PROTECTIVE RELAYING AND MONITORING OF THE RING MAGNET POWER SUPPLY FOR THE ARGONNE NATIONAL LABORATORY ZERO GRADIENT SYNCHROTRON*

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Summary

A description and relaying flow diagram presents the protection and monitoring system presently used in the 115 MW peak pulsed ring magnet power supply (RMPS).

Description of the Ring Magnet Power Supply

Knowledge of a system's design is necessary for an understanding of the protective circuits.[1,2] Figure 1 shows the general power supply and load arrangement. The water-cooled magnet octant coils and rectifier sections form a series sandwich system which minimizes the magnet coil-to-ground voltage. The main and exciter rectifier tubes are identical, single anode, continuously pumped, water-cooled, mercury arc excitrons. The 144 main rectifier tubes, mounted on 8 frames, supply the magnet current. Each frame has its own vacuum system, closed loop cooling water system, and heat-exchanger. Rubber hoses transport raw cooling water to and from these heat-exchangers.

Firing control switches all main rectifiers from rectification to flat-top, inversion, and standby, which completes a magnet pulse. It is done by inserting a variable dc bias voltage, obtained from the Zero Gradient Synchrotron (ZGS) main programmer, in the rectifier grid control circuits. The higher this voltage rises, the smaller the firing delay becomes. Inversion corresponds to a programmer bias of 0 V. The inversion circuits are an integral part of the RMPS and are not externally controlled.

Power to the rectifiers comes from 8 FOA rectifier transformers in parallel. Two transformers are enclosed in one common tank. A flywheel motor-generator (M-G) set generates power for the transformers at an average frequency of 50 Hz. A liquid rheostat controls the M-G set speed and is also used for dynamic braking. Both the motor and exciter receive power from a 13.2 kV incoming line.

The ZGS uses a large variety of magnet current pulses, depending on the experimental requirements. Some pulses have a simple triangular shape while others need two levels of flat-top (e.g., 100 ms at 5000 A and 400 ms at 9000 A). Pulse types often switch instantaneously from one to another. The pulse period is mainly determined by the rms current rating of 5100 A and is usually 2 to 4 seconds.

Protective Circuits

Figure 2 shows a functional protective relaying diagram. The tripping action flows in the direction of the arrows and the protective circuits are arranged in zones such as M-G set, magnet, etc. Actuation of a protective relay results in a complete shutdown (86EM, 86M), partial shutdown (86G, 86T, 5, 4), emergency invert (EI) or only an alarm. Loss of control power to a relay results in a trip. The following description is limited to the most interesting circuits.

The Motor-Generator Set

The motor, the generators, and the generator fields are protected via air circuit breakers. The generator field breaker (41) is electrically interlocked with field discharge contactor (41D), which closes before the breaker opens. A thyrite provides backup protection against excessive field voltage. The protective relays for the M-G set are divided into 3 groups: emergency shutdown (86EM), motor-rheostat trip (86M), and generators trip (86G). High bearing temperature, for example, results in an emergency shutdown (86EM) which deenergizes the motor, the generators, the pulsing bias; starts dynamic braking, closes the shorting switches, and takes a picture. A trip into relay 86G does the same, except for opening the motor breaker and braking.

Dynamic Brake

The ability to stop the rotating mass of the M-G set in a short period of time is of the utmost importance.

The M-G set can be stopped by means of dynamic braking, in which case a preset exciter output provides dc power to the motor stator. This generates a magnetic field in which the rotor turns and causes a resulting answer current to flow

*Work performed under the auspices of the U.S. Atomic Energy Commission.

through the rotor and liquid rheostat. The kinetic energy of the set dissipates there as heat, which is carried away by cooling water. This method of braking reduces the coasting time from approximately 2 hours to about 5 minutes.

Figure 2 shows a summary of the dynamic braking interlocks.

Any one of the following conditions prevents dynamic braking:

1. 52G1-b, 52G2-b, the generator breakers, auxiliary b-contacts are open.
2. 27F, the exciter output voltage, is above 100 V dc. A higher voltage produces excessive current.
3. 63FSY, the rheostat liquid flow, is below normal.
4. LSL, the liquid rheostat, is not in maximum resistance position. Maximum resistance is automatically obtained after a motor breaker trip.
5. 73T, the timer contact, is open. This timer trips dynamic braking 10 minutes after it is applied, and prevents overheating of the motor stator.
6. 86EM, relay contact, is open. This summation relay really determines when dynamic braking starts automatically under emergency conditions, such as loss of bearing oil flow, etc. These conditions are, of course, abnormal. This contact can be manually over-ridden by control switch CS73 when we desire to brake under normal circumstances.
7. 86M, relay contact, is open. This summation relay contact opens when a certain motor or rheostat protective device, in which case dynamic braking is undesirable, is actuated.
8. 69CS73 "SC" and 69CS52"SC" manual control switch contacts are open.
9. 52M-b motor breaker auxiliary b-contact is open.

Any one of the following conditions interrupt braking while it is in process:

1. CS73T and CS73/69T manual control switches,
2. 73T timer times out,
3. 63FSY inadequate rheostat liquid flow,
4. 26LR high rheostat liquid temperature, or
5. 27F exciter output voltage higher than 100 V.

Dynamic braking is not possible during loss of incoming power.

Main Rectifiers

Each tube has an arc back tripping circuit. The tube current flows in the reverse direction during an arc back and this signal is picked up via a current transformer and a diode. It also actuates an arc back counter which is a big aid for locating the failing tube.

Arc backs and arc throughs are our most common failures. An arc back is essentially a short circuit at the transformer secondary side and must be removed fast. A contact from a fast, over-excited mercury relay 32/1 switches the rectifiers immediately into emergency inversion before the generator breakers open. Another 32/1 contact backed up by a slower relay contact 32/2 trips into relay 86C.

Each main rectifier frame has an arc through tripping circuit.

The generator frequency appears across the output of a rectifier frame during an arc through. Tuned circuits, connected from each cathode to neutral, use this signal to start a trip. It takes about 3 cycles. Arc throughs are not so dangerous and we can sometimes ride through one. The slower circuits eliminate unnecessary trips.

Magnet Coils (See also under Invert Circuits)

Carbon spark gaps and high speed vacuum shorting switches protect the coils against dangerous high voltages. The shorting switches across the magnet coils and the rectifier groups close before the generator breakers open. The shorting switch control circuits provide a time delay of about 10 ms between the shorting of the rectifiers and the magnet coils. The gaps are set at 3 times the normal operating voltage of about 1500 V per octant. A setting of 2 times was used initially. The lower setting was unsatisfactory because of too many spontaneous gap breakdowns after previous arc overs. The intense energy discharge sublimizes some of the carbon gap material and deposits this as a small hill in the gap spacing. The gap setting is reduced by this phenomena. The reduced breakdown voltage is at present well above operating values, but came close to them with the lower settings.

A 2 MΩ resistor grounds the midpoint of two octant coils and is used for protection against ground faults. This resistor used to be 50Ω but the larger value assures better current balance in each octant.

A relay 76MC and a detector provide magnet overcurrent protection. The relay is slow. It cannot be set close because of the rapid change in magnet pulse types.

Exciter

The exciter protection is fairly standard. Anode breakers interrupt arc backs. Each tube has an arc back counter.

Invert Circuits

No RMPS system should do without emergency invert protection. Many system difficulties can be satisfied by removal and lockout of the pulsing bias, instead of a partial shutdown. The RMPS remains in a "ready" condition after an emergency invert and also the breakers receive fewer trips.

Emergency inversion (EI) can be started at any instant during a pulse by simply disconnecting the external bias.

Overcurrent can be caused by a failure of the programmer which keeps the RMPS in extended rectify and drives the current up at a rate of about 10,000 A per second. The overcurrent detector compares the instantaneous magnet current with preset levels of about 400 A (level 1) and 800 A (level 2) above the desired magnet peak current. An EI results as soon as the current exceeds the set value of level 1, while backup level 2 results in a trip.

The overcurrent detector is a solid state device of which both levels can be set easily with built-in helipot dials, because dial setting 9 corresponds to 9000 A, etc. Protection against overcurrent was originally from limit switches of the magnet current recorder, but the slow recorder was hard to set and could not keep up with the varying pulse shapes. An optical meter relay was also unsuccessful for the same reason.

A similar fast way of overcurrent protection is provided from the ZGS main programmer via the magnet high field detector.

The overcurrent detector would never detect an extended flat-top, but this condition reduces the M-G set speed below the normal maximum 7% drop and actuates underspeed relay 14M.

The magnet cooling protection consists of pressure switches, leak detectors, and temperature detectors (Klixon), summed up in relay WL1.

Alarms

The rms value of the different magnet current pulses is hard to determine from standard instruments. The same is true for the generator field current which changes with the magnet load and program. We measure the rms current with a transductor that puts a fraction of the current through a precision resistor mounted in an oven. The resistor temperature rise above ambient heats thermocouples, whose output voltage is amplified and put on a meter. The heat capacity of the precision resistor is large enough to insure that the individual current pulses do not move the meter, which makes the system slow. A preset "level detector" gives an alarm for loads in excess of 100%.

Generators' excitation ground faults are detected with a 2 MΩ resistor and a meter relay in a bridge arrangement.

The overload and ground alarms have been added recently.

Lubrication System

The loss of oil flow through the M-G set bearings is disastrous and good protection is therefore required. High pressure oil lift pumps press oil underneath the bearing journal during starting. A shaft pump supplies oil under normal conditions. Backup protection is provided by a 20 hp ac pump, which is automatically transferred to a 60 Hz emergency diesel generator set in case of a complete power failure. This emergency diesel is for general use. A 20 hp dc pump, fed from the RMPS station battery, provides a second backup. This battery has enough energy to supply sufficient oil during 1-1/2 hours. A 25-kW diesel generator and a 5-kW motor generator start automatically when ac power is lost and keep the battery charged.

Monitoring

The temperature of the M-G set stator, bearings and plenums, are printed out on recorders. The more or less standard array of recorders, meters, and gages indicate currents, voltages, pressures, temperatures, vacuum conditions, etc.

Optical and electronic devices stationed along the M-G set shaft are used as shaft twist detectors. They compare the positions of engraved markings on steel bands, mounted at four shaft locations. The markings line up under no-load conditions and separate proportional to the shaft torque. The twist is measured in both shaft sections from the flywheel to the generators.

The relays are grouped into similar type functions and operate a central annunciator. This helps the operators to locate difficulties faster.

Voltage dividers are a must for troubleshooting and understanding of machine behavior. Fused, 100/1, 2 MΩ voltage dividers are connected to various points as can be seen in Fig. 1. There is one voltage divider for every six rectifier phases, but one per phase would have been more convenient. A few selected voltage divider signals are differentially displayed on dual beam oscilloscopes. A camera, mounted at the scope face and triggered during a trip, can take a picture of the near history because every scope retains the displayed trace for a short while. This method of monitoring can be very helpful for troubleshooting.

Voltage dividers of 10/1 would have been a better choice because of the higher signal to noise ratio. The noise becomes greater when the dividers are farther apart.

Plans, Inspections, and Miscellaneous

A system of vibration detectors at the M-G set bearings is being developed. It will be hooked up to the EI or relay 86EM circuits.

We plan to use an infrared temperature meter for observation of the temperatures of rotating parts. The instrument will be triggered and monitor only when the point of interest is in front of the lens. The system is still under development and the primary goal is to observe deviations from normal operating temperatures.

Humidity detectors and steam control the moisture level around the motor and generator brushes. The brush wear increases rapidly during extreme dry conditions. All protective devices and components are checked and maintained on a regular basis. The M-G set shaft, poles, and other critical mechanical parts are regularly inspected for cracks with ultrasonic equipment. It is worthwhile to do this because pulsing goes hand in hand with high mechanical stresses.

Table of Typical Operation

M-G Set Speed	777(51.8 Hz) drops to 735 rpm	
Magnet Current Rise	10,300 A/sec.	
Magnet Current Decay	10,300 A/sec.	
RMS Magnet Current	5000 A	
Magnet	21.5 kG at 10,000 A	
Aux. Transf. Tap	8 or	9
Aux. Transf. Sec.	230 V	230 V
Generator Output	8640 V	9120 V
Rect. Transf. Sec.	1190 V	1257 V

References

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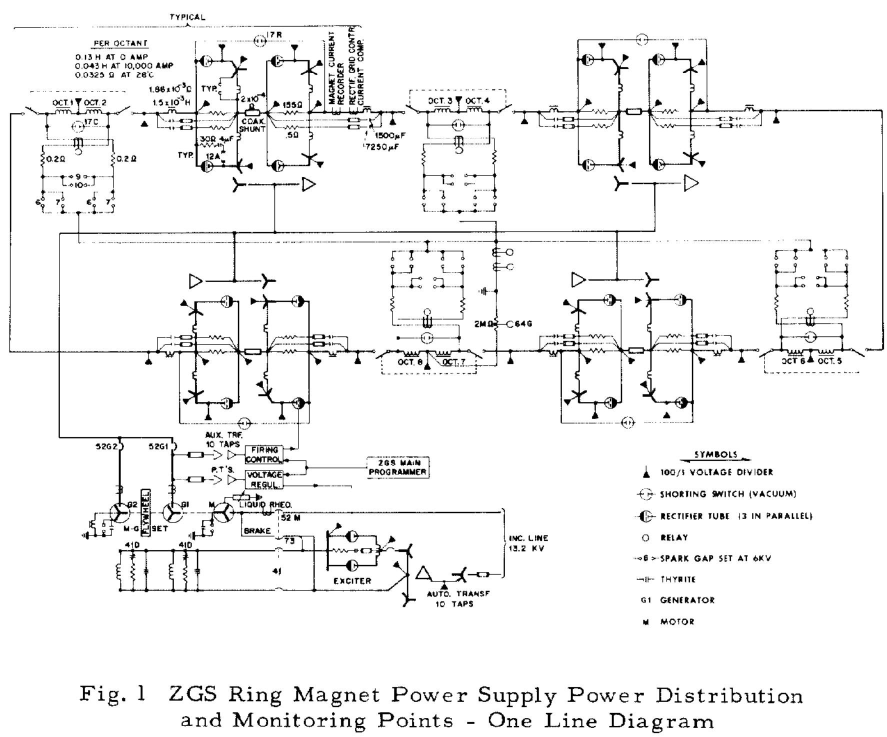

Fig. 1 ZGS Ring Magnet Power Supply Power Distribution and Monitoring Points - One Line Diagram

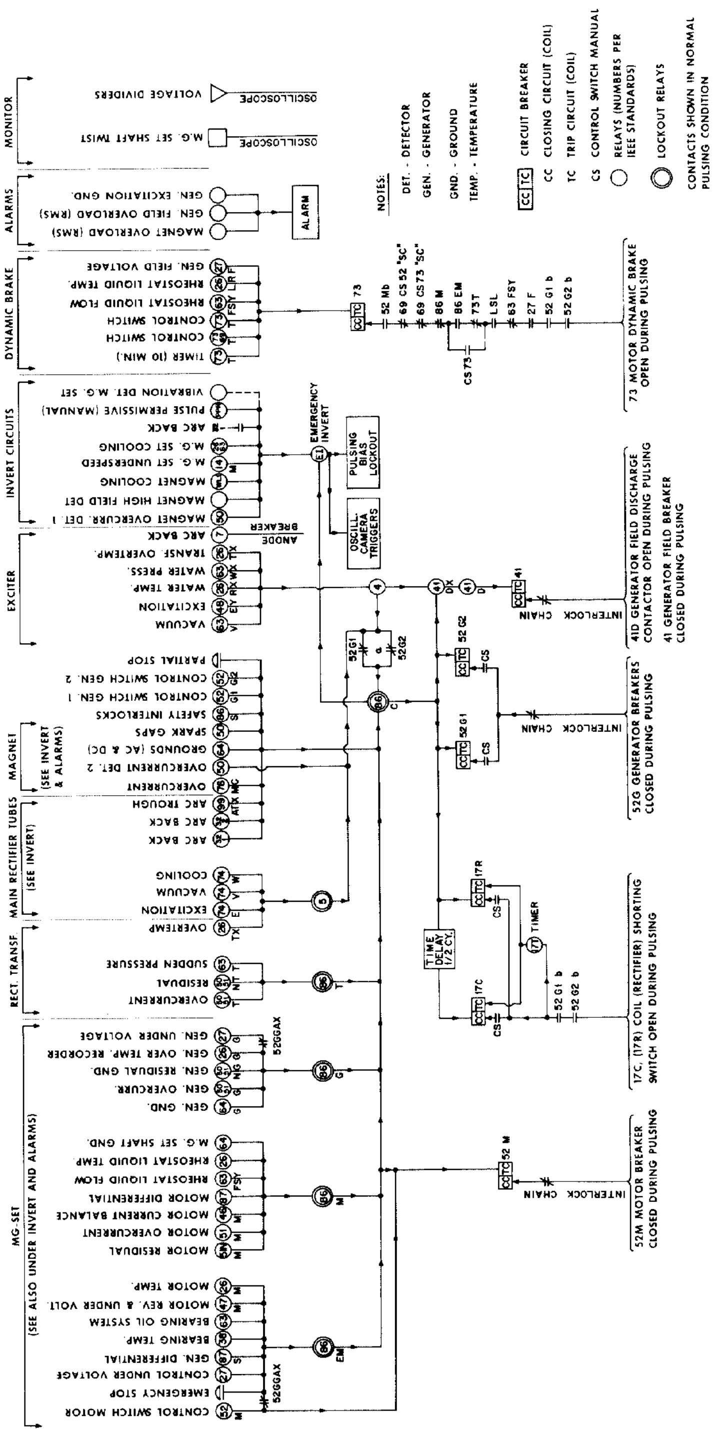

Fig. 2 ZGS Ring Magnet Power Supply Protective Relaying Functional Schematic