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A 10,000 A 1000 VDC Solid State Dump Switch

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A 10,000 A 1000 VDC SOLID STATE DUMP SWITCH

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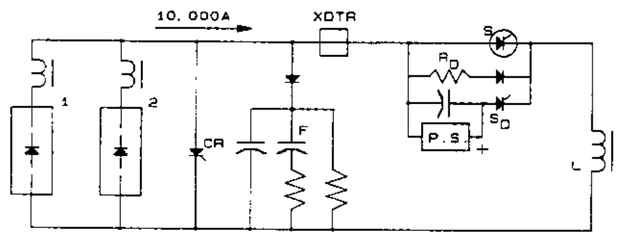
Abstract. The superconducting magnet test program at Fermilab requires a switch, called a dump switch, rated 10,000 A, 1000 Vdc, which must be able to continuously carry rated current. A dump resistor rated 2 MJoules, is connected in parallel with the switch contacts and dissipates the stored energy from a magnet when the switch opens. The required switch opening time is 250 µsec maximum after detection of a fault or a trip command. A successful switch can be constructed from six parallel inverter type Silicon Controlled Rectifiers (SCR's) which each carry their share of the load current. These run SCR's are mounted at watercooled heatsinks and are commutated off from stored energy in capacitors. Each parallel SCR is connected in series with a 1 mΩ watercooled resistor to assure dc current sharing and turn on. A description of the control and construction of the switch is presented.

Keywords. Switch, power switch, dump switch, dump capacitor, dump SCR, dump failure.

INTRODUCTION

Figure 1 shows the circuit in which the dump switch is used. The switch is represented by a simple SCR symbol. Two 5000 A 100 Vdc programmable power supplies are connected in parallel and supply up to 10,000 A to the super-conducting magnet load under test. A ripple filter, a filter crowbar and the dump switch are installed between the power supplies and the load. Other circuit configurations can be made, however attention must be paid to the fact that the dc current should not be interrupted in parts of the circuit, which contain substantial amounts of inductance. The stray inductance of circuits this size can easily be in the order of 1 mH.



1,2 - 5000 A, 100 VDC power supply
C_R - Crowbar SCR
F - Ripple filter
S - Dump switch SCR
R_D - Dump resistor
S_D - Dump SCR
XDTR - D.C. current transductor
L - Superconducting magnet 0 to 100 mH

Fig. 1: Dump switch power circuit.

The circuit of Fig. 1 is used, because the dc current is never fully interrupted in any part of it. The superconducting magnet load may vary from 0 to 100 mH. Opening the dump switch with a 0 mH load forces about 800 Vdc charge into the filter capacitors. This is caused by the stored energy in the filter chokes. These undesirable charge voltages in the filter capacitors get smaller when the test load inductance increases. Firing a crowbar SCR at every dump switch opening prevents this voltage build up at the filter capacitors.

The power supplies are connected in parallel via filter chokes of about 7 mΩ and 6 mH each. This filter choke location in the circuit assures better parallel power supply operation, although it is possible to connect the power supplies directly in parallel. Installing the chokes and filter capacitor behind the dump switch prevents charge build up at the filter capacitors when the dump switch opens.

The air cooled dump resistor is built from stainless steel bars and has adjustable taps at 25, 50, 100, 150, 200, 250 and 300 mΩ. Power dissipation in the 2 MJoules dump resistor is about 10 kJ per pound of steel, which raises the resistor temperature about 50°C. All components are rated to handle one 2 MJoules dump every 5 minutes.

SWITCH CONTROL

Figure 2 shows the control and interlock flow diagram for the dump switch. A combination of high operating currents and high dump resistor values could be destructive when the resulting dump voltage exceeds the switch rating of 1000 Vdc. Limit switches, which are activated by the selected dump resistor tap settings are therefore interlocked to the power supply load current control reference. These dump resistor tap position interlocks limit the load current in such a manner that a dump voltage can never exceed 1000 Vdc.

Another load current control reference limit is obtained from a current sensor mounted at each parallel SCR. This control limits the reference, and thus the power supply current, in steps of 2000 A. Each conducting parallel SCR permits and is rated for 2000 A dc load current. This useful current limit control automatically prevents excessive dc current through the conducting SCR's if some of the parallel SCR's fail to turn on.

The need for the reference limit controls is also the reason why there is an interlock to prevent power supply operation with the built in local reference. All current control must be via the reference limiter. All control is from remote via a computer. All interlocks must be clear before the load current can be turned on. Opening of the dump switch starts a series of events which is best understood by looking at Fig. 2.

Suppose that an energized superconducting load presents a quench unbalance to the detector. What happens? Looking at Fig. 2 we see that the overvoltage detector senses this fault and reports this to a dump distribution circuit. The dump

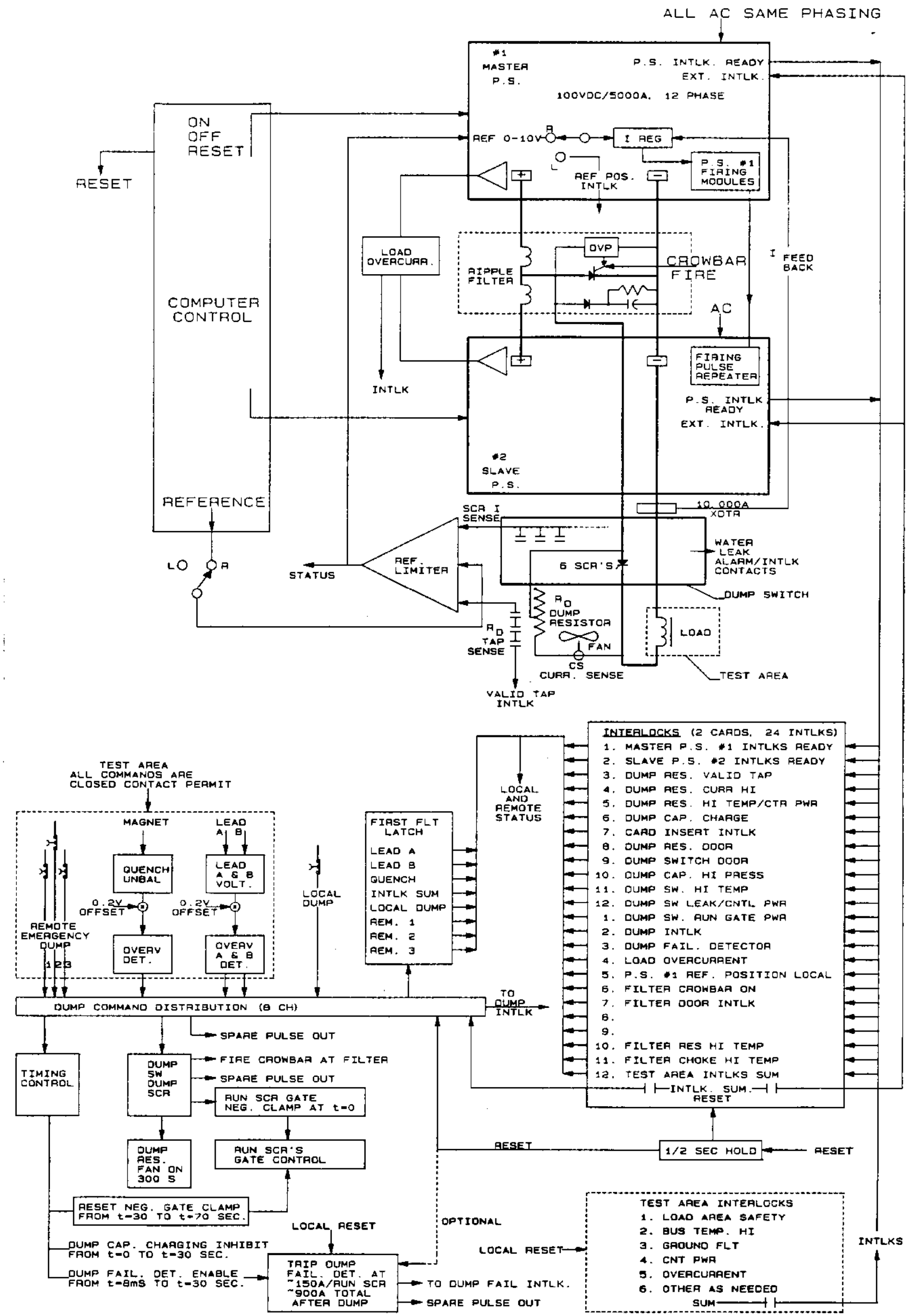
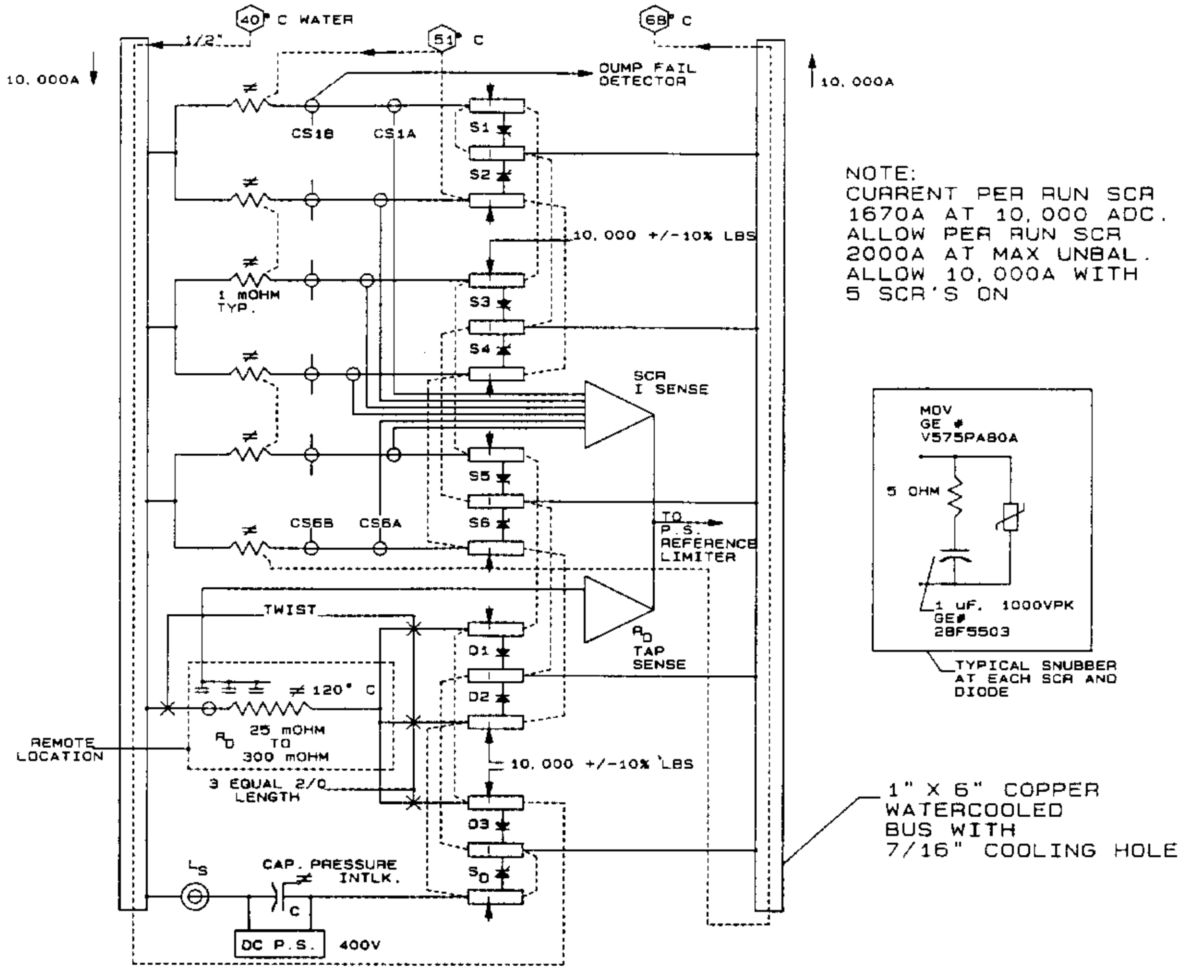


FIG. 2 DUMP SWITCH CONTROL AND INTERLOCK FLOW



COOLING ΔP – 100 PSI LOSSES – 35KW AT 10,000 AMP WITH 6 SCR'S ON

FLOW – 4 GPM

MAX T IN – 40°C V DROP – 3.5 VOLT

MAX T OUT – 70°C

CLAMPING PRESSURE IN LBS
FOR 10,000 LBS FINGER TIGHTEN NUT AND ADD 1 1/2 TURNS
CHECK SCR FORWARD DROP <1.6V AT 2000A/SCR
AT PROPER PRESSURE AND 125°C

WATER COOLED HEATSINK – AAVID ENG. INC. #A-004-349-72

CLAMP – VEP #VE9560-3120, 6" BOLT CENTER

≠		120°C KLIXON TI #9700K01-33
–/\/\/–		WATERCOOLED BALANCING RESISTOR, 1 mOHM 10" 304SS PIPE, 3/4" – 11 GAGE
–⊚–	LS	CUT CORE SOAKING REACTOR, 10 uH
⊤	C	CAPACITOR, 4X GE #17L611NJ, 2232 uF, 1000VPK EACH
S1 THRU S6		IR #88-6563-1800V, 2350A RMS, tq – 100 uS, INVERTER SCR, RUN SCR
SD		IR #S77R18A, 1800V, 3060A AV, dI/dt >300A/uS, RECTIFIER SCR, DUMP SCR
D1 THRU D3		MARCONI #DS2103SW20, 2000V, 5700A AV., 160°C DIODE
RD		DUMP RESISTOR, 2MJ AT 50°C RISE
CS1A – CS6B		CURRENT SENSOR, HAMLIN #59145-020
ENCLOSURE		72" H X 36" W X 30" D, NEMA12, FLOOR MOUNT

FIG. 3 10,000A DUMP SWITCH LAYOUT SCHEMATIC distribution circuit takes the following action:

1. Fires the dump switch open.
2. Latches on to the first fault.
3. Trips the power supply interlocks.
4. Inhibits charging of the dump capacitor for 30 seconds.
5. Activates the dump failure detector.
6. Removes the negative gate clamp from the parallel run SCR's when the dump is over after 30 seconds.

Firing the dump switch causes several other things to happen as follows:

1. A current sensor at the dump resistor, which now carries the load current, switches cooling fans on for 300 sec.
2. A pulse derived from the dump capacitor discharge, Fig. 6, drives immediately all run SCR gates negative to -3.5 V. This feature makes it practically impossible for run SCR's to retrigger during a dump. This negative clamp is automatically removed by the dump distribution circuit, after the dump is over.
3. A pulse derived from the dump capacitor discharge fires the power supply ripple filter crowbar.

All faults can be reset when permits are obtained from all interlocks.

SWITCH DESCRIPTION

Switch ratings are:

Current/voltage	-	10,000Adc/1000 Vdc
Type	-	solid state, SCR
Forced commutation charge	-	400 Vdc in 9000 μF
Switching time	-	~120 μsec
Insulation test	-	2500 Vdc to ground
Control power	-	120 V, 1ϕ, ~5 A
Losses	-	35 kW
Cooling	-	water, ΔP = 100 PSI, 4 GPM, 38°C inlet
Test pressure	-	300 PSI
Size	-	72"H x 36"W x 30"D

The switch layout is shown in Fig. 3. Six run SCR's S1 through S6, mounted at watercooled heatsinks, are operated in parallel to carry 10,000 Adc. Capacitor C carries enough charge to force S1 through S6 off when dump SCR S_D turns on and all gate drives for the run SCR's are removed at the same time. Diodes D1, D2 and D3 prevent current flow from the dump capacitor C through the dump resistor R_D. These diodes need to be large because they have to carry the exponentially decaying load current when the run SCR's are switched off.

Each run SCR has a 1 mΩ watercooled resistor connected in series to force equal load current sharing and assure turn on of all parallel SCR's. Non-conducting run SCR's experience only the forward voltage drops of the conducting SCR and its' series connected resistor. A low forward voltage makes it harder for the SCR's to turn on.

The heatsinks and watercooled resistors are bolted to two vertically mounted 1" x 6" watercooled bus bars, which serve as power and cooling water in and outlets. All SCR's and diodes have been chosen to fit the same size heatsink, mounting clamp and mounting force. These mechanical requirements led in some cases to larger solid state parts than needed for electrical loading.

Dump capacitor

The dump capacitor must be able to withstand 1000 Vdc dump voltage and have enough charge to supply 10,000 A for the duration of the run SCR turn off time t_q. The amount of needed capacitance at 400 V charge can be calculated from:

$$Q = CV \quad \text{which yields:} \tag{1}$$

$$I = C\frac{dV}{dt} \tag{2}$$

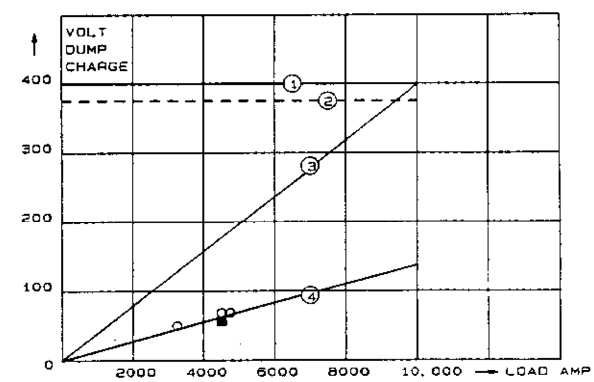
In this case $I = 10{,}000$ A, $dV = 400$ V, $dt = t_q$

$$\text{Thus: } C = 25\, t_q \tag{3}$$

Choosing an inverter style run SCR, makes t_q and thus C smaller. Typical inverter SCR's have a t_q = 100 μsec versus about 200 μsec for rectifier style SCR's. C needs to be about 2500 μF for t_q = 100 μsec. Selecting C = 9000 μF at 400 V charge, yields a safety factor of 3.6.

It is obvious that lower charge voltages than 400 V can be used when a 9000 μF dump capacitor is installed. A safety factor of 3.6 is probably excessive. Of course the charge voltage can always be reduced to lower the safety factor.

A number of interesting tests to determine the minimum required dump capacitor charge voltage were made after the switch was built. The procedure was to set up various d.c. load current values and to determine the minimum required charge for a successful dump at that load current value. These tests were carried out up to about 4500 A with a 1 second load time constant. Longer time constants and higher current values were not used because they can be destructive for the run SCR's. It is most likely that all the decaying load current after a dump failure, due to the lack of sufficient capacitor charge, will be carried by one of the six run SCR's. Excessive sustained currents will destroy the conducting SCR. It is therefore not prudent to perform these tests at high currents and loads with long time constants.



1. Charge voltage used for operation.
2. Charge voltage trip level set.
3. Charge voltage needed for t_q safety factor 3.
4. Minimum needed charge voltage for a dump.

■ - Tested point yielding a dump failure.
o - Tested point yielding a successful dump.

Conditions: Dump capacitor 9000 μF
Switch turn off time t_q - 120 μsec.

Fig. 4: Dump capacitor charge voltage as a function of the load current.

The results of these interesting tests are shown in Fig. 4. It is apparent from Eq. (2) that less and less charge voltage is needed when the load current values get smaller. The test results allow us to draw some conclusions about the "turn off" time of the completed switch. It was found that about

60 V charge at 4500 A was just enough to switch all run SCR's off. Somewhat lower charge voltages caused "turn off" failures. "Turn off" failures are called dump failures. Thus 60 V in 9000 µF at 4500 A load is just enough charge. Putting these values into Eq. (2) yields a "turn off" time t_q = 120 µsec for the complete switch at 4500 A load current. This is slightly higher than the listed t_q = 100 µsec for the SCR's, but well within the 250 µsec required for the switch.

It is obvious that some charge voltage interlock is needed to permit equipment operation. A charge voltage of 400 V into 9000 µF is used for all load current values. An interlock permit is obtained above 375 V charge. Pressure switch interlocks at the capacitor enclosures make sure that they are in good shape. Figure 5 shows the dump capacitor charge control. Voltage regulation is done via the primary of the charging transformer. Several safety interlocks are installed because the charged dump capacitor carries a lethal amount of stored energy. The following interlocks remove the a.c. power to the charging transformer:

1. Safety lock out of the master power supply, since the charge power is supplied via the master power supply.
2. External interlock permits from the test areas.
3. Switch access door interlock.
4. Ground stick interlock. This interlock requires the safety ground stick to be placed on a limit switch hook in order to start charging. This prevents charging with the ground shorting stick inadvertently left at the capacitor, which could damage the charging supply.The ground stick should always be applied during maintenance.

Removal of the a.c. source to the charging supply causes relay K3, Fig. 5, to drop out and discharge the dump capacitors via the 200 Ω current limiting resistors. Charging is inhibited for a period of 30 seconds after a dump command.

Dump SCR and soaking reactor

The rate of current rise through the dump SCR S_D can be estimated to possibly reach 800 A/µsec at 400 V charge. This rate of current rise must be limited to a lower value by means of a soaking reactor. The soaking reactor will prevent di/dt damage at the SCR. A round laminated steel core soaking reactor 6"L x 3.5"O.D. x 1.5"I.D. with a 0.02" gap yields about 10 µH, when the capacitor discharge wires are passed through the center hole. The reactor is made from 4 mil tape wound grain oriented steel laminations and starts to saturate after about 25 µsec, when the current reaches 1000 A. At that point the reactor inductance starts to drop to about 1 µH at 2500 A. The gap reduces the core remnant field to about 200 Gauss. A core without a gap would be rather useless due to the high remnant field after the first pulse.

An auxiliary turn wound around the soaking reactor core is used to command the run SCR gates to go negative, when the dump capacitor discharges, Figure 6 shows how this is accomplished. Another turn fires the filter crowbar SCR. The soaking reactor comes in very handy to supply triggers when the dump fires.

The dump SCR must be able to withstand about a 1 msec long 10,000 A square wave pulse. This is not a problem for many SCR's.

Run SCR's and dump SCR gate drives

Six inverter style run SCR's are operated in parallel and are rated to carry 2000 Adc each at a maximum calculated junction temperature of 122°C. A simple dc gate drive, Fig. 6, delivers about 1.7 Adc to each run SCR gate. Testing revealed that this amount of gate current turns all 6 run SCR's on at 1500 A total load current. DC gate drive currents in the order of 0.7 A require an additional 1 Volt forward voltage across the SCR before they will turn on. A gate current of ~1.7 Adc is therefore a practical value to use in this application.

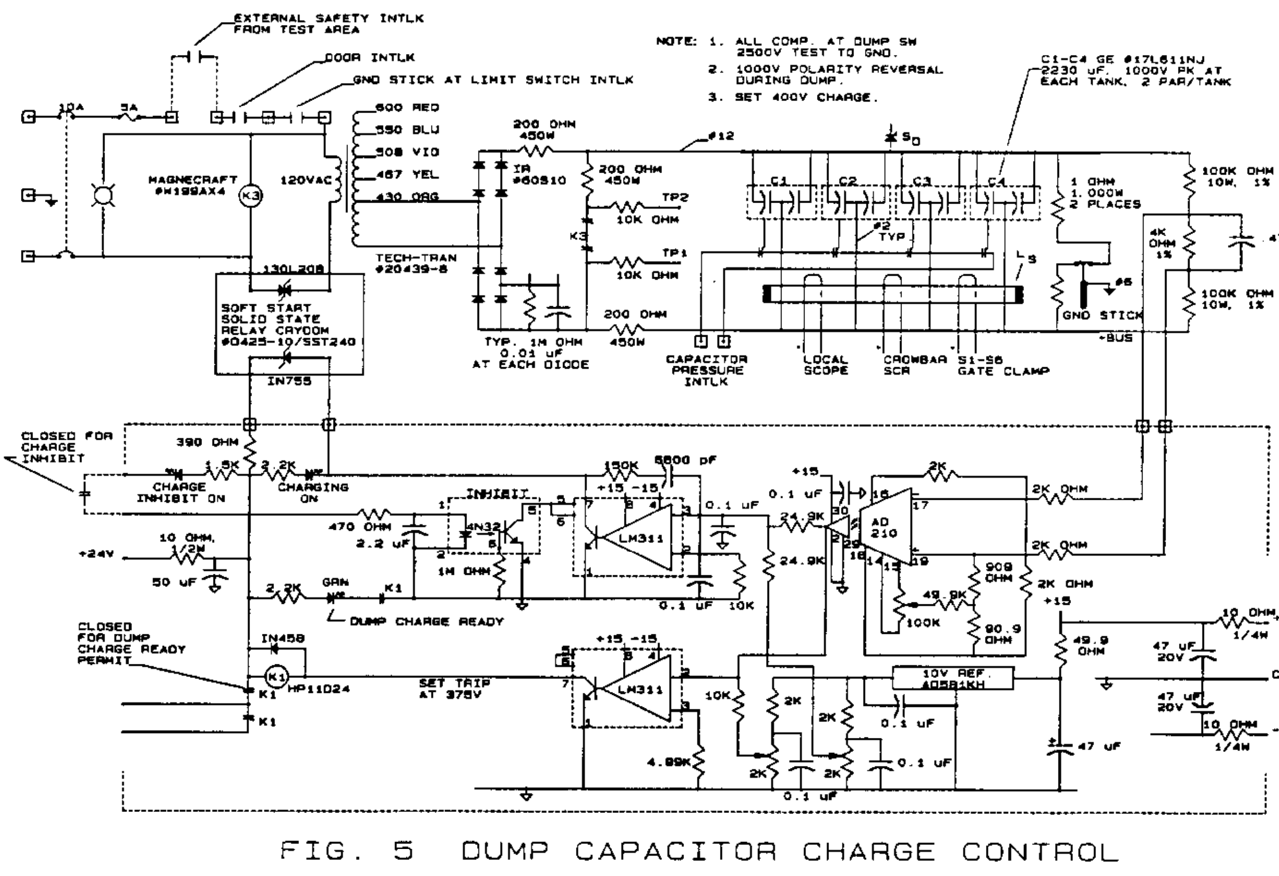


FIG. 5 DUMP CAPACITOR CHARGE CONTROL

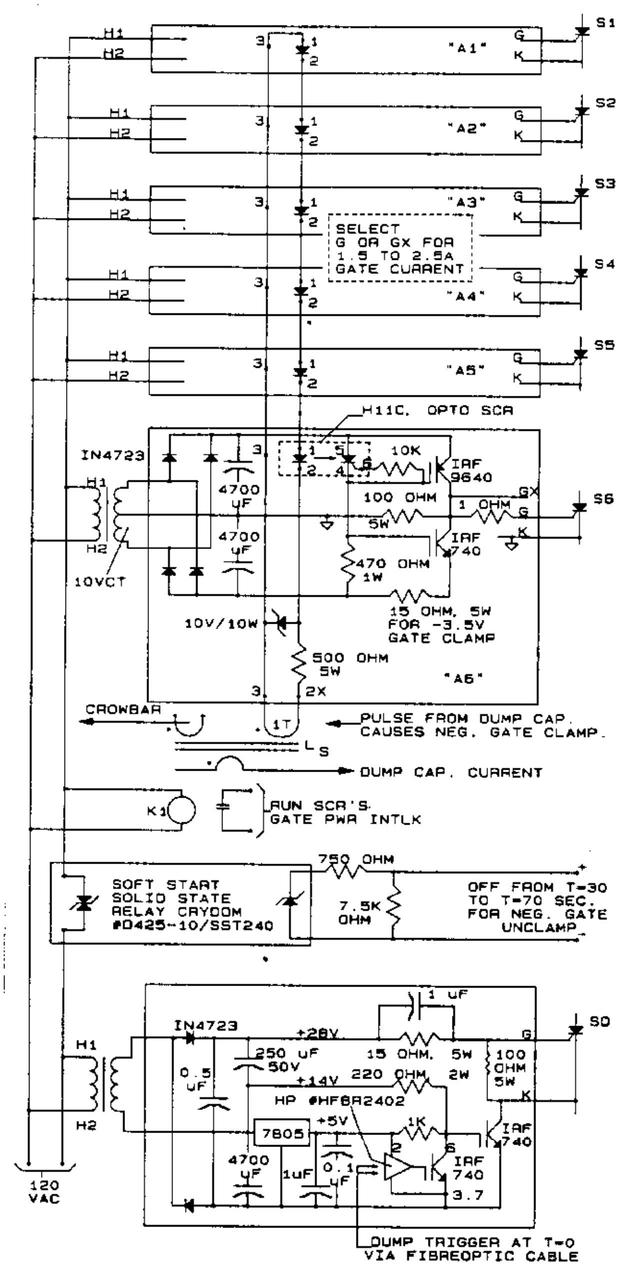


Fig. 6: SCR gate drives.

All six run SCR gates are driven 3.5 V negative when a dump occurs. This is accomplished via optically coupled SCR's H11C, installed at each gate drive board. The trigger diodes of these SCR's are connected in series to a winding installed around the soaking reactor core, and therefore receive a pulse when the dump capacitor discharges. Connecting the triggers for the opto-SCR's in series gives the best assurance that all run SCR gates get biased negative, when a dump command occurs. Leaving one run SCR on at high load currents would ruin it. It would be better to leave all six run SCR gates on during a dump failure. The run SCR gates will stay negative as long as the a.c. feed remains connected to the gate drive boards. Only removing the a.c. feed for about a 20 second duration causes the opto-SCR's to stop conduction and thus remove the negative bias at the run SCR gates. This is a very desirable feature, because even power glitches during a dump, cannot remove the negative gate clamp at the run SCR's. It is therefore practically impossible for the run SCR's to turn on from electrical noise during a dump. A soft start solid state relay interrupts the a.c. feed to all run SCR gate drive boards for 40 seconds to remove the negative gate clamp. The soft start relay prevents high inrush currents and thus possible nuisance trips when all the gate drive transformers switch on again.

The trigger for the dump SCR S_D is coupled in via a fibre optic cable as shown in Fig. 6. This is done to obtain good noise immunity and isolation levels to the remote location where the dump command originates. The rate of load current rise di/dt through the dump SCR S_D can be very high. High rates of current rise require a fast gate drive pulse for the dump SCR. A 28 V gate pulse is therefore switched to the gate of the dump SCR and causes the gate current to rise to 4 A in 200 nsec and to reach 10 A in 800 nsec. This is more than adequate, especially since a soaking reactor is employed.

Current sensing

Current sensing is done by mounting proximity switches close to current carrying bars or resistors. They switch on or off when the current in their vicinity is about 100 A. This method yields a very simple current sensing mechanism presented at isolated contacts. These contacts are used for current reference limit control and dump failure detection. Switching speed is in the order of a few hundred µsec.

Dump failures

Dump failures are registered when a run SCR carries current immediately following a dump command. Current sensors, mounted at the balancing resistors, are enabled shortly after a dump command and indicate a dump failure when they sense a current. High current dump failures at one run SCR will destroy the SCR because of excessive current.

Dump failures produce a dump failure output pulse via the detector. This pulse can be used to fire a backup switch. Backup switches are not used in this installation.

CONCLUSIONS

Tests indicate that switch operation is reliable. Each run SCR was tested to carry 2000 Adc. First time switch turn on went very smooth. The switch opens in 120 µsec at 5000 A load current. Measurement of the switch opening time is described at the dump capacitor description.

Parallel run SCR turn on at low load current is better than expected. Future switches could be built with 0.5 mΩ balancing resistors instead of 1 mΩ. This will reduce losses. It is not necessary to match the electrical parameters of the parallel run SCR's.

Attention must be paid to the mounting location of the current sensing limit switches. They should be mounted away from the 1" x 6" power bus bars. Currents in these bus bars can cause false switch pickup. Installation of a small steel shield alleviates false pickup if the switches are too close to other bus bars.

ACKNOWLEDGEMENTS

Walt Jaskierny made substantial contributions to the improvement of various control circuits and assembled the switch.

CONVERSION FACTORS

Dimension	1 mil	= 2.54×10^{-3} cm
Dimension	1 inch (1")	= 2.54 cm
Dimension	1 foot (1')	= 30.48 cm
Force	1 lb(s)	= 0.4536 kg(s)
Flow	1 gallon per minute (GPM)	= 3.7848 liters per minute
Pressure	1 pound per square inch (PSI)	= 0.0703 kg per square cm