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DOUBLER-TEVATRON μP QUENCH PROTECTION SYSTEM

Robert H. Flora and Gerald S. Tool*†

SUMMARY

1014 superconducting magnets, distributed around a four mile ring and storing a total energy of 1/3 GJ, are to be protected by six microprocessor monitors. During a quench, the monitors initiate global shutdown and selectively activate individual protection heaters. During normal operation, they actively test major protection components for proper operation and aid in the cooldown and warmup process. The high priority safety scan assembly language programs are time sliced with the low priority BASIC language operator and central computer inferface programs. The monitors themselves are continuously checked for proper operation by "heartbeat" detectors.

INTRODUCTION

The superconducting magnet system of the proposed Energy Doubler 1 TeV synchrotron consists of a series circuit of 774 dipoles and 240 quadrupoles distributed around a ring of 1 km radius.[1] This magnet will be repetitively excited from 500 A to 4300 A as often as 3000 times daily. Inadvertent quenches will occur in the superconductor due to eddy-current heat generation caused by this cycling and due to beam interception by the magnets. A highly reliable system is required for detecting quenches early in their development and for removing the stored energy from the quenched superconductor.

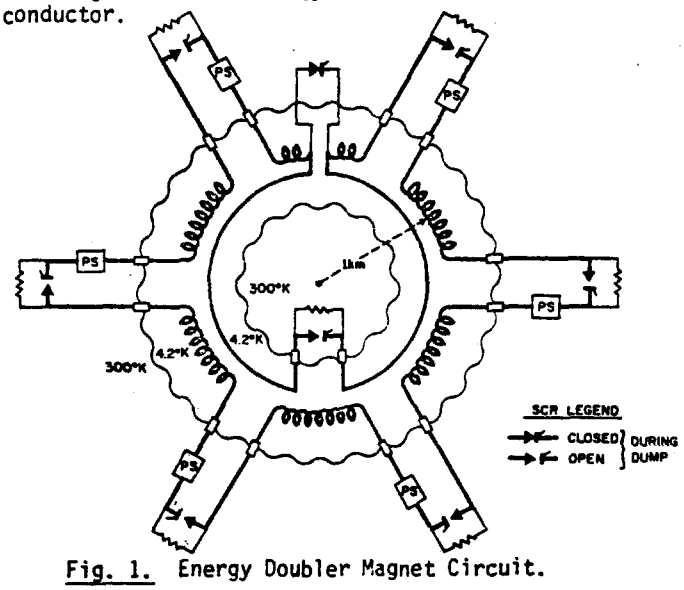

Fig. 1. Energy Doubler Magnet Circuit.

The Tevatron ring is logically divided into six sectors as shown in Fig. 1; each sector has an energy transfer power supply, an energy dump system, and a microprocessor monitor. The magnet string in each sector is further divided into half-cells which are also considered as quench protection units (QPU). A typical protection unit shown in Fig. 2 consists of four dipoles and a quadrupole. Moderate sized connections to the magnets called safety leads exit the cryogenic system at the ends of each protection unit for the purpose of diverting the magnet ring energy around any QPU which is quenching. These safety leads also serve as monitor taps for detecting resistive voltage drops in the magnet string which indicate the beginning of a quench.

*Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.

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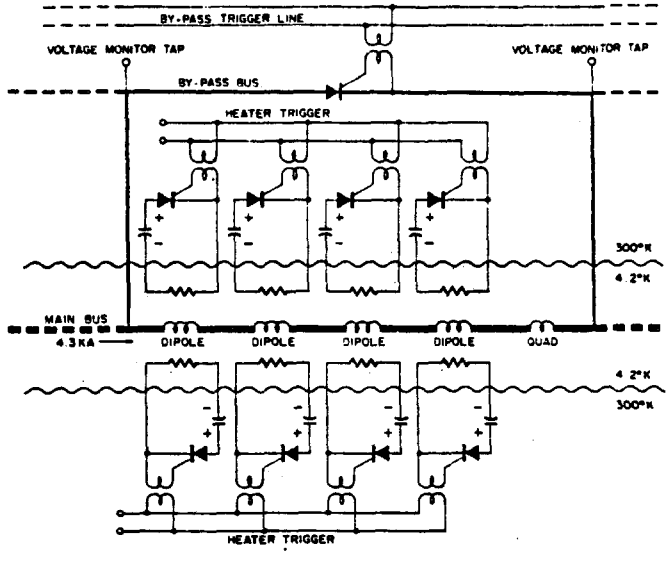

Fig. 2. Quench Protection Unit.

Each microprocessor monitors thirty-three of these protection units and a collection of analog signals and external interlocks as indicated in Fig. 3. The primary output from the microprocessor is a single signal which permits the power supply operation and inhibits the energy dump system until a quench or other abnormal condition occurs, at which time the power supply is turned off and bypassed, and the energy dump system is activated.

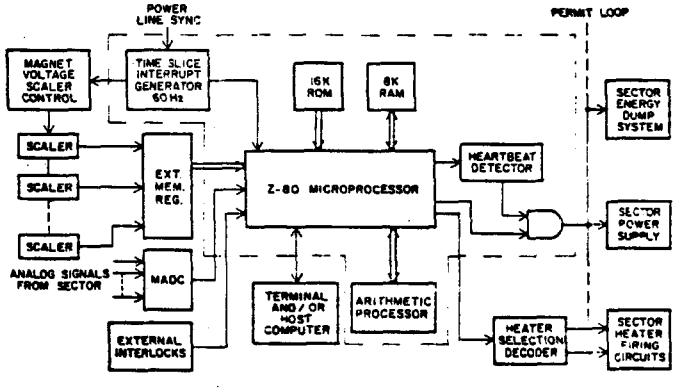

Fig. 3. Microprocessor System Block Diagram.

QUENCH DETECTION

Voltage taps are provided between each of the 198 quench protection units around the synchrotron (Fig. 4). These voltages are transmitted through hazard isolation resistors and cables up out of the radiation environment of the tunnel, to the service buildings on the surface. Because the hazard isolation resistance is comparable to the measurement circuit input impedance, each channel is coupled to its neighbor, however, decoupling is accomplished in the μP safety scan.

The safety scan is a line-frequency interrupt driven firmware module which is given primary real-time safety responsibility for the magnet system (Fig. 5). It uses the known inductance, L_u, and the measured ramp rate, $\frac{dI}{dt}$, to find the expected inductive voltage for each protection unit. The amount by which the measured

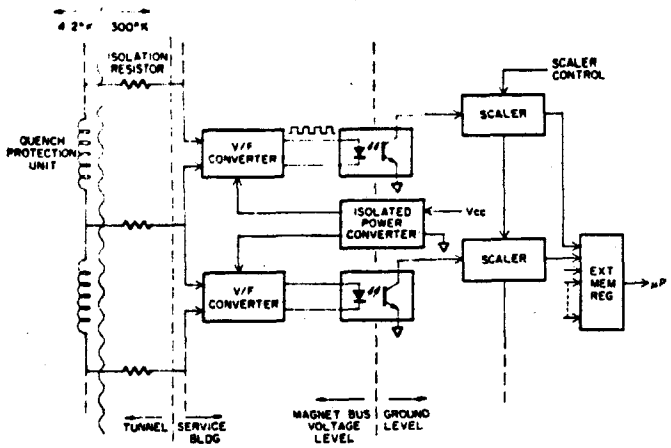

Fig. 4. Voltage Measurement Circuit.

voltage exceeds the inductive voltage, $V_u - L_u \frac{dI}{dt}$, is an indication of resistive voltage. When this exceeds a nominal noise threshold of ~ .2V, a quench is indicated in that QPU, and the emergency dump sequence is initiated.

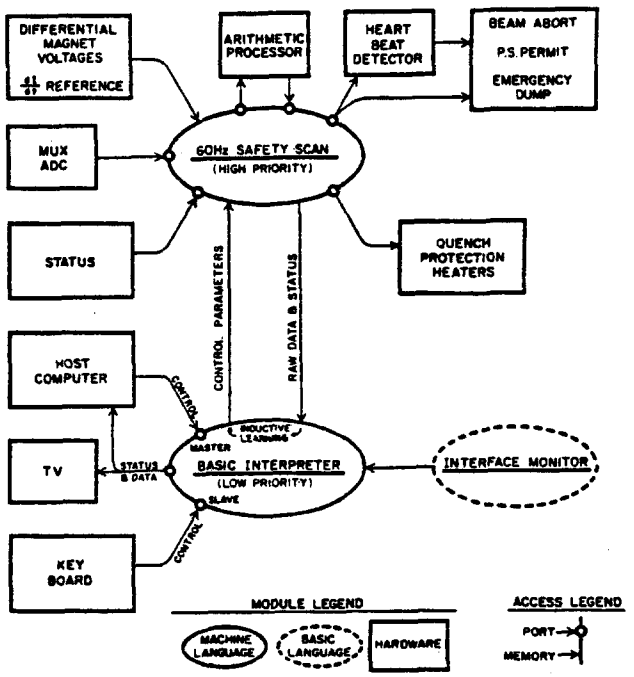

Fig. 5. System Communication Map.

The operational integrity of the safety scan is ensured by the requirement that it turn on and then off, under firmware control, a special "heartbeat" bit before the time out of a retriggerable one-shot adjusted slightly longer than one interrupt cycle. Should it fail at this task, an emergency dump sequence would be initiated automatically.

QUENCH PROTECTION

The proton beam is aborted when a quench is detected to prevent additional beam-induced quenches. All power supplies are turned off, and six 0.5 ohm energy dump resistors are commutated into the main magnet bus circuit as shown in Fig. 1. This allows the stored 1/3 Gigajoule magnetic field energy to dissipate with a time constant of 11 sec, even if the main ac power fails. A similar resistor is commutated into the return bus circuit, bringing its current down in about 0.15 sec, ensuring complete protection of the return bus. The main bus current is bypassed around the return bus by an additional SCR at the top of Fig. 1.

Low current operation is safely protected by the 11 sec dump, however, magnet protection at high current must include additional measures. Damage to a magnet will occur after only 7×10^6 A^2 sec. Each bypass SCR in every protection unit is gated on to allow the main coil bus current to continue around the QPU, if necessary. The heaters in every unit that quenches, and only those that quench, are fired by the safety scan. The heaters ensure rapid and even dissipation of the internal QPU stored energy.

SUPERVISORY FIRMWARE

A specially developed BASIC interpreter and control monitor, which run asynchronously and at a lower priority than the safety scan, are responsible for setting up safety scan parameters, analyzing statistics, reporting status and in general, communicating with the operator, either directly or via a link with the central host computer.[2] During system start up, the control monitor helps the safety scan to gradually learn the in-situ apparent inductance of each quench protection unit. This feature increases detection sensitivity and spurious rejection.

The control monitor is also responsible for coordinating in-situ proof testing of all active protection components and setting up the safety scan to monitor special magnet cooldown or warmup procedures.

MICROPROCESSOR HARDWARE

The 8-bit Z-80 microprocessor and closely-associated circuitry shown inside the dashed line of Fig. 3 are housed in a standard 2-wide NIM module. Other low-level parts of the system are contained in additional standard NIM modules. Timing is based on detecting zero-crossings of the 60 Hz line terminals available at the NIM power connector. The resultant safety scan once every 17 ms is well-matched to early detection of a developing quench and allowance for sufficient firmware processing.

A separate AM-9511 arithmetic processor is included to reduce the time required to perform arithmetic operations during the safety scan. It is configured as a pair of I/O ports with the capability of causing the Z-80 to pause for completion of the processor's operation if it has not been completed by the time the Z-80 code requires the results.

A special 1-wide NIM module 12-bit MADC has been designed for optimum hardware/software coordination in this application, minimizing the time required for scanning analog signals. These signals include magnet current, voltage-to-ground, and voltage drops across the vapor-cooled power leads that bridge the transition from room temperature power supplies to the cryogenic magnet string.

As indicated earlier, upon detection of a quench, the heaters in magnets belonging to the quenching protection unit are energized by discharging capacitors into the heaters. Heater activation is a serious measure; the identity of heaters to be fired must be determined precisely. The Heater Selection Circuit decodes heater firing commands from the microprocessor, demanding a "key" sequence of commands in order to fire a heater circuit.

The interface to a terminal or host computer is implemented using a standard serial RS-232 full duplex connection. A full range of baud rates is available to

interface with a large variety of terminals.

The most important inputs to the microprocessor are the magnet voltage measurements. A differential voltage of more than 60 V full scale must be measured with a resolution of approximately 50 mV at an isolation voltage up to 2000 V. Thirty-three such channels must be provided for each sector's microprocessor. An expanded schematic of the technique to be used for this measurement is shown in Fig. 4. The isolation resistor and single cable per channel protect against ground faults and personnel hazard.

A voltage to frequency converter is used to convert the analog signal, at the elevated magnet string potential, to a single digital signal per channel which is easily transformed to ground level using an optical isolator. These digital pulses are counted for a predetermined length of time, i.e., the time slice interrupt period, and then latched into a register located directly in the processor memory space. This provides differential sensitivity, high-frequency noise reduction and line-related noise cancellation due to the inherent integration over one line cycle, measurement simultaneity, 12-bit resolution (at 250 kHz) and inherent direct memory access. The reference $\frac{dI}{dt}$ signal is obtained in a similar manner to correct for line frequency variations.

OPERATING EXPERIENCE

Two generations of prototype monitors have been constructed and used. The first generation utilized an array of commercial pc cards and served to test our initial concepts. The second generation utilizes NIM packaging and a locally designed circuit card, but still uses a commercial card housing the CPU, memory and some I/O decoding. Three copies of this version are in use; one of them is connected to a string of twenty-five superconducting magnets installed in the "A" sector of the Fermilab accelerator, just as final Energy Doubler magnets will be installed.

The installation and operation of this magnet string is known as the Mini-Sector Test. The magnet string has been cooled to the superconducting state, powered to the eventual injection level and operated with injected beam for three separate study periods. This string utilizes all aspects of the quench protection system except heaters and quench bypass switches. These are not required at injection energy. The microprocessor system and associated quench protection equipment have operated very well during these tests, detecting magnet quenches induced by beam hitting the magnets, and removing the energy to allow for quick recovery. One false unexplained trip indicating an overvoltage on a power lead has occurred.

The present prototype system utilizes a voltage-divider to ground measurement and multiplexed A/D converter system rather than the differential v-to-f technique described in this paper. The present technique is adequate for tests in which we are now involved, but the differential scheme under development will provide an order of magnitude improvement in sensitivity which is needed for eventual reliable high energy operation.

A second copy of version two has been implemented to protect a 4 magnet string in the quench protection test facility. In this string test, the heater operation has been tested at full magnet current and the magnets have successfully dissipated their own internal energy with no difficulty.[3]

Third generation microprocessor hardware using all locally-designed pc cards to optimize performance/size tradeoffs and increase the memory capacity of the system is in development.

ACKNOWLEDGMENTS

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