SCR is naturally commutated, the pulse waveform is well defined and its frequency components can be identified.

Thus, the pulse-forming network can be modelled by a dependent current source between the input filter and the resonant network. The waveform and frequency spectrum of the source current are determined by design parameters of the pulse-forming network, and its magnitude depends on the desired level of magnet current.

At steady state, operating conditions of the power supply are determined by ac transfer characteristics of the resonant network. The resonant network amplifies the fundamental component of input pulse currents and attenuates harmonic components to produce a sinusoidal magnet

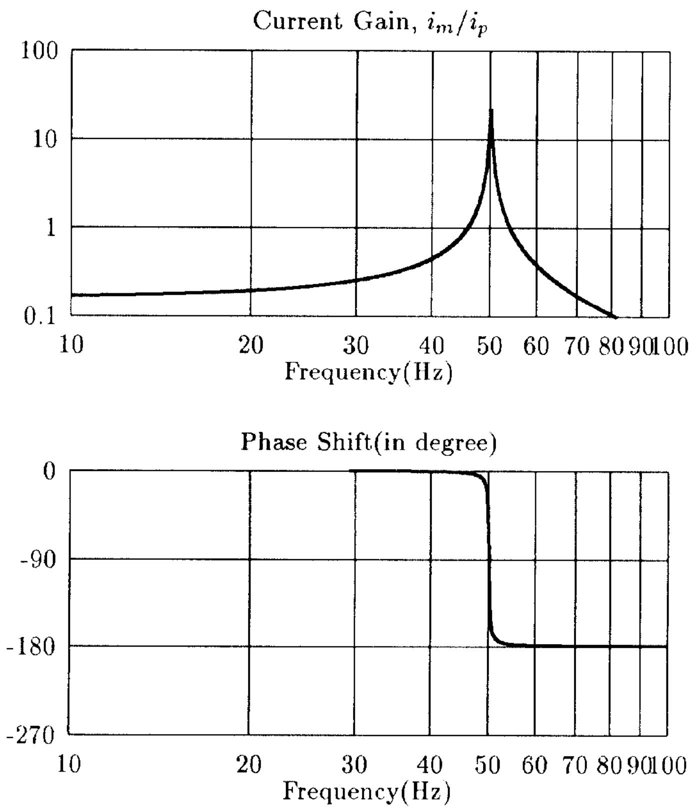

Figure 2: Bode Plot of Current Gain, i_m/i_p

current. This ac transfer characteristics is a typical second-order response with high Q factor.

Fig. 2 shows the Bode plot of the current transfer, i_m/i_p, where i_m is the magnet current and the i_p is the pulse current. As an example, circuit parameters of the dipole magnet power supply for the KAON Factory Booster Synchrotron is used in the analysis and simulations. The parameters are specified in the Accelerator Design Report[3].

As illustrated in Fig. 2, if the resonant frequency varies due to secondary effects such as temperature, the gain and phase shift change quite dramatically due to the high Q factor of the resonant network, and the magnitude and phase angle of the pulse currents must change significantly in order to maintain a constant ac excitation of the ring magnets.

III. Frequency-Domain Analysis

To analyse a resonant-type ring magnet power supply in frequency domain, the following steps are used:

1. For a given design of the pulse-forming network, the pulse ringing frequency, ω_p, and the frequency spectrum of pulse currents are determined.
2. Then, the fundamental component of the pulse current is adjusted to generate a desired level of the magnet current, using the ac transfer characteristics of the resonant network with a given resonant frequency.
3. The required fundamental component and the frequency spectrum of pulse currents determine the peak pulse current as well as its dc component.
4. To see the effect of resonant frequency variation, repeat the previous two steps for a set of resonant frequencies.

The peak pulse current variation is shown in Fig. 3(a) as a function of resonant frequency. As the resonant frequency drifts away from the accelerator frequency, the current gain decreases and increased pulse currents are required for a constant ac excitation of ring magnets. Due to the high value of Q factor, however, the change in the current gain can be quite dramatic as shown and as predicted in the ac transfer chracteristics of Fig. 2.

The voltage requirement of the energy make-up network can be obtained by considering that, during the pulse period, the average voltage of the filter capacitor, must be equal to the average voltage of the resonant capacitor voltage, assuming no losses in the pulse forming network.

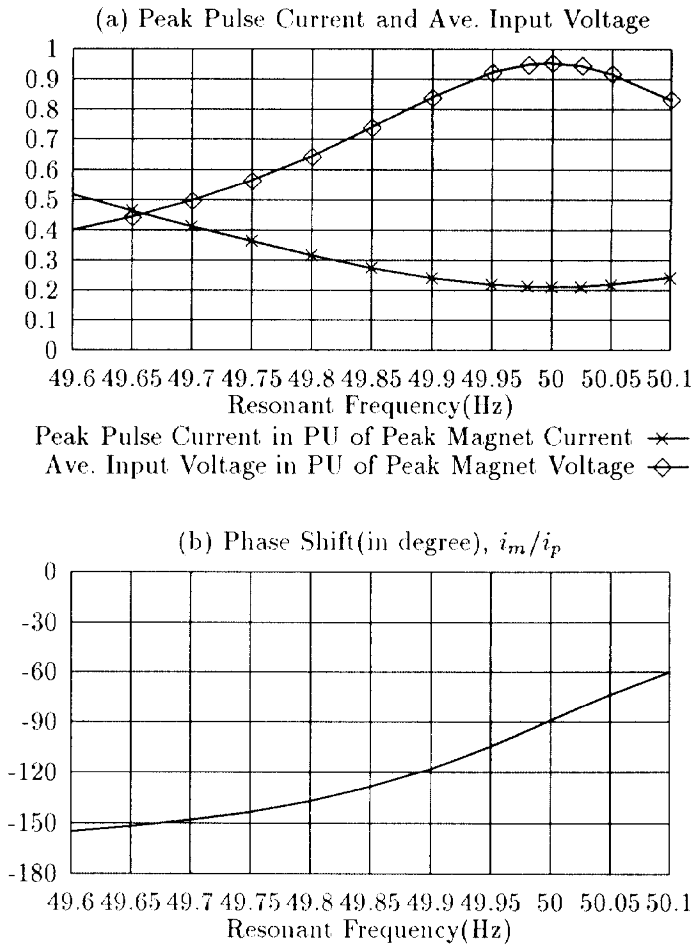

Figure 3: Effects of Resonant Frequency Variation

However, the Bode plot of Fig. 2 indicates that the position of the pulse period in relation to the magnet current shifts as the resonant frequency changes. As ω_o approaches ω_a, the phase shift get closer to 90° and the pulse current coincides with the zero crossing of the magnet current and the peak of the magnet voltage. The average input voltage to the pulse-forming network during the pulse period is also shown in Fig. 3(b) as a function of resonant frequency. The variation in the phase shift is shown in Fig. 3(b).

The results of frequency-domain analysis illustrated in Fig. 3 identify that the current and voltage requirements of the pulse-forming network change significantly with the variation of the resonant frequency. Nonetheless, the variation in current and voltage requirements does not mean the variation in the make-up energy to be pumped into the resonant network.

As long as the ac excitation of ring magnets is kept at a constant magnitude, the ac loss in the resonant network remains nearly constant and so does the energy to be pumped into the network via the pulse-forming network. With the variation of resonant frequency, the average input voltage and current change in such a way that the input power to the resonant network remains constant. This result has been verified by the SPICE simulation of the power supply system[4].

IV. Experimental Results

The experimental results for the effects of resonant frequency variation have been reported in [2], using the dipole test set-up for KAON Factory Booster Ring. The analytical results presented in this paper confirms the experimental findings, as shown in Fig. 4. Fig. 4(a) illustrates the resonant-network gain predicted by the analysis agrees with the experimental results.

In Fig. 4(b), the make-up power to the resonant network is estimated using the frequency-domain analysis and compared to the experimental results. Some discrepancy can be identified at the high magnet current. This is due to the loss in the energy make-up unit of the experimental set-up. In the analysis, the ideal energy make-up is assumed and no power loss is accounted for.

V. Conclusions

The frequency-domain analysis of resonant-type ring magnet power supplies is introduced in this paper. It is shown that the analysis based on frequency spectrum of pulse currents and ac transfer characteristics of the resonant network provides more informations than the approximated analytical solutions. The analysis can not only determine the operating conditions for different design parameters of the pulse-forming network, but it can also relate them to parameters and conditions of the resonant network. The analysis identifies significant effects of resonant frequency variation on the current and voltage requirements of the pulse-forming network, which have not been possible with the approximated analytical solutions.

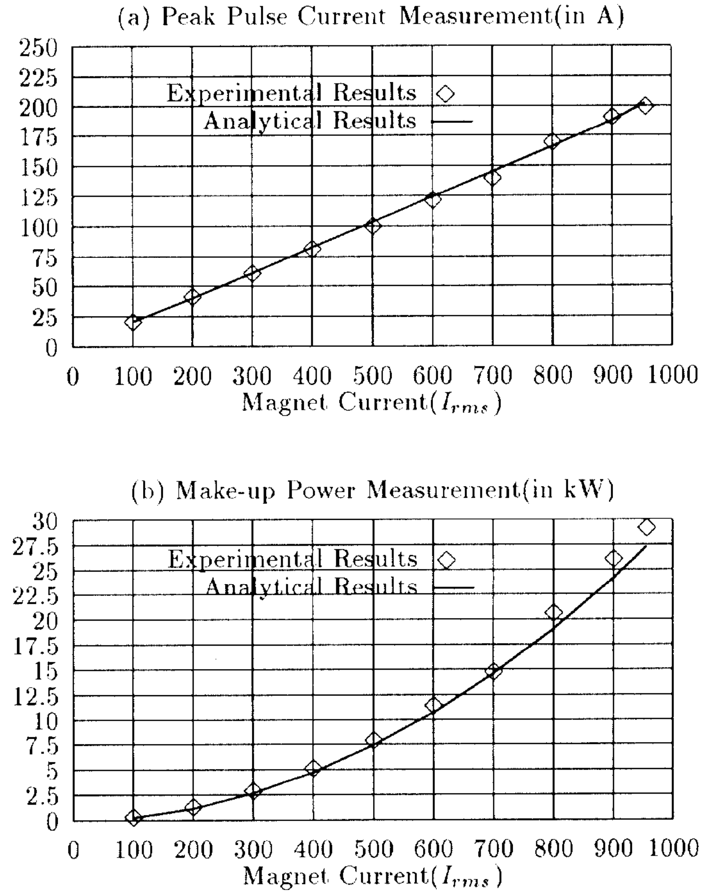

Figure 4: Experimental Results

The degree of resonant frequency drift will be minimized by switching trimming capacitors, but the frequency-domain analysis can be used to quantify the maximum drift of resonant frequency that can be allowed.

VI. References

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