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

IMPROVING REGULATION IN THE FERMILAB MAIN RING MAGNET POWER SUPPLY SYSTEM

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Summary

In the past two years a number of changes have been made to the Main Ring Magnet Power Supply System to improve current regulation and long term drift. Some of the modifications discussed include new computers, new passive filters, direct analog feedback, a voltage-to-frequency converter for bend bus regulation, and a "smart" Nuclear Magnetic Resonance probe. Among the improvements to be described are the attenuation of power supply ripple by a factor of five and the reduction of long term flattop drift by an order of magnitude.

Introduction

The Fermilab Main Ring Power Supply System consists of 60 1 KV, 2.8 MW SCR power supplies powering three separate magnet buses; bend, quad focussing, and quad defocussing. The power supplies are located in 24 service buildings distributed around the four mile ring. There are 48 bend supplies, 6 quad focussing supplies, and 6 quad defocussing supplies. During typical operation, the current ramps from 100 amps to 4600 amps (400 GeV flattop), with a cycle time of 10 seconds. The following describes recent improvements to the magnet current regulation system.

Computer Changes

One of the major factors hindering the development of better magnet current regulation was the lack of processor time. The iteration rate of the computer system is 720 Hz, the fundamental frequency of the SCR power supplies. The old computer system, consisting of two Lockheed MAC 16 computers, had essentially no time left for trying new ideas or adding improvements. The MAC 16 computers were replaced by two DEC PDP 11/55 processors that are approximately two times faster. An added floating point capability purchased with the DEC machines greatly improved the accuracy and precision of many of the calculations. The added flexibility and time not only helped in improving the day to day operation of the magnet power supply system but also enabled us to analyze many of the regulation problems with greater ease. Many of the modifications mentioned below would not have been possible without the increased capability of the new machines.

Power Line Feed-Forward

A line feed-forward method is used to help compensate for power line variations. It involves a signal that is derived from the 345KV main site feeder. This signal is used in the computer as a multiplier to modify the required ramp voltage (called profile). This method can reduce the low frequency flattop wobble by a factor of two. It is particularly helpful during times of frequent power line variations.

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

Variable Update Gain

In order to achieve the required regulation it is necessary to use a learning system that applies some portion of the error calculated from past ramp cycles to the present ramp profile. The magnitude of the correction is dependent upon a parameter called the update gain (see Ref. 1). The quad bus regulation system uses two different regulating power supplies; a transistorized supply at injection and a SCR supply during the ramp. The transistorized supply is operated with a higher loop gain then the SCR supply, and this extra gain reduces the effective update gain of the system, slowing the learning rate. By increasing the update gain a factor of five while the transistorized supply is on, then smoothly returning to the normal gain, we reduced the ramp learning time from 10 minutes to two.

Feedback Compensation

Through special compensation in the bend bus feedback loop, we have been able to increase the DC loop gain by a factor of two. Figure 1 shows the measured open loop response of the complete regulation system with and without this modification. As can be determined from the figure, this change (consisting of a digital R-C roll-off at about 20 hz) helps compensate for transmission line effects in the magnet bus.

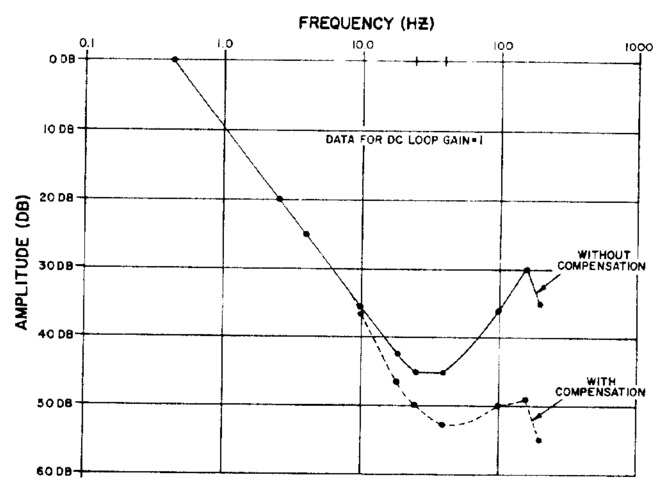

Fig. 1 Bend bus open loop response.

V/F Converter

In the past the bend magnet field was regulated by a second harmonic probe during injection and three switched analog integrators operating off a db/dt coil during the ramp. The switching between integrators was controlled by software, and depended on bend field magnitude. While running on our coarsest scale integrator, the maximum DC loop gain of the regulation system was limited by the 14 bit resolution of the MADC that read these integrators. To overcome this problem

0018-9499/81/0600-3088$00.75© 1981 IEEE

and simplify probe switching we have installed a system that uses a one MHz voltage-to-frequency (V/F) converter operating off the db/dt coil and a 20 bit up-down counter. We have been able to increase our DC loop gain by a factor of eight and are now limited only by stability criteria.

NMR

A problem encountered with the V/F converter system mentioned above was its long term drift. None of the commercially available converters surveyed had acceptable long term drift characteristics even if operated in a temperature controlled environment. To solve this problem it was decided to use an NMR (Nuclear Magnetic Resonance) probe to measure the absolute flattop field and thereby correct for the V/F converter imperfections. For operational reasons it was desired that the NMR measurements be automatic, requiring no manual adjustments for different flattop levels.

The field in the bend reference magnet is monitored with a CERN type 9298 NMR[2] modified to operate under the control of a microprocessor. The reference voltage necessary to tune the NMR to resonate at the proper field is calculated by the microprocessor. The 9298 NMR has the capability to measure static fields from 1 to 21 Kg with a single water sample. In addition, it will track slow field variations over a range of several gauss. A 30 Hz modulation field sweeps the sample thru resonances periodically, at which point triggers are generated and a measure of the modulation current is stored in a sample and hold. These triggers are used by the microprocessor to read the voltage in the sample and hold into memory. The measurement system is enabled only during flattop. In the measurement sequence, individual error samples are averaged to provide a correction to the NMR tuning voltage for subsequent measurements. This is called the LOCK mode of operation. If an insufficient number of samples are generated, the process is aborted and no correction is made. If three consecutive measurements are aborted, the decision is made to search for a new field. Initially, the NMR tuning voltage is calculated from data read from a current transductor on the magnet bus during flattop. In the SEARCH mode of operation, the system will make N increments of delta f above and below the calculated starting point. This mode can be interupted on any cycle if a sufficient number of samples are generated. Immediately following flattop, the microprocessor will read the NMR frequency. If the system is in the LOCK mode, a BCD representation of the frequency will be sent to the power supply computer. In the SEARCH mode, however, a dummy output (FFFF) is sent. Most of the parameters related to the measurement may be locally updated and read by means of hexidecimal thumbwheel switches and displays.

The NMR reading received from the microprocessor is compared to the average of 20 V/F converter readings taken for that same flattop. The error is used to adjust a scale factor used on subsequent V/F converter readings. In practice we have never seen this error exceed 0.25%. Bringing the NMR on line has decreased the long term flattop drift by a factor of 10. Our 400 GeV level over the past year, checked against our transductor, has been 4611 amps plus or minus one amp.

DAF

Up to now most of the regulation improvements have been concerned with the bend magnet bus. At Fermilab the focussing and defocussing quad magnets are powered from separate buses than the bend magnets. The quad currents are regulated to a program-controlled Q/B ratio. Until recently this was accomplished by first reading the bend (B) and the bend minus quad (B-Q) transductors, calculating the Q/B ratio, comparing this to the programmed value, and sending the error to the corresponding quad regulating power supply. This system had resolution problems in reading the B-Q transductor and in the digital control of the regulating power supply. Problems were also encountered with the inherent delays in the computer (1.38 ms to 2.76 ms) and interference between the two sampling systems represented by the computer and the SCR power supply used as the regulator. We have now adopted a system called Direct Analog Feedback (DAF). In this system the computer reads the bend bus transductor and calculates the desired B-Q current. This number is then sent over a digital transmission system to a 16 bit D/A converter where it is compared to the actual B-Q transductor reading. The resulting error is used to modulate the phase of the regulating power supply about a computer set operating level. This system eliminates much of the digital nature of the previous system (especially at flattop when the program is constant) and therefore resolves many of the problems mentioned above. The DAF system improves flattop regulation by a factor of two.

Passive Filters

A major modification of the passive filters affecting all the Main Ring Magnet power supplies is nearing completion. The old passive filters attenuated only the 720 Hz ripple components and utilized a series choke that saturated badly above 2000 amps. Figure 2 is the schematic diagram and frequency response of the filters being installed. It should be mentioned that the new filters have little effect as measured at the regulating transductors, but dramatic effect suppressing high frequency ripple in those magnets closest to the power supplies.

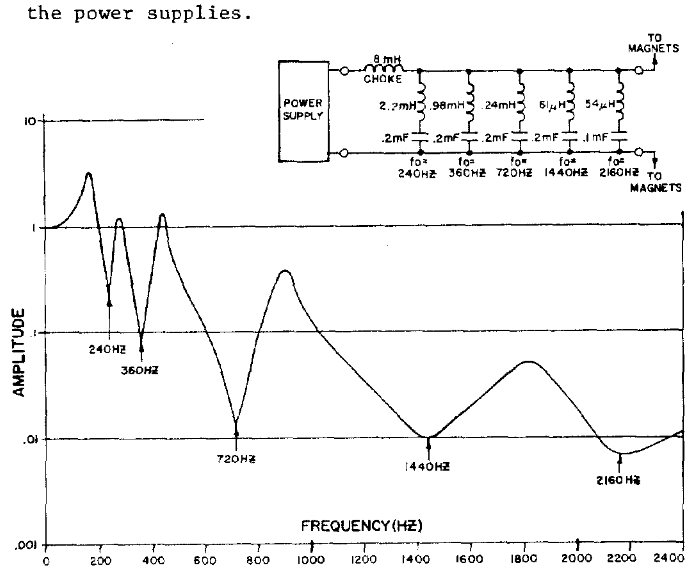

Fig. 2 Power supply passive filter.

120 Hz Feedback

The magnet power supplies are phase controlled SCR power supplies without voltage feedback and are therefore subject to line fluctuations and unbalances. A learning system working in conjunction with current feedback corrects for slow line fluctuations. The sub-harmonic 120 Hz ripple components caused by line unbalances however, can not be countered adequately by the above method. While it is possible to modify the passive filter to handle 120 Hz, a method of voltage feedback was considered to be less costly and easier to implement particularly with regard to the space constraints ocurring at the power supplies. In the feedback method, the unfiltered power supply output voltage is fed through a 120 Hz bandpass filter. The resulting signal is used to modulate the operating phase of the power supply. A variable gain, depending upon the DC level of the power supply, is used to compensate for the non-linearity of the phase vs output voltage inherent in these type power supplies. This method reduces the 120 Hz ripple by a factor of 10. This system has not yet been installed in the bend power supplies and therefore 300ma of 120 Hz ripple can be seen in Figure 3 on the bend bus.

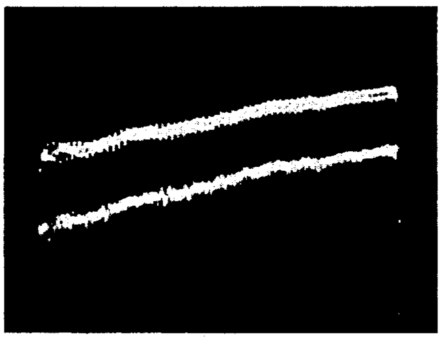

Fig. 3 Bend and Quad currents during flattop (slope due to field relaxation in magnets). TOP: Bend .5 Amp/div. BOTTOM: Quad .5 Amp/div. HORIZONTAL: 0.1 sec./div..

Conclusion

The results of our modifications are partly indicated in Figure 3, which shows regulation on both bend and quad buses of plus and minus 30 ppm at flattop. The added stability, reproducability, and faster learning have all contributed towards making the Main Ring Power Supply System a smoother running element of the accelerator.

Acknowledgements

The power supply improvements described above required the efforts of many people. We wish to acknowledge the contributions of Fermilab's Electrical Support group, Main Ring Electronics group, Controls group, and the Magnet Facility.

References

1. H. Pfeffer, D. Jong, Fermilab Main Power Supply Controls Programs, IEEE Trans. on Nucl. Sci., NS-24, p. 1725 (1977).

2. K. Borer, G. Fremont, The Nuclear Magnetic Resonance Magnetometer Type 9298, CERN 77-19, Experimental Physics Division, 26 Oct. 1977. Division, 26 Oct. 1977.