TRANSIENT PROTECTION SYSTEM FOR THE RING MAGNETS OF THE ZERO GRADIENT SYNCHROTRON*

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Abstract

The ring magnet octants of the Zero Gradient Synchrotron are connected between four dc power supplies to achieve symmetry and reduced operating voltages with respect to ground. Rectifier faults and other equipment malfunctions disturb this symmetry and cause transients of as much as 5 kV between octant terminals and ground. In order to limit these transients, a solid state protection system has been installed. It operates within a few μsec. The system applies ground to the four octant phantom grounds, is capable of carrying 10 kA, and causes an emergency shutdown of the ring magnet power supply (RMPS) should any one of the phantom ground voltages exceed 300 V. This limits octant transient voltages to about 1.7 kV. In addition, the system returns energy stored in the magnets to the RMPS and stops RMPS pulsing if a phantom ground voltage is $250 < E < 300$ V. Visual indication of the location of the overvoltage to ground is provided. The transient voltages at the magnet coil terminals and at the phantom grounds are recorded on magnetic tape for diagnosing faults.

I. Introduction

Pulsing power for the ring magnet of the 12.5 GeV Zero Gradient Synchrotron (ZGS) at Argonne National Laboratory is supplied by a flywheel motor-generator (M-G) set and four groups of mercury-arc rectifier units.[1] A block diagram of the power circuit is shown in Fig. 1. The four rectifier groups are connected in paralel on the ac side to two generators. On the dc side the rectifiers are connected in series with four sections of the magnet windings (quadrants) to reduce the operating voltage to ground. The midpoint of one quadrant is grounded through a resistor. A typical cycle of the ZGS ring magnet is illustrated in Fig. 2. During each ZGS pulse there is an exchange of stored energy between the M-G set and the magnet. During the rise of the magnet current the rectifier groups

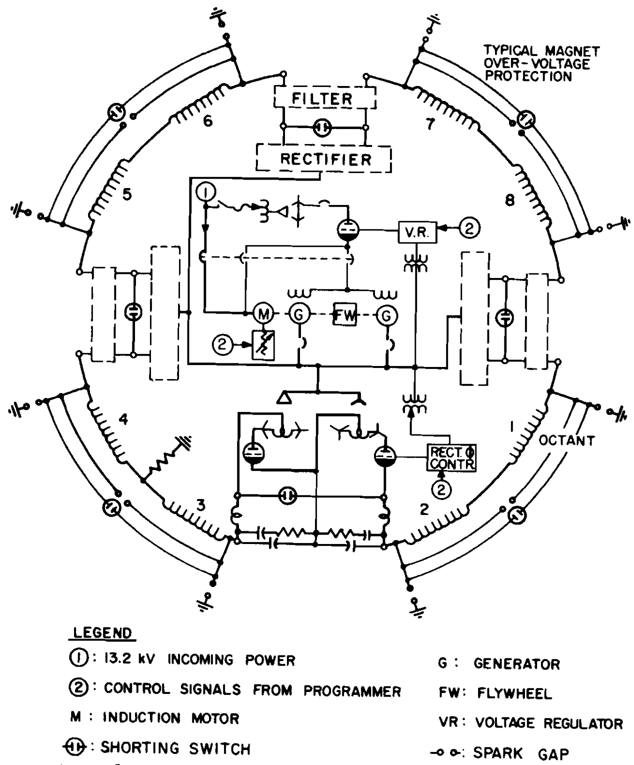

Fig. 1. Block diagram of ZGS ring magnet power supply.

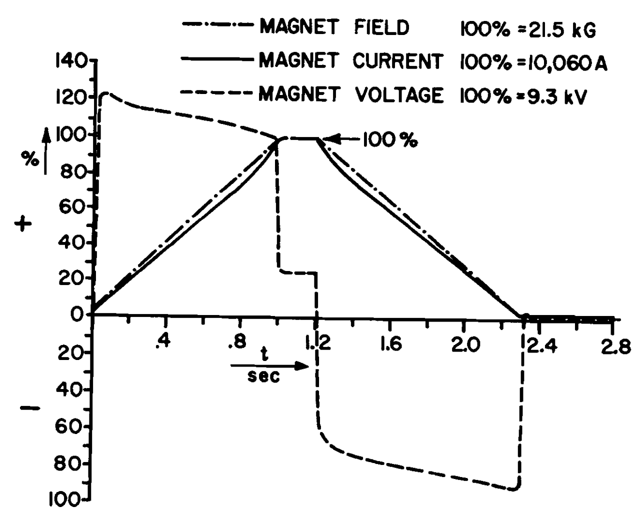

Fig. 2. Time cycle of ZGS ring magnet.

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transfer power from the generators to the magnet, with a drop in speed of the M-G set. The magnet current is reduced from its peak value of ≤ 10 kA to approximately 150 A by operating the rectifier groups as power inverters to transfer power from the dc to the ac circuit. During this time the generators operate as motors and the speed of the M-G set is increased. Between pulses the induction motor supplies the system losses. At the peak pulse current approximately 40×10^6 J of energy are stored in the ring magnets.

The magnet windings are protected against overvoltage by spark gaps across each quadrant and from quadrant terminals to ground. These enclosed spark gaps have carbon electrodes and require careful high voltage conditioning after they have carried current. It requires approximately 30 minutes to recondition a gap. Switches are provided to short-circuit the rectifier groups and magnet quadrants when the 86 C tripping relay of the RMPS initiates an emergency shutdown to protect the ring magnet against surges. The shorting switches across the rectifiers close approximately 20 msec ahead of the shorting switches across quadrants to reduce voltage transients. Their respective nominal closing times are 40 msec and 60 msec.

During the first 2-3/4 years of operation of the ZGS the spark gaps to ground were adjusted to operate at 3 kV and the gaps across quadrants were adjusted for 6 kV. The quadrant terminal voltages are ≤2800 V and the phantom grounds between magnet octants are ideally at zero potential. This voltage symmetry is disturbed by rectifier arc-faults, by ground faults on high voltage terminals, and by operation of the rectifier shorting switches during an emergency shutdown of the RMPS. A rectifier arc-through produced by a random intermittent cause may clear itself by recommutation. Therefore, a time delay is incorporated before arc-throughs energize the 86 C relay. However, if the voltage transient generated by an arc-through fires a spark gap, protective relay circuits will energize the 86 C relay without delay. No time delay can be tolerated for rectifier arc-backs. During an emergency shutdown, initiated by the protection circuits of the RMPS, voltage transients are generated by the difference in closing time of the rectifier shorting switches. This difference is of the order of a few msec. For example, the magnet coil potentials with respect to ground during early rectification, are shown in Fig. 3 for various operating conditions. Trace "a" shows the voltage distribution during normal operation. Trace "b" illustrates the voltage

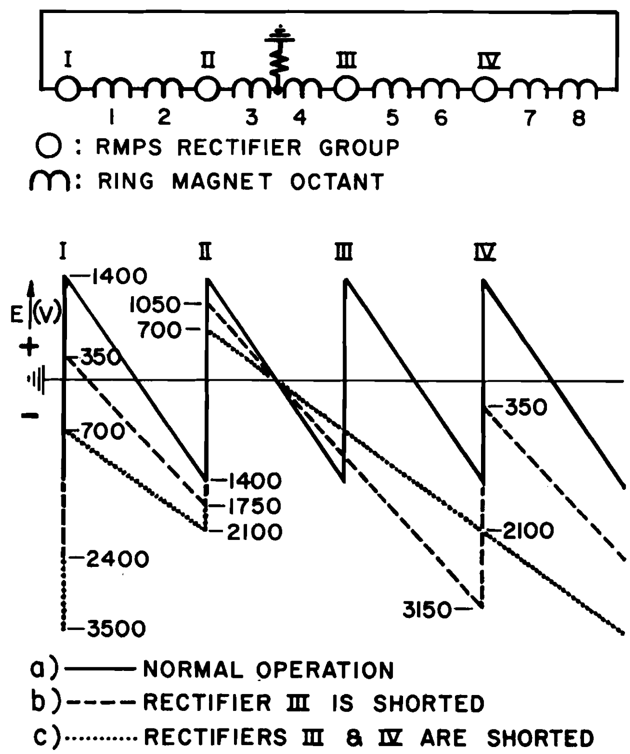

Fig. 3. Potentials to ground of ZGS ring magnets.

distribution if only the shorting switch across rectifier power supply III has closed, trace "c" shows the distribution if both power supplies III and IV have been shorted simultaneously. In reality, the sudden removal of a rectifier power supply will not cause a step change in octant voltage as shown in Fig. 3. The energy stored in the underdamped LC-filter requires time to discharge through the shorting switch, which reduces the voltage transient. The filter responds to a step change in approximately 12 msec.[2] There is considerable reduction of the transient voltages if the difference in closing time of the shorting switches is very much smaller than 12 msec. However, if the difference in closing time is ≥ 10 msec transients of up to 3.5 kV are generated.

Spark gap operation accounted for a considerable downtime of the ZGS. In May of 1966 it was decided that the coil insulation could tolerate spark gap settings of 5 kV to ground and of 9 kV across quadrants. The gaps were readjusted to those higher levels and the number of spark gap operations was greatly reduced.

Operation of a spark gap, besides causing downtime of the ZGS for gap reconditioning also puts very high voltage stresses on some of the coil turns. When the spark gap between a coil terminal and ground operates, a steep transient voltage wave travels through the coil. As illustrated by the equivalent circuit of Fig. 4, the

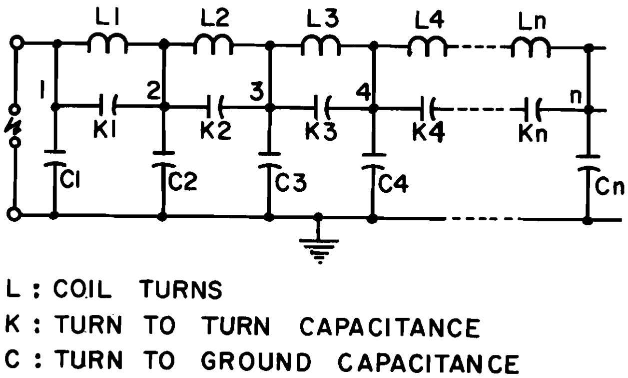

Fig. 4. Equivalent circuit of coil with arc-over between terminal and ground.

arc-over discharges capacitance C1 and point 1 is at ground potential. However, at the moment of arc-over, point 2 is still at the potential which was present before the arc-over. Therefore, the insulation of the first turn is exposed to a voltage which is very much larger than its operating voltage. As the capacitances C2, C3, C4, etc., discharge through the coil, the turns L1, L2, L3, etc., of the coil are exposed to high transient voltages. For instance, with the gap adjusted for 5 kV the first turn of the 30-turn octant coil is exposed to a transient voltage which is 107 times larger than its normal operating voltage of 47 V.

On April 21, 1970, after 41 million ZGS pulses, the coil of octant No. 2 failed and was replaced with a spare coil. A second coil failure, octant No. 3, occurred on January 9, 1971 after a total of 45 million ZGS pulses.

II. Circuit Description High Speed Phantom Ground Switches

General

Thus far no specific cause for these coil failures has been found. However, following the second coil failure an effort was made to reduce transients caused by arc faults of the rectifiers, by operation of the shorting switches during emergency shutdowns of the RMPS, or by operation of the spark gaps. All of these fault conditions increase the voltage between the phantom grounds of the ring magnet and ground. Therefore, fast acting voltage sensitive switches which would clamp the phantom grounds to ground if any one phantom ground voltage exceeded 300 V, would also limit most voltage transients on quadrant terminals to ≤ 1700 V. Figure 5 is a block

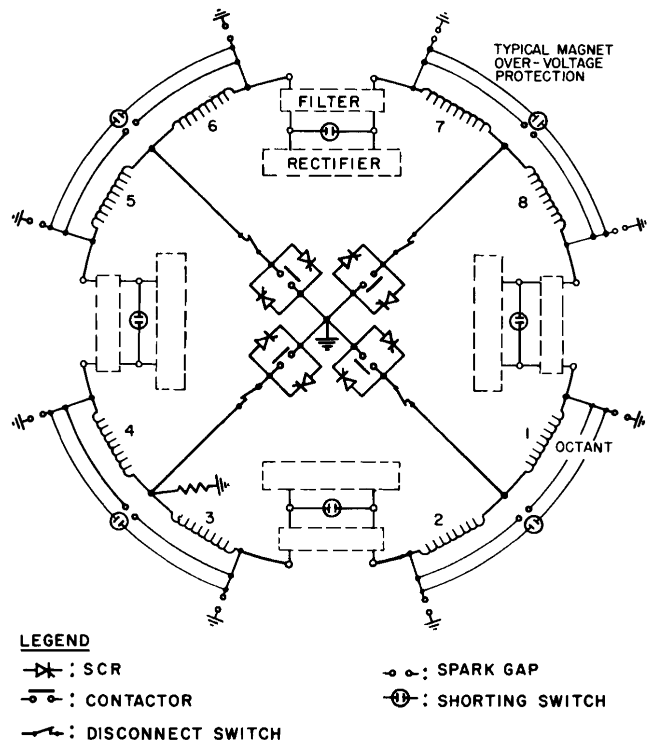

Fig. 5. Block diagram of ZGS ring magnet and phantom ground switches.

diagram of the ring magnet, the RMPS, and the high speed magnet phantom ground switches. These bipolar switches are energized within μsec of each other to ground the magnet phantom grounds, if the potential of a phantom ground exceeds 300 V or if the protection circuits of the RMPS initiate an emergency shutdown. Each of the four switch assemblies consist of a pair of antiparallel connected silicon controlled rectifiers (SCR's) and a parallel connected contactor. Initially the SCR's provide the ground paths; after approximately 80 msec the contactors close relieving the SCR's from carrying current.

Detailed Description

Figure 6 is a schematic diagram of the bipolar grounding switch and its auxiliary circuits.

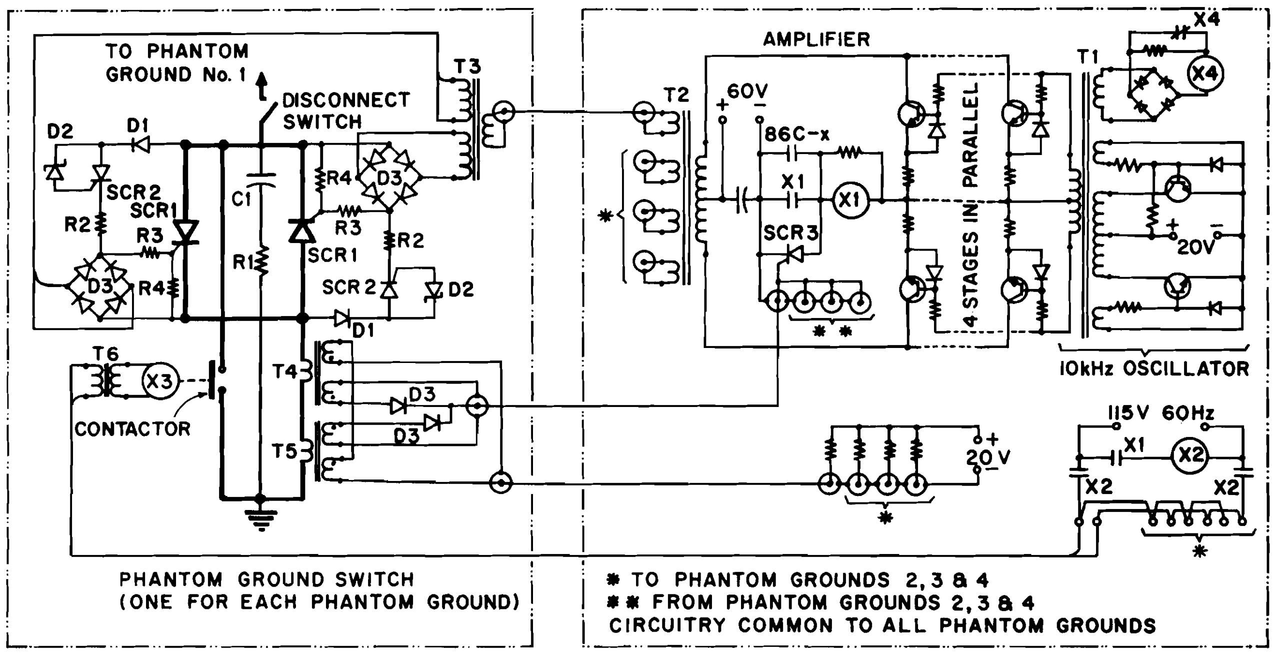

Fig. 6. Schematic diagram of high speed bipolar grounding switch for voltage transient protection of ZGS ring magnets.

The charge on capacitor C1 follows the phantom ground voltage. When this voltage exceeds the 300 V breakdown level of Zener diodes D2 one of the two SCR2's is triggered, which in turn triggers one of the two SCR1's. Diode D1 blocks a path to ground via R2, R3, R4, and D2. Energy to fire one of the SCR1's comes from the phantom ground and from capacitor C1. Resistor R1 in series with C1 limits the initial current through SCR1. This initial current has a fast risetime and, therefore, generates a short pulse in one of the two pulse transformers T4 or T5 which are located in the discharge path of C1. Each of these pulse transformers has a toroidal supermalloy core, a one turn primary capable of carrying 10 kA, a dc reset winding, and a pulse output secondary. Depending on the polarity of the primary current either T4 or T5 will go from one polarity of saturation to the other polarity of saturation while C1 discharges, thereby generating a pulse. Diodes D3 isolate the outputs of the pulse transformers from each other. The pulse generated by either T4 or T5 triggers SCR3 which in turn switches on the driver amplifier of a 10 kHz square wave inverter. The output of the amplifier, via transformer T2, drives the gates of the SCR1's of all four phantom ground shorting switches via pulse transformers T3 and bridge rectifiers D3. Relay X1 in the inverter chassis is energized by the amplifier transistor collector currents. Its contacts seal-in the 10 kHz amplifier and pick up interposing relay X2. Contacts of relay X2 in turn energize the operating coils X3 of the contactors in the four phantom ground shorting switch installations. These contactors then short out the SCR1's relieving them of current, and ground solidly all four phantom grounds. Isolation transformer T6 ahead of the contactor coil maintains the high voltage integrity of the phantom grounds.

Other contacts of relay X2, not shown in Fig. 6, give a ground fault annunciation and energize relay 86 C of the RMPS which causes an emergency shutdown of the RMPS.

If the 86 C relay is energized from any other protective device of the RMPS, it will close the above phantom ground switches by energizing the 10 kHz amplifier via contacts 86 C-x, which are in parallel with SCR3. This grounds the ring magnet coils long before the shorting switches operate. The circuit associated with relay X4 monitors the 10 kHz square wave oscillator and initiates an alarm if the oscillator stops. Undervoltage alarm relays are provided for every power source of the circuit.

Phantom Ground Overvoltage 250 V < E < 300 V

Normal phantom ground voltage fluctuations are less than 200 V. Voltage dividers between the four phantom grounds and ground provide signals for a second sensing circuit which energizes a relay if a phantom ground voltage exceeds 250 V. Contacts of this relay will then initiate alarms and will cause an emergency inversion of the RMPS. Pulsing of the ZGS is stopped after the magnet energy has been transferred to the M-G set. In this case the RMPS will not be shut down. Pulsing of the ZGS can resume at any time after the alarm has been reset.

Installation Details

The four phantom ground switches and overvoltage detection circuits are located on the first floor of the center building of the RMPS. Figure 7 shows a phantom ground switch installation.

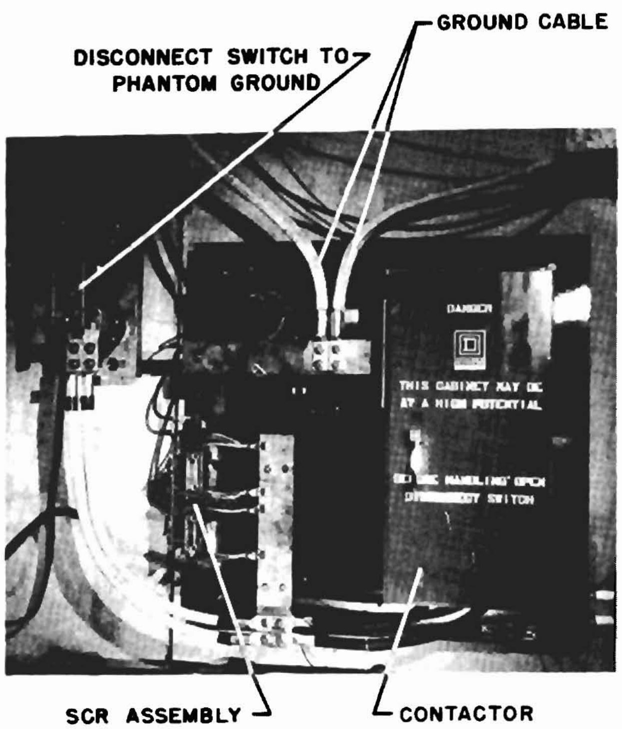

Fig. 7. Phantom ground switch installation.

Centrally located on this floor is a relay rack for the auxiliary power supplies, relays, inverter chassis, annunciator chassis, etc., which are common to the four phantom ground switches. Indication is made of the type of phantom ground fault, and the fault location, with displays locally and in the RMPS power house control room. All phantom ground trips, inverts, and operation of the RMPS - 86 C - relay require phantom ground resets. The equipment can be reset locally or from the RMPS power house.

A magnetic tape recording system records the quadrant terminal voltages and the phantom ground voltages. The recorder runs with a 3-minute endless tape which stops automatically after a fault has terminated pulsing of the ZGS. The fault recording is then transferred to a Visicorder for a permanent record. These recordings are useful in diagnosing RMPS faults and in checking the operation of the transient protection system.

III. Conclusions

The transient protection system for the ring magnets of the ZGS has been in operation since May 1971. It has permitted reduction of the spark gap settings from quadrant terminals to ground from 5 kV to 2 kV and across quadrants from 9 kV to 4 kV. After May 1971, the ZGS has been pulsed approximately 5.5 million times. During this period the phantom ground switches have operated 275 times, but only once did a spark gap arc over; this demonstrates the effectiveness of the system.

IV. Acknowledgments

I express my gratitude to Ray Kickert for his assistance in installing the equipment and to C. Potts for helpful discussions regarding the shorting switches. Special thanks is due Dale Suddeth who designed and tested the annunciator circuits and the phantom ground overvoltage circuit and provided the recording system.

References

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