IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

FERMILAB MAIN ACCELERATOR QUADRUPOLE TRANSISTORIZED REGULATORS FOR IMPROVED TUNE STABILITY

R. J. Yarema, H. Pfeffer
Fermilab
Batavia, Illinois

Summary

During early operation of the Fermilab Main Accelerator, tune flucutations, caused by the SCR-controlled power supplies in the quad bus, limited the beam aperature at low energies. To correct this problem, two transistorized power supplies were built in 1975 to regulate and filter the Main Ring quad magnet current during injection and beam acceleration through the rf transistion region. There is one power supply in series with each quad bus. Each supply uses 320 parallel power transistors and is rated at 300A, 120V. Since the voltage and current capabilities of the transistorized supplies are limited, the supplies are turned-off at about 25GeV. A real-time computer system initiates turn-on of the SCR-controlled power supplies and regulation take-over by the SCR-controlled supplies, at the appropriate times.

General Operation

Each of the two Main Ring quadrupole buses are comprised of a series connection of power supplies and magnets. During the initial part of each Main Ring cycle, each bus is regulated by one of the two new quadrupole transistorized power supplies (see Figure 1). When beam is injected into the Main Ring, all of the remaining quadrupole supplies are off and power is supplied to the quadrupole bus from the transistorized quad supply (TQS). A bypass diode across the supply is reversed-biased, preventing any bus current from flowing through the diode. During injection, the reference input to the TQS consists of the desired current program plus a correction signal which is learned through the computer feedback system. The correction signal substantially increases the low frequency gain of the regulator.

As acceleration of the beam begins, the other quad supplies begin to phase-on to provide additional voltage and to regulate the quad bus for the remainder of the Main Ring cycle. While these supplies are coming on, the transistorized supply is programmed to remain in its operating region and provide current filtering up to a quad bus current of 300A (past beam transistion). During this mode, the TQS reference input consists of the desired current program plus a small ramped offset which brings the TQS to the middle of its operating range (see Figure 2). In this range the TQS acts as a low frequency active filter to reduce the current ripple up to 360Hz which is generated by other supplies in the quad bus. The transistorized supply continues to filter the quad current until the ramp current reaches the maximum level the supply can safely handle (300A).

Above 300A, the power source for the transistorized regulator automatically phases off, allowing bus current from the other quad power supplies to bypass the transistorized supply for the remainder of the cycle, through a large (6000A rms) diode. Thus, the transistorized supply provides regulation and filtering during the critical injection and transistion times of the Main Ring cycle.

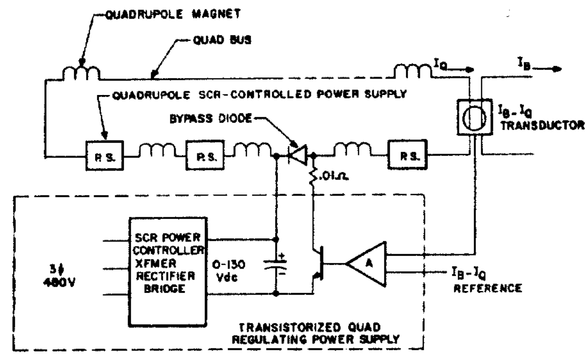

Figure 1. - Block Diagram of Transistorized Quad Regulating Power Supply

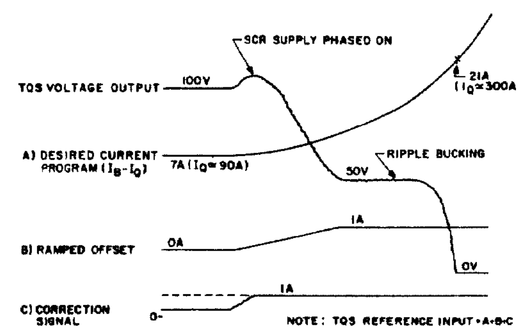

Figure 2. - Transistorized Quad Supply Signals

In practice, the transistorized supplies control the quad current by regulating the difference seen between the current in a bend magnet bus and a quad magnet bus as shown in Figure 1. (The bend current is programmed and regulated separately). The amount of difference which is required is set by the bend minus quad reference signal. Power for the supply is derived from the Main Ring pulsed power system which is stepped down from 13.8kV to 480V and then passed through a 3-phase, 6-SCR controller and step-down transformer. The transformer output is full-wave rectified to provide a maxiumu output voltage of 130V dc. The typical peak current which the power supply passes is 300A.

Since the output of the transistorized regulator is connected to a high power Main Ring bus, proper voltage isolation of the supply is essential. The main power isolation is provided by a conventional 30kVA distribution transformer which is hi-potted to 5kV before use in the system. Auxiliary power to the circuits operating at the main bus potential is supplies by a 40kV isolation transformer. The analog control signal up to the equipment on the bus is transmitted by means of a optically coupled amplifier with very high voltage isolation to eliminate any possible high voltage breakdown to the low-level electronics. The current transductors which provide the current feedback signals have a minimum of 33kV of isolation from the Main Ring bus. Under normal conditions, the maximum peak voltage-to-ground is less than 2kV.

Successful operation of the transistorized power supply is dependent on the ability to transfer the Main Ring bus current from the power supply to the bypass diode at a preset current level, or at least to limit the amount of current through the power supply to about 300A.

As long as the transistorized supply puts out voltage and reversed-biases, the bypass diode, all of the Main Ring ramp current, which can rise to 5000A, attempts to pass through the power supply. Excessive current through the supply could destroy the semiconductors and damage the associated buswork. Several levels of protection for the power supply are used. First, a quad bus current signal is used to phase-off the 6-SCR ac power controller when the quad bus current reaches 300A, allowing the bypass diode to become forward-biased. Second, if the power supply current reaches 350A, an internal current monitor quickly sends a trip signal to open the contactor supplying 480V power to the unit. Third, if the first two levels of protection do not work, a slower acting ac current limit circuit in the 6-SCR controller takes over when the ac current to the supply becomes excessive and limits the ac current so that the maximum dc current passed by the supply is about 275A. The remainder of the dc bus current is passed by the bypass diode. Fourth, if the lower levels of protection have failed, allowing the bus current to rise to about 450A, an overcurrent relay pulls-in, causing a Main Ring permit trip resulting in the shutdown of all the quad power supplies. As added protection, a 0.01Ω is placed in series with the transistorized supply output at the Main Ring bus to limit the bus current which could flow down the power supply cables in the event a short circuit occurred at the power supply output. The voltage across the resistor due to bus current would forward bias the bypass diode, limiting the current through the shorted leads to a maximum of about 100A.

A more detailed description of the operation of the power supply circuitry is presented in Reference 1.

Equipment Packaging

Space where the transistorized supplies are installed is very limited. Power circuitry for a Transistorized Quad Supply is packaged in one standard 19" relay rack. The 3Ø SCR controller, rectifiers, capacitors, and auxiliary power supplies are located in the upper half of the rack. The compact water-cooled transistor modules[2] which form the power transistor bank are located in the lower half of the rack as shown in Figure 3. A plexiglass cover is mounted over each transistor bank so that the indicator-type fuses associated with each power transistor can be inspected while the equipment is operating.

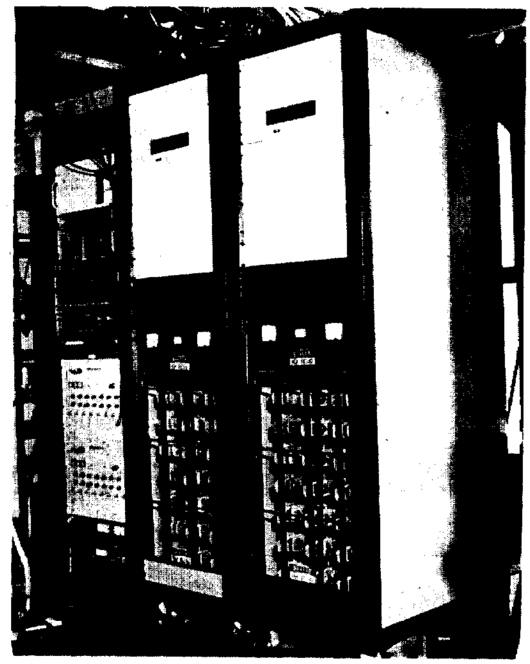

Figure 3. - Two Transistorized Regulators with Associated Electronic Equipment

Computer interface, overcurrent protection, regulating and interlock circuitry is located in an adjacent controls rack. Space did not permit the transformers to be located near the power circuitry. Therefore the transformers were installed about 75 feet away in an unused area.

Operating Results

Quad Bus Characteristics: To allow testing of the power supplies with a simulated load, the frequency characteristic of the Main Ring bus was measured. The response curve, along with the test set-up, is presented in Figure 4. Also shown in Figure 4 is a quad bus equivalent circuit derived from the test data. Subsequent construction and use of the equivalent circuit has shown the equivalent circuit to be an accurate model for the distributed Main Ring quad bus.

Tune Improvements: With the transistorized quad regulating supplies, substantial improvements from injection through transition have been realized in the Main Accelerator's tune fluctuations over the use of the conventional Main Ring SCR-controlled regulating power

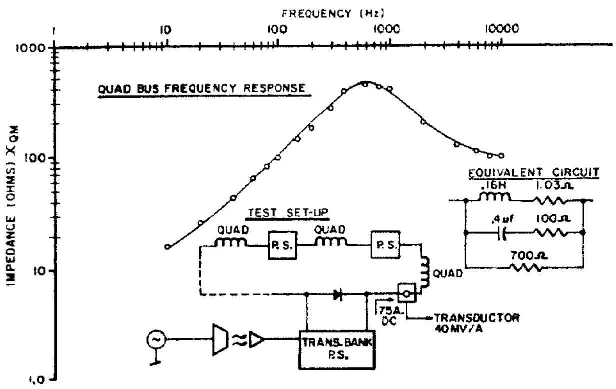

Figure 4. - Quad Bus Frequency Response

supplies. During injection, with the TQS, the typical quad bus ripple is about 10mA peak-to-peak at a power supply output level of about 90A. The resultant tune fluctuations are small as can be readily seen on a tune plot during injection of the Main Accelerator. Figure 5 shows the tune fluctuations for the conventional SCR-controlled power supplies, and Figure 6 shows the improved tune fluctuations obtained when the 2 transistorized power supplies are used. The smaller tune variations with the TQS during the initial critical part of the Main Ring ramp effectively make the Main Ring have a larger beam aperature. Thus, the machine can be tuned more easily and higher beam intensities are possible in the Main Ring without necessarily higher beam losses.

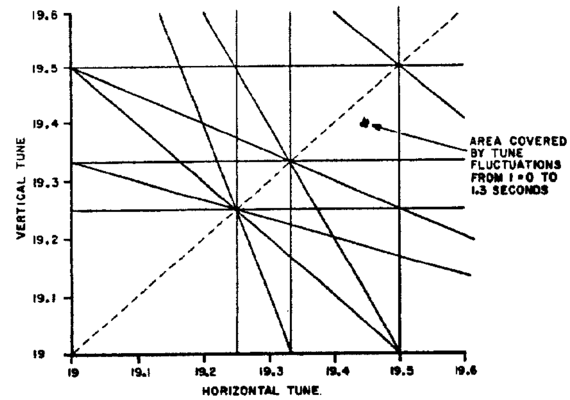

Figure 6. - Tune Fluctuations During Injection with Transistorized Quad Regulators

Acknowledgements

The authors wish to thank Dick Cassel for his advice and direction which was most helpful on many facets of this project. We further wish to thank John Green and Bill Bielefeldt for their many hours of help in assembling and testing the transistorized regulating supplies.

References

1. R.J. Yarema, "Main Accelerator Quadrupole Transistorized Regulators for Improved Tune Stability", Fermilab Internal Report, July 16, 1975.
2. F.F. Cilyo, "Power Transistor Module for High Current Applications", IAS Annual Meeting Conference Record, 1975, pp 464-466.

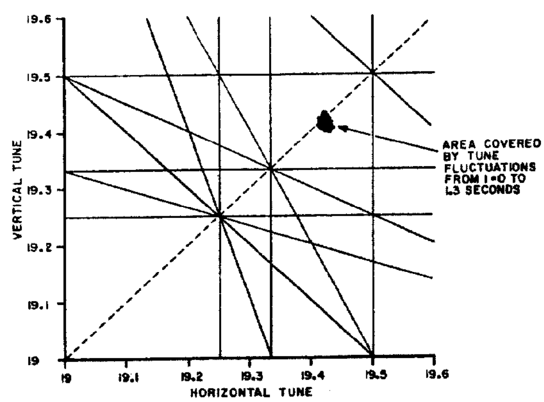

Figure 5. - Tune Fluctuations During Injection with Conventional SCR Controlled Power Supplies