IMPROVEMENTS IN THE ZERO GRADIENT SYNCHROTRON (ZGS) MAIN MAGNET COIL PROTECTION*

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Summary

Two main coil failures in a one-year period initiated a review of on-line protective circuitry. Two existing circuits, which would limit damage, were made more reliable. Four new circuits were added to monitor coil condition and protect against voltage transients.

Introduction

After a few button-joint failures early in the life of the ZGS main coils, the coils performed well for many years. On April 21, 1970, after 41 million pulses, the octant 2 coil failed with layer-to-layer and layer-to-kicker plate shorts, as shown in Fig. 1. The spare coil was installed in about eight weeks, and the accelerator resumed operation.

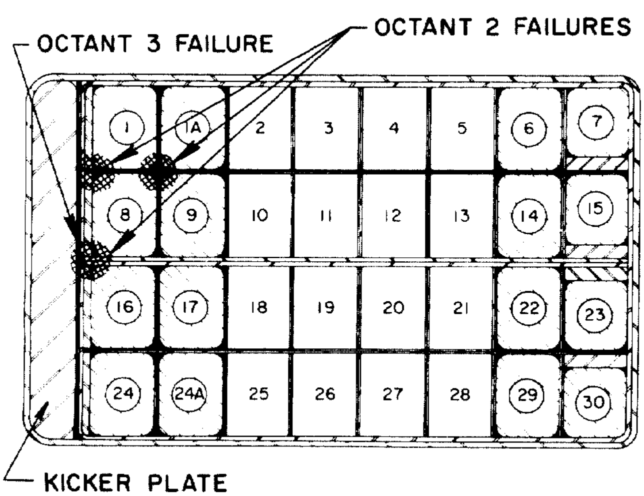

Fig. 1 ZGS Main Coil

On January 9, 1971, after 45 million pulses, octant 3 coil failed in a manner similar to octant 2 coil, except that the damage was less extensive, being concentrated between the outer turns and the kicker plate.[1] This damage was repaired with an ingenious technique and, again, operation resumed successfully.

The attitude after the first coil failure was that it was caused by circumstances peculiar to coil No. 2, and no extraordinary response was called for. However, after the second failure only seven months later, it was felt that some systematic failure mechanism might be in progress which should be understood and, if possible, corrected.

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The response was twofold. Firstly, the Operations Group was asked to review existing coil protective circuits and develop new ones to sense impending trouble, or at least minimize the damage if trouble occurred. Secondly, an investigating committee was appointed from persons totally independent of machine operations to seek the cause of our problems. This committee's findings[2] led the Operations Group to add certain circuitry and to greatly increase our off-line testing as described in a companion paper.[3] This paper describes the modifications to the on-line protective circuitry.

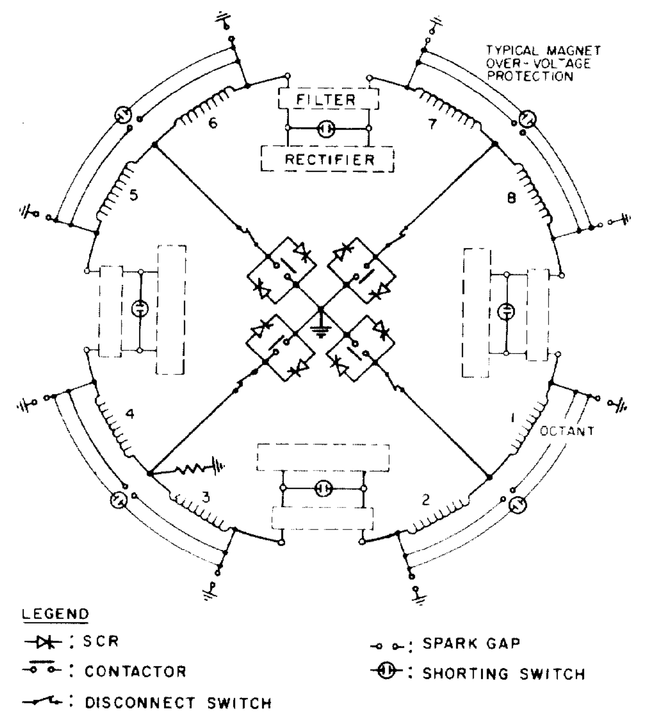

Fig. 2 ZGS Main Coil Circuitry

Existing Circuitry

Figure 2 is a schematic of the ZGS main coil. Power to the ring magnet is added in four locations to achieve a potential distribution as shown in Fig. 3. Note that there are eight points of nominally zero potential to ground. One of these points is tied to earth ground through a resistor, and ground current is monitored here. A most important point to note is that this potential distribution is only symmetrical when:

1. Potential is added symmetrically and
2. one of the zero points is tied solidly to ground.

The size of the ground resistor was initially 50 Ω. Sometime in 1966, this resistor was changed to 2 MΩ.

Since there are numerous leakage resistances two orders of magnitude lower than this resistance, the system was essentially floating and not perfectly balanced. In fact, the trip devices that sensed ground current flow took about 700 V to trip; more than half the turns in a coil will never reach that voltage under fault conditions. While this was questionable practice, it does not seem to have contributed to our failure.

Our modification of this circuit had to be a compromise between our desire for a solidly grounded reference point for protection purposes and the fact that, like all weak-focusing accelerators, unbalanced leakage currents cause large warps in the proton beam orbits. The action taken was to ground the ring through a 1-kΩ resistor (an order of magnitude smaller than any single leakage path) and make sensitive (33 V at 33 mA) but slow (0.6 s with 33 V applied) protection circuits. With this sensitivity, all but one of the turns in an octant was protected and yet the slowness of the response has kept spurious transients such as excitron arc-throughs from falsely tripping the ground protection.

The other existing protection circuit was detection of ground current flow to the kicker plate. Trimming of individual octant fields is made by current in this plate. Referring to Fig. 1, the reader will note that this stainless steel plate is inside the main coil ground insulation wrap. Spring loaded, electrically insulated anchor bolts attach to the kicker plate to hold the main coil in place when it tends to deflect due to the magnetic forces during pulsing. Since there are 286 anchor bolts on every octant, ground failures are common. The size of this plate creates a capacitance to the grounded magnet iron of ~ 60 nF.

These kicker ground detection circuits were disconnected from the ring magnet power supply (RMPS) interlock circuit because they caused too many "false" trips. The "false" trips were probably capacitively coupled ground currents during RMPS transients. Indication of these kicker faults was made inside the accelerator building, and tripped circuits were logged and reset once a day. Only when the same circuit tripped repeatedly was further action taken.

Examination of the damaged coil indicated the possibility of turn-to-kicker plate shorts before turn-to-turn shorts occurred. If that was the case, main coil voltage would have forced kicker ground current. Thus, on-line kicker ground protection circuits might have limited the damage. On this thesis, kicker ground detection circuitry was devised that had two levels of protection. The most sensitive level was to alert operating personnel to monitor the ground current flow. These current signals were sent back to the ZGS Main Control Room (MCR) through multiplexing circuitry. The less sensitive level was interlocked to shut down the RMPS when the kicker ground current became large enough to create significant orbit distortions. Dual set point meter relays were put inside a diode bridge to get bipolar dual level protection. These circuits have worked admirably; almost every ground indication has been real and nuisance trips have been few.

New Circuitry

High Frequency Transient

The main body of evidence of damage pointed to a layer-to-layer short; but whether caused by overvoltage, local resonances, corona damage, water blockage, etc. is discussed elsewhere.[2] High frequency studies of the main coil located a resonance at about 84 kHz, which would provide a nonlinear potential distribution within the coil at this frequency. The RMPS filters and buswork were found to be capable of transmitting such frequencies, but no evidence for their existence in the RMPS voltage was established.

In response to this, the RMPS filter buswork was rearranged to make it less transmissive at high frequencies and local high frequency filters were added at each octant to bypass such transients.

Octant Balance Bridges

As an extension of the technique used on our dc extraction magnets, we have installed bridges to compare the voltage of the upper half of an octant to the voltage of the lower half. During periods when $\frac{dB}{dt} \neq 0$, autotransformer action insures inductive balance of the upper and lower halves. The circuit is most sensitive when current is maximum, and that is on magnetic flattop. This circuit identifies either current unbalance (by shunt paths) or resistive unbalance due to unequal cooling between upper and lower halves of the magnet. The main difficulty in constructing this circuitry resulted from the necessity of maintaining high voltage isolation for the safety of equipment and personnel. The circuit is interlocked to shut down the RMPS when a 0.2% resistive unbalance occurs. This would result from a one-turn excess temperature rise of 7.5°C. The circuit response time is 0.25 s.

Octant-to-Octant Comparison

Measurement of the Q of an octant at its parallel resonant frequency is a sensitive method for monitoring for leakage paths between turns or layers. This, of course, is difficult in an on-line manner. A sensitive method that can be performed on-line is the comparison of the induced voltage in two different octants. Circuits were built for this comparison which trip off the RMPS when a 100 A-turn unbalance lasts for 10 ms. This is equivalent to a 30-Ω shunt path between adjacent layers of the coil. While the proton beam would have disappeared long before the insulation degraded to this extent, the beam's existence depends on so many diverse factors that it's a poor indicator of magnet quality. Off-line testing will catch the insulation degradation before it gets this bad. However, sudden changes might be missed by off-line methods. The above circuit should prevent us from repeatedly pulsing into a partially faulted magnet coil.

Phantom Ground Clamps

With the exception of the transient filter modification, every other modification or addition has been to detect and limit damage after it has occurred. The last and most significant system to be described, the phantom ground transient protection system, is primarily preventative.

Certain types of RMPS faults initiate the closing of the vacuum shorting switches shown in Fig. 2. The shutdown timing sequence of these switches leads to the potential distributions as illustrated by Fig. 3. Relative changes in the timing of one switch to another of 2 ms could produce not only high voltages to ground as shown, but high turn-to-turn voltages. Arc faults in the rectifier power supplies and operation of protective spark gaps produce similarly distorted potential distributions. To eliminate this problem, a system was needed which could maintain the nominal zero potential points (phantom grounds) in the presence of applied voltage dissymmetries.

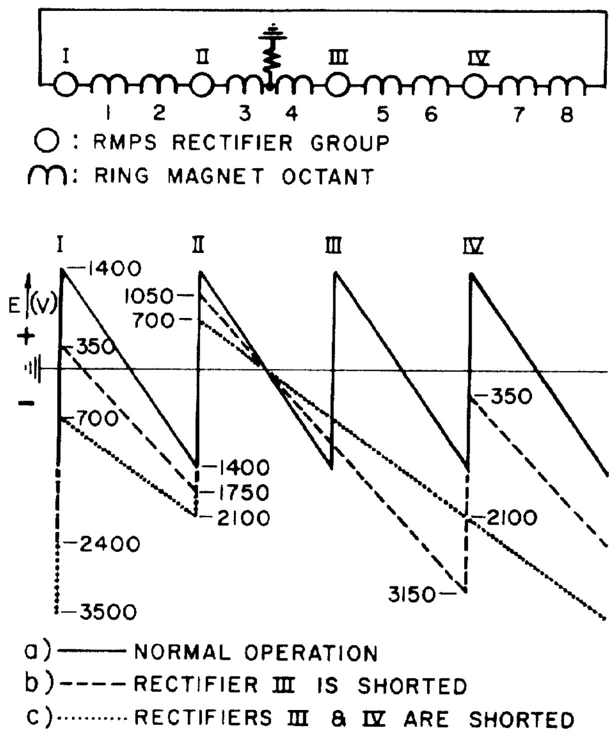

Fig. 3 ZGS Main Coil Potential Distribution

Inverse parallel SCR's capable of carrying 10,000 A for 1 s were installed at each of the three ring magnet phantom ground points and in parallel with the 1-kΩ ground resistor. Contactors rated 5000 A are connected in parallel with the SCR's. When the protective circuits of the RMPS detect a fault likely to cause a potential dissymmetry, the SCR's are gated on before the voltage transient occurs. The contactors close some 80 ms later to transfer most of the current from the SCR's.

The SCR's are also gated on automatically when any one phantom ground point changes by more than ± 300 V with respect to ground. Zener diodes conduct at this voltage, triggering the gate circuits. This firing is detected by current transformers which in turn trigger circuitry that sustains the SCR gate voltage and gates on the other three SCR circuits within a few microseconds. The SCR gate drive is sustained with a transformer coupled 10-kHz square wave signal. Appropriate memory circuits indicate which SCR bank fired first. A more detailed description of these circuits may be found in another publication.[4]

This system is so successful that it detects phantom ground potential rises due to excitron tube faults that are not detected by the tube diagnostics. This, of course, means a small loss in operating time; but it is a small price to pay for the increased protection.

Conclusion

While the cause of the ZGS main coil faults is not positively known, the increased on-line surveillance equipment should limit the damage if it ever occurs again. Transients and excess voltages in emergency shutdown situations are possible causes, and they have been largely eliminated.

Acknowledgments

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