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BIPOLAR OPERATION OF THE MAIN RING MAGNET SUPPLIES

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INTRODUCTION

In the summer of 1976, a proposal was made to do proton-on-proton colliding beam experiments with the existing Fermilab 400 GeV accelerator and proposed energy doubler. According to the proposal, protons would be accelerated in the existing main ring, then stored in the doubler. The field in the main ring would be reversed and subsequent beam would be injected and accelerated in the reverse direction. The existing 61 supplies which power the bending and quadrupole magnets in the main ring can supply current in one direction only; therefore it becomes necessary to either modify selected power supplies or equip them with reversing switches for this mode of operation.

Studies have been made of these two alternatives on the basis of feasibility and cost. Modifications of 40 existing power supplies for bipolar operation would require the expenditure of $470K. The addition of reversing switches, however would cost only $280K. Since both approaches involve approximately the same effort, the reversing switch approach was chosen.

The proposed installation is illustrated in figure 1. Only power supplies equipped with reversing switches are switched into the magnet buss. The reference magnet and current monitor used for field measurement and control are placed within a diode bridge to retain the unipolar characteristic of the existing current regulation system.

A typical bending magnet buss current profile is illustrated in figure 2. To reverse the current, the power supplies are put into the normal "invert" following "flattop", but the current is drawn toward zero. When this current falls below 0.5 amps, the SCR's in the reversing switch will drop out of conduction. At this point, the Main Accelerator control system changes the Polarity Reference Bit (PRB) which instructs the firing circuits in the reversing switch to turn off SCR's F_1 and F_2 and turn on SCR's R_1 and R_2 (see figure 1). Following this, the injection field is reestablished and the acceleration sequence commences.

GENERAL SWITCH DESIGN

A summary of the reversing switch features is listed as follows:

1. Maximum DC current - 7000 amps forward
   3600 amps reverse
2. Reverse breakdown voltage - 1000 volts peak
3. Voltage to ground - 2000 volts peak
4. Cooling water - 10-15 gal/min @ 95°F inlet temperature
5. Size - 2 modules, each 24" x 20" x 10"
6. Protection - will trip power supply on overcurrent or SCR breakdown

A typical module shown in the photograph of figure 3 includes two legs of the switch, one with a capacity of 7000 amps, the other a capacity of 3600 amps; the associated firing and protection circuits; and power supplies. They are interconnected according to the diagram of figure 4.

Seven-eights inch heavy wall copper pipe supplies both cooling water and power to each module through heavy duty 3/4" copper unions mounted on the rear of each module as shown in the photograph of figure 5. The technique of having a common water and electrical connection ensures that cooling should be available when the electrical connection is made. Water leaks are also visible indications of poor electrical connections.

SCR'S AND COOLING

The optimum design for the basic current switch centers around a nominal 65 mm "Hockey puck" SCR available from either Westinghouse or International Rectifier. Such a device will handle a DC current of 1800 amps with a maximum dissipation of 2700 watts. Non-repetitive breakdown voltages of 2200 volts provide better than 100% safety margin over the nominal 1KV blocking voltage requirement for the switch. This margin coupled with the snubbers and MOV's gives us reasonable transient protection. A "finger voltage" requirement of 2.0 volts was included in the specification to ensure that all devices will turn on when operating in parallel. A thermal impedance θ_{JC} = .02°C/w allows conventional double-sided cooling to be used. In the 7000 amp leg, five devices are paralleled. Should one device "no fire", the remaining four devices will handle full load current indefinitely. Current sharing is ensured by including 600μΩ water cooled stainless steel resistors in series with each SCR in the switch legs. Snubbers and MOV's are included for transient protection across each switch leg as indicated in figure 4.

Both cooling water and current are supplied to each device through heat sinks coupled to a water-cooled 7/8 inch heavy wall copper buss. The thermal impedance θ_{CW} of each heat sink (water to pole face) is 0.02°C/w at 1 gal/min which permits the junction temperature to rise to 116°C under full load (four devices). To ensure this low thermal impedance, the devices must have a clamping force of from 8000 to 10,000 lbs. A very low profile clamp was designed using 3/4 x ½" 4150RS Annealed steel bars as springs. The clamping force is proportional to the deflection of these springs (.003"/1000 lbs) and is measured with a portable dial indicator fixture which is placed on top of the clamp as shown in figure 6.

FIRING CIRCUITS

SCR gates are driven by a 10 kHz "picket fence" current from the dual firing circuit shown in figure 7. Each gate receives a train of 600 ma pulses on alternate half cycles of the output. This technique results in a more uniform demand on the power supply. Series diodes isolate SCR's which share a common secondary winding. The open circuit voltage is 20 volts. Two identical firing circuit drivers share a common source of excitation through a logic network. It is through this network that the PRB selects which driver will be excited. This same network tells the protection circuitry which SCR bank is on; and enables that

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circuitry to inhibit the drivers in case a fault is detected.

PROTECTION AND STATUS

Status information regarding the condition of each module is gathered by the use of hall effect switches which detect the presence of individual SCR and buss currents. These devices can be made quite sensitive (approximately 50 amps) through the use of flux concentrators. These concentrators are simply ferrite toroids which surround the conductor and are gapped to accept the hall effect device. This approach has proven to be both inexpensive and reliable. One such switch is mounted on an insulating bobbin mounted over the conductor on the anode side of each SCR (see figure 8). A nominal ½ inch 3E2A ferrite core serves as a flux concentrator for the hall effect switch. The switch turns on when a nominal 200 amps is being carried by the SCR. Two switches monitor each leg in a module; one switch is used to detect when the current is near zero, the second is positioned to turn on when the buss current exceeds 1800 amps. Its purpose is to validate the number of SCR's which are on since all SCR's are normally conducting at this current. If all devices are on, the status is NORMAL. If one device is not conducting, a NO FIRE warning is given. If more than one device is not conducting, the power supply system is turned off and an OVERCURRENT alarm is given. The transition between which devices are conducting and the condition of the module is made by using the SCR current detectors to address a ROM programmed to output the number of devices conducting and the status of the module. The low current switch is used by the comparator to determine if a device has either broken down or erroneous data has been supplied to the switch (PRB). The comparator simply uses the status of the firing circuit input as set by the PRB to determine which leg of the module should be nonconducting. If current is detected in this leg, then a BREAKDOWN condition is established, the firing circuits are inhibited, and the power supply is tripped off. Status information is latched so that the fault may be detected after it has cleared. The low current switch turns off when the buss current drops below 35 to 50 amps at a nominal rate of 6000 A/sec. This would cause the detector to give an "anticipated" zero buss current indication a few milliseconds before it actually occurs. This is cured by delaying the detector output by 500 msec.

INSTALLATION

The two reversing switch modules are sized to fit into our existing power supply cabinets in an area presently used by the power supply controller. Such a position is ideal because it directly intercepts the power supply output buss and a minimum of power supply rework is required. The switch represents two parallel water paths to the cooling system. Each of these paths has a flow of from 5-7 gal/min. The routing of cooling water in each module is set up so that each of the main paths cool one side of each of the SCR's. This represents a uniform thermal load on the system.

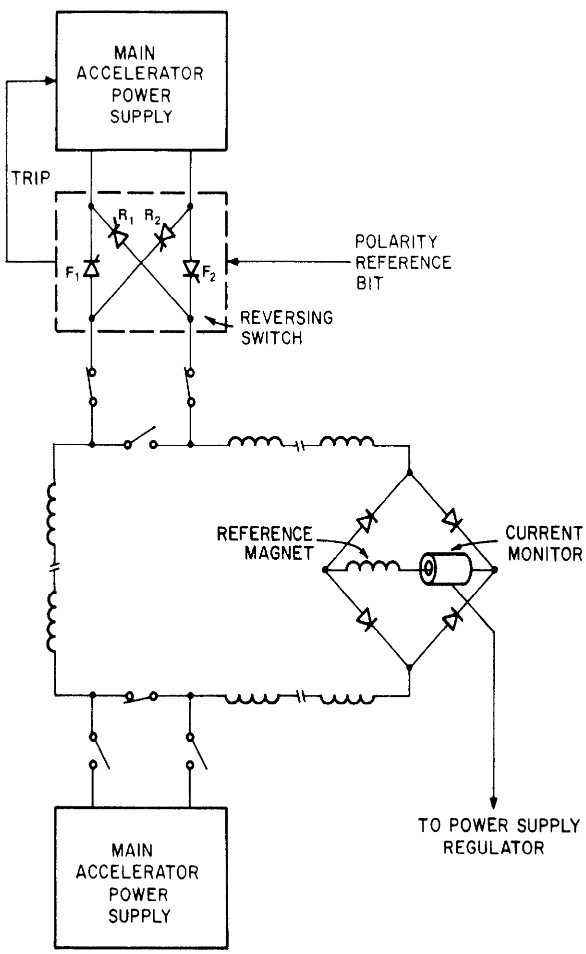

Figure 1. Typical bipolar Main Ring magnet supply.

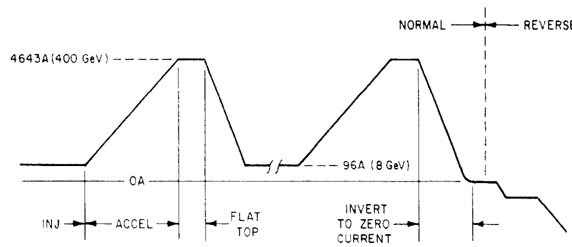

Figure 2. Current profile in bending magnets.

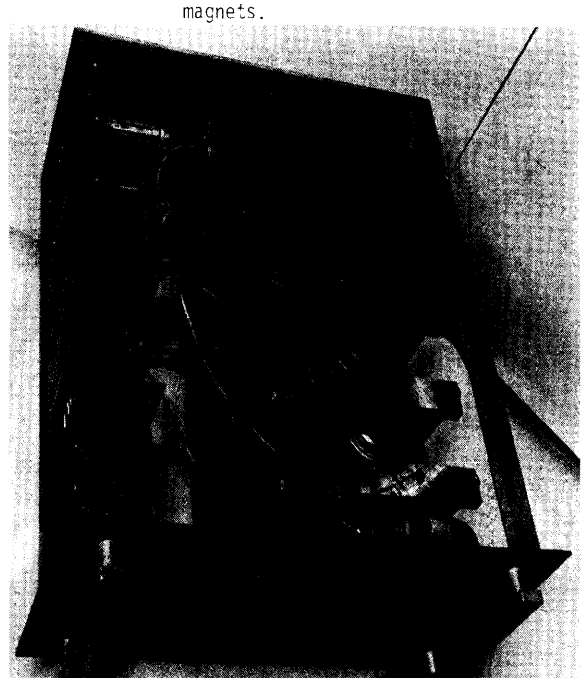

Figure 3. General view of reversing switch module.

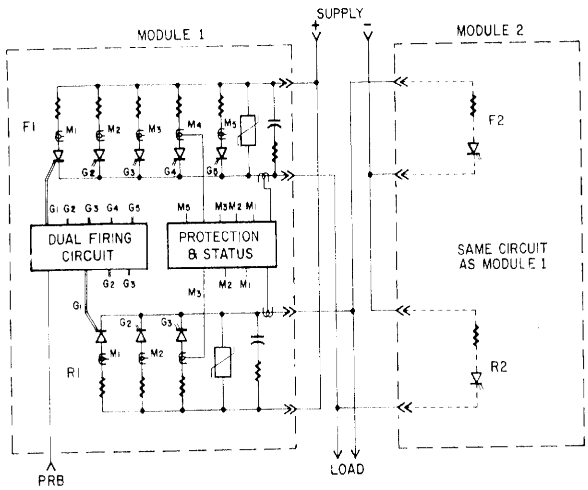

Figure 4. Basic two module reversing switch.

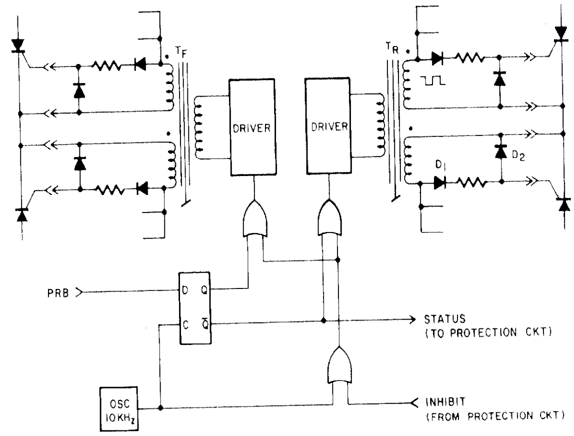

Figure 7. Dual firing circuit.

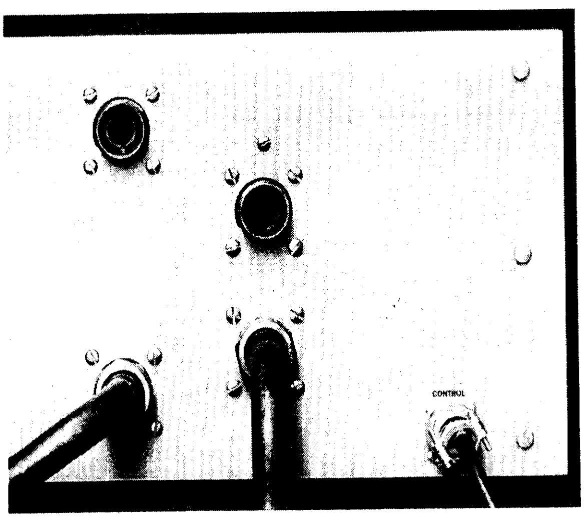

Figure 5. Module rear view showing water cooled buss connections.

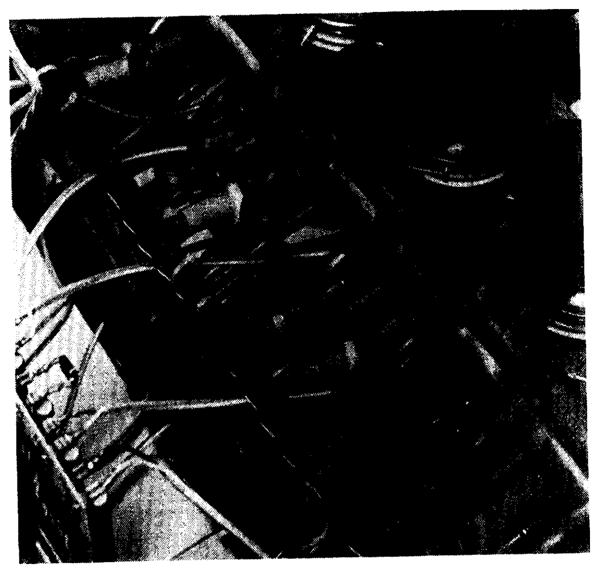

Figure 8. Hall effect switch current monitors mounted on SCP anode lead.

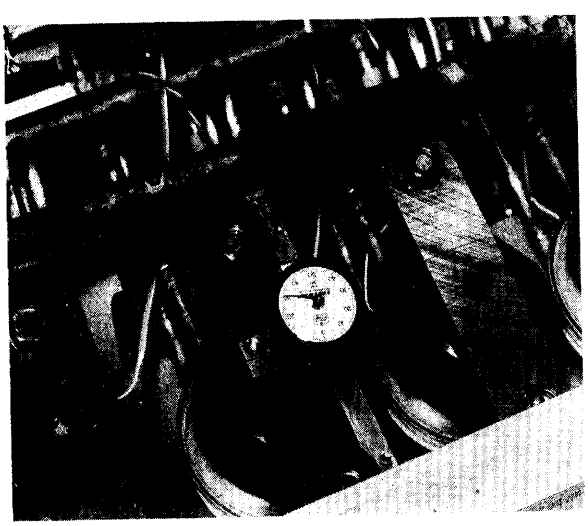

Figure 6. Dial indicator used to measure clamping force.