© 1981 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

ACTIVE FILTER FOR HIGH CURRENT dc MAGNETS

F.F. Cilyo, F.E. Mills, Fermilab
and
Y. Miyahara, KEK Laboratory

Fermi National Accelerator Laboratory*
P.O. Box 500
Batavia, IL 60510

Introduction

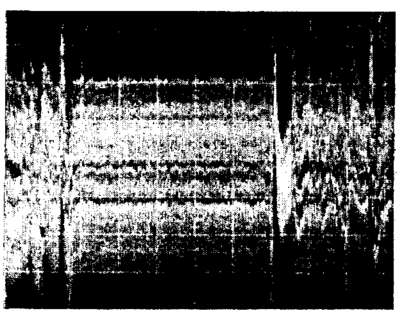
Thyristor type regulated power supplies operated from 3 phase power lines are sensitive to phase unbalance, voltage fluctuations, line impedance and to other loads connected to the same line. At Fermilab, the large variety of pulsed equipment provides such perturbations in a wide frequency domain. This paper describes active filters used to stabilize magnet power supplies for a storage ring against fast fluctuations.

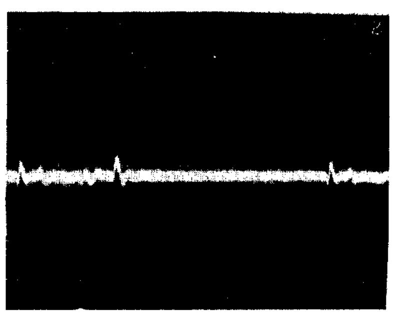
Description Of Our Solution

For a period of approximately 1 year, FNAL had 9 Active Filters operating with the quadrupole magnet power supplies in its Cooling Ring. The operating currents range from 200 to 550 A dc, while the voltages range from 20 to 80 V. For a typical 500 A, 20 V quadrupole power supply, the magnet current fluctuations with and without the active filter are shown in Figs. 1 through 4.

Figure 1 shows the current fluctuation over a period of 20 seconds, while Fig. 3 shows the same current over a period of 200 milliseconds, with Booster and Main Ring Accelerators operating and the Active Filter switched OFF. In Fig. 1, the effect of Main Ring ramp is clearly visible, while Fig. 3 shows the 15 Hz component generated by the Booster acceleration operation. Superimposed on the 15 Hz waveform is the 360 Hz ripple whose amplitude is 0.2 A p-p or 0.04% of the operating current (500 A). Peak-to-peak amplitude of the 15 Hz component is approximately 0.7 A or 0.14% of the operating value, while the Main Ring ramp modulates the 15 Hz waveform between 0 and 0.16% of the operating current.

Result of switching the Active Filter ON is shown in Figs. 2 and 4. The peak-to-peak amplitude of the 15 Hz component is reduced to well below 50 mA (0.01%), while the Main Ring ramp effect is reduced to approximately 50 mA p-p. The stray pickup, common mode limitation of the test equipment at millivolt levels and effects of strong electro-magnetic fields emanating



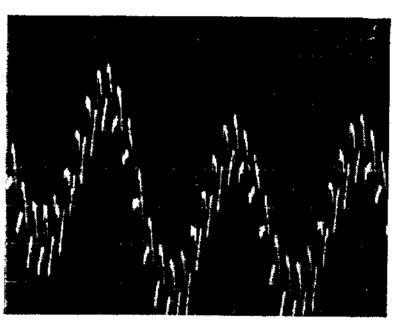


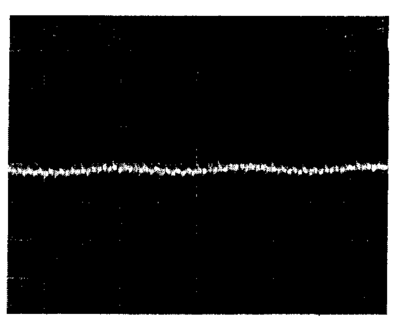
Sweep: 2 Sec/Div

Scale: 100 mA/Div

DC Current: 505 A

Magnet Current Fluctuation at 2 Sec/Div
Fig. 1 - Filter OFF Fig. 2 - Filter ON





Sweep: 20 MS/Div

Scale: 100 mA/Div

DC Current: 505 A

Magnet Current Fluctuation at 20 MS/Div
Fig. 3 - Filter OFF Fig. 4 - Filter ON

*Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

0018-9499/81/0600-3014$00.75©1981 IEEE

from the Thyristors are also visible in Fig. 4. Reduction of these factors is one of the objects of our future work.

1. Circuit Description

This system was designed and implemented as an add-on type because power supplies with adequate regulation are not standard commercial items, and because of limited time, budget and technical support. Under these conditions, the technical problem was to develop and implement a compact filter where the already low (approximately 1 A p-p) current fluctuation is to be reduced to milliampere levels.

A shunt type circuit was chosen because of the voltage levels and the availability of power transistors. The current mode of feedback was chosen because it is the primary variable and because of the successful development of suitable current sensor. The active filter is shown schematically in Fig. 5.

bypassing the load. The degree of reduction of ac current in Z_L is determined by the loop gain of the system. The magnitude of the transistor current i_{NS}, will be greater than the magnitude of the load current i_{NL} with filter switch S_2 open, the amount depending on the impedances of the reactor L_2 and the load Z_L.

The quality of the filter action depends on sensitivity of the load current sensor and loop gain of the system consisting of current sensor, amplifiers U_1 and U_2 and the power transistor Q_1. Some of the system parameters are:

Current sensor calibration	10 mV/A
Current sensor resolution	1 mA (10μV)
Current sensor frequency response	dc to 50 kHz
Current sensor range	0 to 1000A
Nominal power transistor current	1.5 A dc
Transconductance of the power stage	1.5 mA/mV

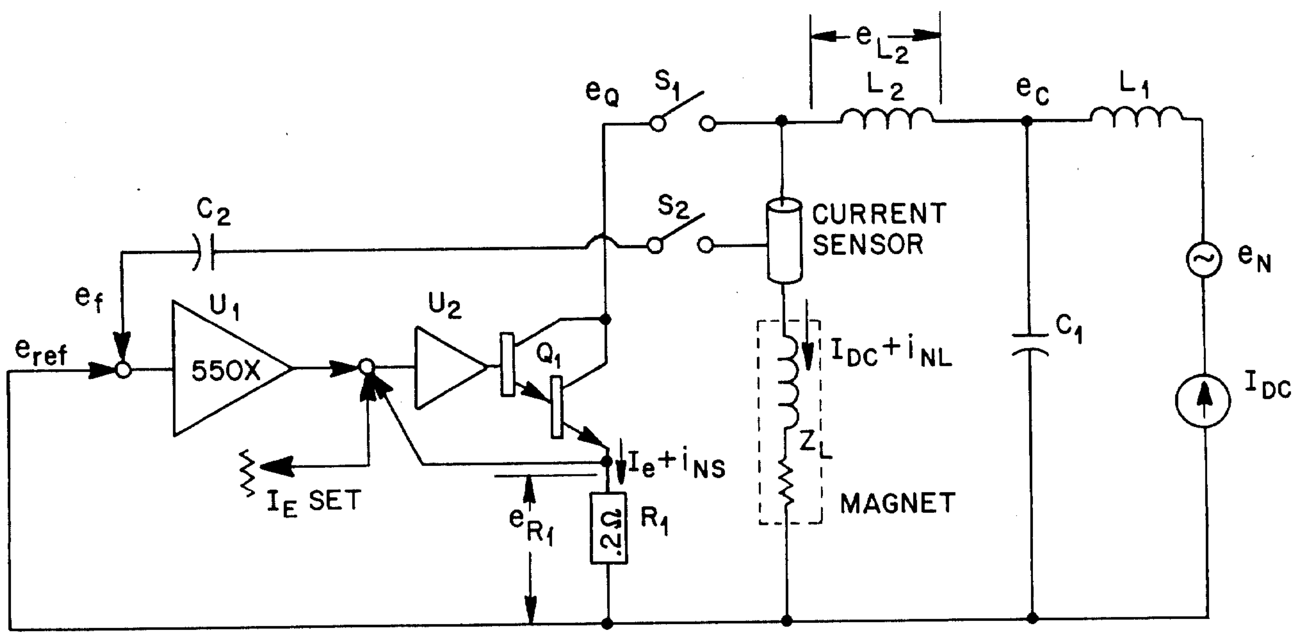


Figure 5 Functional Diagram of the Active Filter

Referring to Fig. 5, the filter action is based on the negative feedback concept whereby the output of a closed loop system e_f follows its input, e_{ref}. The fidelity, i.e. amplitude and phase of the output depends on the amount of feedback or loop gain of the system.

With the active filter disconnected, S_1 open, the current through the load is $I_{dc} + i_{NL}$. I_{dc} is the current as established by the closed loop dc current regulator. The i_{NL} is the undesirable alternating component of the load current and includes the effect of ripple voltage, line voltage disturbance and phase unbalance. The amplitude of i_{NL} is proportional to the amplitude of e_C (the e_N reduced by the passive filter L_1C_1) and impedance of the load circuit, $L_2 + Z_L$. Obviously, reducing e_C by increasing C_1 and L_1 reduces i_{NL} and is particularly effective at higher frequencies. At lower frequencies, below 30 Hz, the effectiveness of L_1 and C_1 is limited by practical considerations, particularly at current levels above 100 A.

By closing S_2 with S_1 already closed, the ac current signal e_f causes ac current to flow in Q_1,

Inductance of the load magnet (typical, measured with a 1 kHz bridge)	3.4 mH
Inductance reactor L_2 (measured with a 1 kHz bridge)	1.4 mH
Loop gain at 15 Hz	375
Power supply ripple current spec.	0.1% rms
Power supply ripple voltage spec.	60 mV rms

Increasing the current through the power transistor for constant value of the ripple voltage e_C, is equivalent to lowering the impedance seen by this voltage. Consequently, the amplitude of the ac current through the power transistor i_{NS} is no longer limited by the load impedance and could reach relatively high levels. To keep current through the power transistor at relatively low levels (1-3 A), an inductor L_2 is placed in series with the load, ahead of the power transistor.

2. Equipment Description

The critical element in this filter is the current sensor which determines the lower limit of the ac component to be removed. In addition, the current sensor should have practically zero ripple output, in the frequency range of interest, otherwise this ripple may be added to the load current.

The current sensor used in this filter has a calibration constant of 10 mV/A (10uV/mA), over the frequency range of dc to 50 kHz, resolution of 1 mA (10 uV) and the noise level of approximately 10 uV when operating in a relatively high impedance circuit. For reasons of timing and quick results, the current sensor was mounted on the negative terminal of the power supply along with the low level electronics. Although an attempt was made to locate these components in a relatively low noise region, the thyristor switching spikes and associated noise do find their way into the electronics box, fortunately without appreciably degrading performance of the system.

The power transistor is mounted in the back of the power supply on an air cooled heat sink along with a regulated power supply for the current sensor. In operation, the steady state collector current is set and regulated to approximately 1.5A ac, while its instantaneous value may swing from 0 to 4 A.

To limit the ac component to 5 A p-p, an iron core inductor L_2 is used. This inductor has an inductance of 1.4 mH when measured by a 1 kHz bridge and is designed to operate up to 1000 A dc. It is water cooled and has approximate dimensions of 18x18x18".

Future Work

Of the 9 operating power supplies, 7 are 20 V, 1 is 40 V and 1 is 80 V. An effort is underway to extend the use of this filter to 150 V, 200 V and 550 V power supplies. In addition, the entire system is being repackaged to minimize the noise pickup and to improve the operating features.

Acknowledgments

We wish to acknowledge the help of Omri Crewe, Harrison Ransom and Loretta McMath in the assembly of electronics components and the encouragement and support of Donald Young.