NAL QUADRUPOLE POWER SUPPLY ACTIVE FILTER

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Summary

A 40 kW active filter is used with each of the main accelerator's 12 quadrupole power supplies to reduce the power supply's voltage ripple. The active filter operates on a voltage-bucking principle with the filter output transformer coupled into the quadrupole magnet bus. The filter electronics is designed to respond to the first three harmonic components of ripple in the power supply output. Voltage ripple attenuation during injection, acceleration, and extraction is approximately 30 dB. Quadrupole magnet current ripple is correspondingly reduced.

Introduction

Current ripple in the quadrupole magnets produces undesirable fluctuations in the main accelerator's proton beam. During extraction the problem is particularly critical since the ripple can produce 100% modulation of the extracted beam. To reduce the problem, the voltage ripple from each of the quadrupole power supplies is attenuated by means of an active filter during the entire pulse cycle. Calculations show that the filtered ripple from the quadrupole power supplies has little effect on the extracted beam. [1]

General Operation

The main accelerator's quadrupole power supplies are 12-phase, SCR-controlled units which have a fundamental ripple component at 720 Hz. The associated active filters are designed to attenuate the 720 Hz, 1440 Hz, and 2160 Hz harmonics in the quad supply output.

Figure 1 shows a simplified block diagram of the active filter and how it is connected to the quad power supply. While the power supply output is ramped from zero to 1000 V and back to zero, a ripple voltage of varying amplitude and harmonic content is present in the supply output. The active filter reduces the power supply ripple by driving the output transformer to "buck-out" or cancel the supply ripple and thus present a filtered output to the magnet load.

Power for the active filter is derived from the quad power supply's 350 V ac power transformer. The voltage is stepped-down, rectified, and capacitor filtered to provide a 40 V dc source. A transistor bank, with 16 parallel current amplifier modules, drives the output transformer from the 40 V dc source. Base drive for the transistor bank is derived from a power amplifier which is driven by low-level frequency selective amplifiers. The low level input signal to the amplifiers comes from a high impedance voltage divider. The transistor bank, connected as an emitter-follower to the power amplifier, operates in a Class A mode with a total bias current of 500 to 800 A dc driving the output transformer primary.

Open-loop gain of the active filter is set by the voltage divider, input amplifier, frequency selective amplifiers, power amplifier, transistor bank, and turns ratio of the output transformer. The amount of harmonic ripple attenuation is essentially equal to the open-loop gain of the filter at the various harmonic frequencies in the power supply output. Nominally, the open-loop gain for the first 3 harmonics is about 30, resulting in about a 30 dB reduction in power supply ripple.

Filter Frequency and Time Response

Figure 2 is a feedback block diagram which shows the components which affect the filter's frequency and time response. Assuming that the attenuator, input amplifier, summing amplifier and driver amplifier have a frequency response which is flat in the area of interest, the gains of these sections may be combined with a constant value M. The closed-loop response of the negative feedback filter is then given by Eq. (1).

$$\frac{E_o(s)}{E_1(s)} = \frac{1}{1 - MA_3(s)A_4(s)A_6(s)} \qquad (1)$$

To provide system stability and good performance over a variety of operating conditions, the frequency selective amplifier was chosen to be a set of 3 parallel bandpass filters tuned to the first 3 harmonics of the power supply ripple. Fast, high and low frequency, gain roll-off is provided by the bandpass circuits with a minimum of phase shift to the system. For ease of adjustment, a negative immittance converter realization of the bandpass circuit is used. [2] Using the NIC circuits, the transfer function for the frequency selective amplifier is given by Eq. (2)

$$A_3(s) = \sum_{n=1,2,3} \frac{-K(RC)_n s}{s^2(RC)_n^2 + s(RC)_n(2-K) + 1} \qquad (2)$$

where $K < 2$ and $(RC)_1$, $(RC)_2$, and $(RC)_3$ correspond to the first 3 harmonics in the power supply ripple output.

A lead compensating network is used to improve the filter's response to quad power supply output voltage ramp. The transfer function for the lead circuit is given by Eq (3), where T' corresponds to the low frequency cutoff point.

$$A_4(s) = \frac{T' s}{1 + T' s} \qquad (3)$$

Amplifier A6 represents the low frequency characteristic of the equivalent power transistor emitter resistors and output transformer primary inductance. Eq. (4) defines

$$A_6(s) = N \frac{L}{R_e} \left(\frac{s}{1 + sL/R_e}\right) \qquad (4)$$

$A_6(s)$ where N = Transformer voltage turns ratio, L = Transformer primary inductance, and R = Equivalent transistor emitter resistance. The equivalent emitter resistance changes with the number of power modules which are on, causing a change in the response given by Eq. (4).

Substituting Eqs. (2), (3), and (4) into Eq. (1) provides the complete expression for closed-loop gain of the active filter. The closed-loop gain expression can be simplified to Eq. (5) at the first 3 harmonic frequencies.[3]

$$\left.\frac{E_o}{E_1}\right|_{f_n} \cong \frac{2 - K}{MNK} \qquad n = 1, 2, \text{ or } 3 \qquad (5)$$

Typically K = 1.96, M = 0.1, and N = 5.25. A plot of the active filter's closed-loop response is shown in Figure 3.

Of concern in the filter design was the filter response to the power supply's voltage ramp during beam acceleration. For a ramp of 10^4 V/sec without the compensating circuit, the bias current through the output transformer would decrease by about 230 amps in the filter causing an undesirable operating mode.[3] With the compensating circuit, however, the change in bias current does not occur, allowing the filter to operate normally throughout the entire power supply cycle.

Experimental Results

During a quad power supply pulse cycle, the harmonic content of the power supply output changes. Also, the harmonic content changes with the current in the quadrupole bus (energy level) due to power supply phase overlap. In all cases which have been observed, however, the predominant components are the 1^{st}, 2^{nd}, and 3^{rd} harmonics.

Figure 4a shows a 1^{st} and 3^{rd} harmonic ripple present in the unfiltered power supply output during extraction at 300 GeV. The filtered output for the same time and energy level is shown in Figure 4b. When all of the quadrupole power supplies are filtered as shown inFigure 4, the corresponding quadrupole magnet current ripple is proportionately reduced. With the active filters operating at 300 GeV, the harmonic current ripple at 720, 1440, and 2160 Hz is found to be on the order of $1/10^5$ or less.

References

1. Lee Teng, National Accelerator Laboratory, Private Communication, Feb. 1973.

2. Handbook of Operational Amplifier Active RC Networks, Burr-Brown Research Corp., 1966.

3. R. J. Yarema, Quadrupole Power Supply Active Ripple Filters, NAL TM-407, January 24, 1973.

† Operated by Universities Research Association.

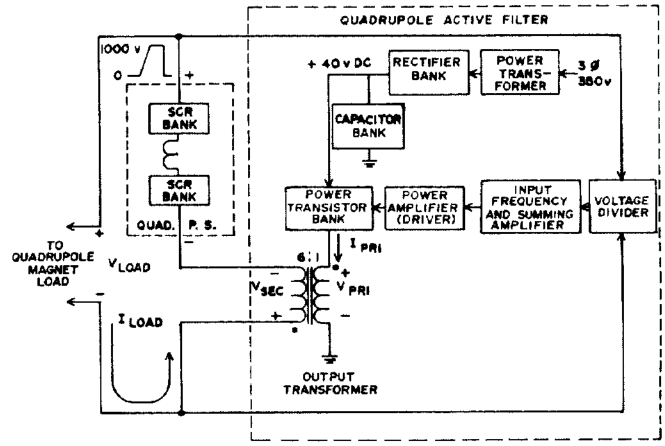

Figure 1 - Active Filter Block Diagram

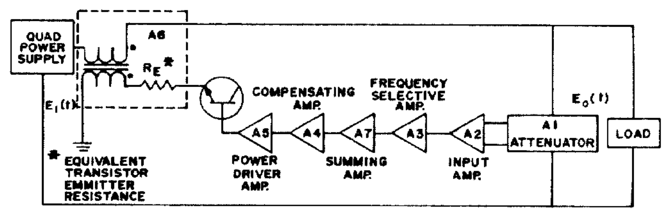

Figure 2 - Active Filter Feedback Block Diagram

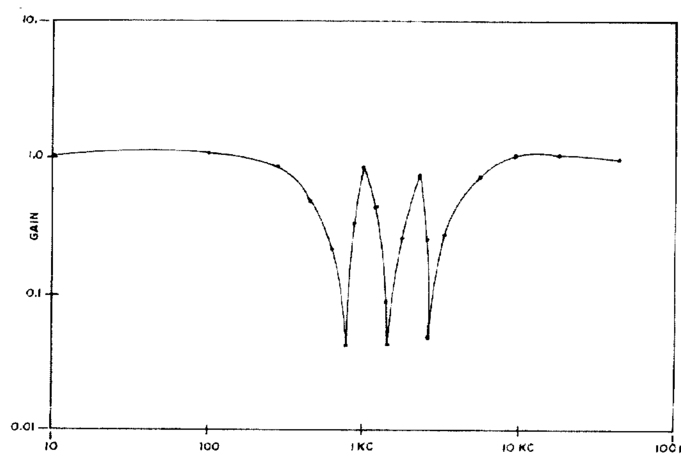

Figure 3 - Active Filter Closed-Loop Response

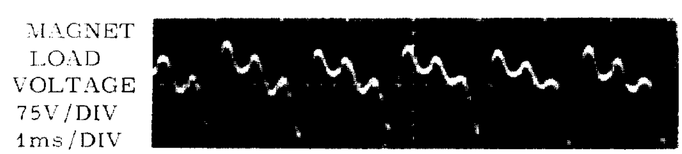

Figure 4a - Load Ripple With Active Filter Off

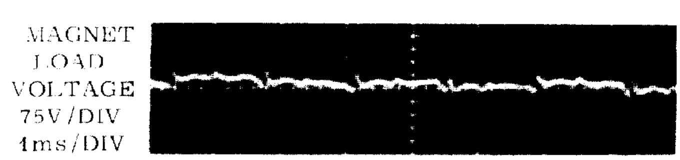

Figure 4b - Load Ripple With Active Filter On