UCRL 15097

P.O. 4163409

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QUENCH DETECTION

AND

MAGNET PROTECTION STUDY

FOR MFTF

LLL FINAL REVIEW

JUNE 1979

MASTER

IGC REPORT No. 679-7

SUBMITTED TO:

LAWRENCE LIVERMORE LABORATORY

LIVERMORE, CALIFORNIA

SUBMITTED BY:

INTERMAGNETICS GENERAL CORP.

GUILDERLAND, NEW YORK

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FOREWORD

This report covers work sponsored by the University of California, Lawrence Livermore Laboratory, under Purchase Order 4163409. The Lawrence Livermore Laboratory Project Engineer is Daniel W. Shimer. The Program Manager of the study is Dr. Michael J. Hennessy.

Acknowledgement is also due to the many individuals at IGC whose skills have been essential in preparing this study, including Dr. R. T. Woods, A. W. Heintz, and R. F. DiGesare.

This report covers work performed for the period January 1, 1979, through June 29, 1979, and the report was submitted July 2, 1979.

ABSTRACT

This report summarizes the results of a Quench Detection and Magnet Protection Study for MFTF. The study was directed toward establishing requirements and guidelines for the electronic package used to protect the MFTF superconducting magnets.

Two quench detection schemes were analyzed in detail, both of which require a programmable quench detector. Hardware and software recommendations for the quench detector were presented in the report as well as criteria for dumping the magnet energy in the event of a quench.

Overall magnet protection requirements were outlined in a detailed Failure Mode Effects and Criticality Analysis, (FMECA). Hardware and software packages compatible with the FMECA were recommended, with the hardware consisting of flexible, dedicated intelligent modules specifically designed for magnet protection.

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1.0

BACKGROUND

In the past, superconducting magnets have been inadequately protected.¹ The natural inclination is to over-react and to dedicate a large computer system with comprehensive software to handle the entire task of magnet protection. An approach such as this is undesirable. Inadequate protection instrumentation can obviously lead to magnet devastation, and large computer systems can become expensive, complicated, and, more importantly, can be unreliable. A more sensible, reliable and effective solution to the problem of magnet protection utilizes intelligent microprocessor instrumentation, which provides inexpensive dispersed signal processing and simple local control. It has been this application of microprocessors that has enabled Intermagnetics General Corporation and others to streamline this difficult but important protection task.

In the complex MFTF system, magnet protection is of utmost importance and crucial to the value of the entire project. Obviously, the time available for plasma experiments is directly related to magnet reliability and performance, which, in turn, requires an electronic-protection design that is conservative, highly effective, and easily maintained. Electronic components often fail. The ease of getting back on-line in the event of a component failure is related to the degree of modularity, the use of standard hardware, and diagnostic capability designed into the system. The present study is based on these ideas as well as IGC's experience in magnet protection for commercial superconducting magnets² applied to medicine and plasma physics, a recent example being TRW's Prototype Magnet System (PMS) where the end user of the magnet need not necessarily be an experienced superconducting magnet operator.

2.0

DESIGN PHILOSOPHY

The ultimate reliability of the MFTF magnet system will be determined by the stability of the superconductor and magnet as a whole as well as the sensitivity and lifetime of the protection circuit components. Important design guidelines used in this study reflecting an emphasis on both reliability and simplicity are:

- Critical circuit paths should be simple with the number of components along each path minimized.
- Programmable or selectable features should be either hard-wired or contained in read-only-memory (ROM).
- Critical circuit paths should be periodically tested and monitored.
- Circuitry should be modularized for ease of maintenance and, wherever possible, interchangeable stand-alone modules should be used.
- The system should be interlocked, protecting the system from any possible operator error.
- All outside interfaces should be isolated and decoupled to prevent false triggering of the logic by noise.
- The protection system should be sufficiently independent to survive an LLL computer failure, a power supply failure, and a facility main-power-service failure.
- Redundancy should be included in the system so that a single component failure in the protection system will not alter the effectiveness of the protection system and endanger the magnet.
- Self-testing during power up or after a magnet energy dump should be a requirement.

- Diagnostics should be included in the system so that problems may be pinpointed by either real time readout or by recording what the status of the system was at any time before or during system failure.

The importance of establishing a solid design is underlined by the fact that, if a quench occurs and goes undetected or the protection circuits fail, the magnet could be damaged. Also, if the fast dump circuitry trips falsely, the magnet would be needlessly de-energized, dissipating helium and resulting in down time.

In the next sections, specific detailed guidelines are given for the design of the MFTF protection system, emphasizing the criticality of the protection task.

2.1 Reliability

Below are listed the specific guidelines associated with design reliability --an important requirement in the overall design philosophy recommended for MFTF. It should be noted that all reliability requirements can be met with commercial, off-the-shelf hardware.

2.1.1 System Design

The general guidelines for the system design should include minimization of the number of components along critical paths, especially along paths between the quench detectors and 6000 Amp circuit breakers. Reliance on only a single component, especially a microprocessor, for a critical function should be avoided. Redundant circuitry and busses should be included where necessary to avoid having the entire system dependent on a single element.

2.1.2 Pretesting

To overcome infant mortality failure, all parts installed in the system should be burned in for at least 100 hours. This will

insure that most failures due to defective components, especially IC's and transistors, will be identified before helium is committed. A useful device to be used for this pretesting of the entire system is a magnet simulator, a piece of test equipment designed to simulate magnet sensors and voltages as they would appear in the cooled magnet.

2.1.3 Testing

While the magnet system is being energized or after a quench, the protection system should be designed to activate self tests for insuring the integrity of the hardware. For example, the quench detectors should be put in a test mode to verify that the input amplifiers are working. (Other tests are enumerated in the foregoing sections.) These tests will be valuable in maintaining the system integrity over a long period of time and will pay for themselves by increasing the mean time between operational failures. If tests do not pass, the normal response should be to lock up the current controller so that the magnet cannot be charged or, if charged, that it is automatically discharged to zero current. Details of how this philosophy is incorporated in the design will be discussed in subsequent sections.

2.1.4 Interlocks

The basic guidelines for interlocks should be that interlocks be provided so that (1) the operator cannot damage the magnet through any manipulation such as inadvertent testing, or (2) the system cannot be operated unless the system has been fully connected and tested.

2.1.5 Diagnostics

If the magnet system fails, it is extremely important from a reliability standpoint to know exactly what the conditions were

prior to and at the time of failure. The purpose of the diagnostics is to reconstruct events leading up to the magnet energy dump since there is inevitably a question as to whether a dump was caused by a real quench or by extraneous circumstances. Adequate memory, therefore, should be provided to read out the conditions of the system at any time before a critical transition has occurred. This event recording capability or "snapshot" capability should be built into the entire system. Examples of information that should be recorded are relay and valve positions, bus conditions, and magnet current and tap voltages before quench.

2.2 Simplicity

One of the most important factors that affects system reliability, cost and performance is simplicity. To achieve maximum simplicity, the following guidelines are recommended.

2.2.1 Local Intelligent Instrumentation and Control

When computer intelligence is required, the intelligence should be segmented as much as possible into single, straightforward tasks that can be handled by a dedicated microprocessor. This keeps the software simple, makes the entire system easier to debug and maintain. For example, in the MFTF, a large task like quench detection can be partitioned into relatively simple tasks among several dedicated microprocessors. Microprocessors have the advantage of being simple, interchangeable and independent to the degree that, if one fails, others can continue looking for normal zone formation without interference. Each intelligent instrument should also have provisions for self-test on command, which will reduce the complexity of a complete system test to that of assessing the condition of each independent module.

2.2.2 Interconnection

Between modules, the system should include a non-critical communication bus for diagnostics testing and transmission of

non-vital information, and a separate bus for critical tasks such as dumping. Each critical bus should be accompanied by a redundant bus for extra reliability. Each critical bus should be kept completely independent of all the other busses and flow through separate IC's with no interconnection between them. This redundancy should be carried as far as possible even to the inclusion of redundant breakers. This independence insures complete redundancy and thus enhances overall system reliability. The busses should be standardized for all units so that the modules can be interchanged and, if necessary, expanded.

2.2.3 Modular Approach

Modules should be used as much as possible to simplify and reduce cost.

2.2.4 Inputs

Inputs to the protection system should be either single contacts, as in the case of relay or valve positions, or transistor drivers capable of driving LED's. Each instrument, such as the helium level indicator, should have a single bit output indicating above or below a settable low limit threshold. Continuous reading of variables like the helium level could be provided for data logging but is not required for quench protection hardware. Only a single threshold output from each instrument is required for protection. The thresholds normally do not change.

2.2.5 Indicators and Controls

The front console should include clearly-marked visual indications of the status of each input. The controls and indicators should be simple, and compatible with human engineering needs.

2.3 Stand-Alone Concept

A key part of the design philosophy recommended in this study is the stand-alone concept. The system should be designed so that individual modules or parts of the system may fail without quenching the magnet or without leaving it unprotected. For example, if the central MFTF computer goes down, or if the main facility power service fails, the protection system should have enough local intelligence and control to ramp the magnet down slowly while, at the same time, protecting it in the unlikely but possible event of a quench. The system should also be designed so that if a problem exists which does not endanger the magnet, the operator can take command at the console and override automatic control. The stand-alone concept is consistent with the simplicity, modularity and human engineering aspects of the design.

2.4 Modularity

Inherent in the design should be modularity to the extent that modules may be isolated, removed and replaced with a minimum of magnet down time. Modularity also simplifies overall system complexity and reduces system costs. Using common bus structures, the system should be flexible enough to expand, if necessary. In this study, we recommend 12-1/4" x 5-3/4" modules (1/3 of a 19" rack) because this size allows adequate cooling and adequate space to include three or more large wirewrap circuit boards, power supplies and front panel area without crowding.

2.5 Noise and Isolation

The environment of the MFTF system is expected to be quite noisy. Precautions should be made to reduce RFI and EMI from all power sources and from the incoming 60 Hz power lines. The following

guidelines should be followed to improve noise immunity.

- 1) All instrumentation should be enclosed in metal enclosures with all external cables and connectors shielded.
- 2) A single ground should be defined for the system. (This ground should be tied to the center tap of both dump resistors to reduce voltage breakdown.)
- 3) Digital IC's should have high noise immunity at least as good as B-type CMOS.
- 4) Line filters to reject EMI and RFI should be included in each module of instrumentation.
- 5) All external inputs to the system should be optically coupled and clocked so that transients cannot couple into the logic. Optical couplers should be specified in excess of 20 Volts/nsec for common mode transient immunity (see IGC input module in section 4.4).
- 6) Voltage taps should be isolated from quench detector circuits during a fast dump to prevent any damage to the taps in the magnet. If magnet taps were to be destroyed in the cryostat, it would be almost impossible to sense a quench.
- 7) Isolation amplifiers should be used in quench detectors to reduce noise coupling into the system.
- 8) Extreme care should be taken in isolating the breaker driver circuits so that switching transients do not couple into the protection logic.
- 9) Contacts should be used wherever possible to simplify the design and reduce noise. For example, thermostat contacts should be used for over-temperature indications as opposed to active thermometers that are sensitive to noise.

- (10) Comparators should be designed with filtering and hysteresis.

The noise sensitivity of the system will influence the ultimate reliability of the protection system, especially in the case of the quench detectors which can be prone to tripping due to noise transients if improperly designed.

2.6 Self-Test Features

The protection system should include provisions for self-testing and diagnostics. This will both greatly enhance overall protection system reliability as well as streamline protection system maintenance. Self-test features should include:

- 1) Watchdog timers for all microprocessors. In most cases, these circuits should lock out the microprocessor from interacting with the rest of the system and alert the operator. If the operator does not respond in a reasonable amount of time, the system should respond by ramping the magnet down slowly.
- 2) All cables should be interlocked so that the magnet cannot be charged if a cable is disconnected.
- 3) Backup power sources should be constantly monitored.
- 4) Compressed air lines that power critical relays should be constantly checked.

Test requirements for the quench detectors should include:

- 1) Continuity tests for the voltage taps.
- 2) Isolation amplifier tests.
- 3) Algorithm tests.

- 4) Output bus driver tests.
- 5) Timeout logic if the microprocessor fails.
- 6) Cross comparisons between redundant busses such as the fast dump bus.

Redundancy should be added in cases where critical sensors and circuits cannot be checked. A magnet simulator (explained in section 2.1.2) should also be connected periodically to check parts of the system that cannot be checked otherwise.

2.7 Human Engineering

In view of the complexity of the MFTF, simplicity of operation is of primary importance. One concept held by IGC is that the operator should not need a manual to understand what state the system is in, what problems (if any) exist, or how the system is responding to those problems. Functions that require special trained operator intervention should be guarded by using keylock switches. In addition, wall-mounted panic buttons and "ramp to zero current" or "slow discharge" buttons should be available for emergencies. For indicating the status of the system, LED indicators and adequate snapshot memory to record the state of the system at dump for later readout are recommended.

From a human engineering standpoint, the current controller is the most important hardware component. This is where the operator interacts with the magnet directly. The front panel should be designed so that the operator can use the controller without a manual. The front panel should have enough information to tell the operator what the magnet current levels and rates are programmed to. Meters should indicate how the magnet is performing.

The operator should be able to override computer control and take control of the magnets individually or as a group. The current controller is described in Section 4.8.

3.0 QUENCH DETECTION

3.1 Quench Detector

3.1.1 Normal Zone Propagation

Quench behavior is difficult to predict. Normal zone propagation in the MFTF magnet may take many forms depending upon the nature of the event that triggers the normal zone formation. The results of the MFTF test coils show that normal zones can propagate at a velocity of one meter per second.³ Analysis shows that some zones can form very rapidly and thermally run away in one second. Other zones may form more gradually.

LLL estimates that if normal zones form that exceed $\frac{1}{2}$ to 2 turns long, the magnet conductor would be endangered.⁴ To protect the magnet from overheating, it is recommended that the magnet be discharged at a rate that would put 1000 volts across its terminals.⁵ About 10 seconds is available from time of detection to time of initiating the dump.⁶

Other harmless normal formations can also occur that pose no immediate damage to the magnet. Stable normal zones may form less than one-half a turn long lasting forever until the magnet current is reduced, at which time they may vanish. Protection in the event that a stable normal zone appears should take the form of a slow discharge of the magnet as opposed to a fast dump. Finally, other events may occur in which a normal zone appears instantly, then gradually recovers. The latter requires no action from the quench protection system.

All of these requirements must be met by the protection hardware and software. The quench detectors described in Sections 3.2 and 3.3 can distinguish between a monotonically increasing normal zone beyond $\frac{1}{2}$ turn (which is defined as a quench) and other non-quench conditions such as a recovering normal zone or steady state zone. A summary of requirements for the quench detector is found in Section 3.1.5.

3.1.2 Power Supply Noise

The power supply noise will be characterized by voltage ripple

across the magnet in the form of a complex SCR wave form with a 360 Hz fundamental frequency with an amplitude of 12 Volts RMS. At constant current the average voltage will be approximately zero. When the magnet current is being changed the average voltage will increase proportional to dI/dt due to the inductance of the magnet.

The effect of the power supply noise on the quench detectors appears as common-mode noise across the magnet taps which has to be balanced and filtered out at the quench detector. The AC noise across the taps also couples to the cryostat ground and forms loop currents. AC loop currents causes AC unbalances in the quench detector which are very difficult to filter out. Shielded coaxial cables on taps help reduce the AC loop currents somewhat by letting the shields carry the current, but some filtering is still required. Inductive coupling into the taps is also a problem and should be eliminated by twisting the taps together wherever possible.

3.1.3 Mutual Inductance Effects

Figure 3-1 shows a representation of the magnet circuit for mutual inductance between the MFTF magnets. The voltage across a given segment of the magnet is proportional to the rate of change of current in the parent magnet as well as being proportional to the rate of change of the current in the neighboring magnets. The formula for the voltage of segment a is expressed in terms of the mutual inductance.

$$V_a = (L_a + M_{ab} + M_{ac} + \dots M_{ah}) \dot{I}_1 +$$

$$(M_{a2}) \dot{I}_2 + I_1 R \text{ (assuming a normal zone)}$$

The first term proportional to $\dot{I}_1$ can be lumped together as an effective inductance ($L_a \text{ eff}$) which does not change. If $\dot{I}_2$ were zero, the system behaves as a single magnet and a conventional

(a) Circuit Representation

Segment	a	b	c	d	e	f	g	h	Total
Mutual Inductance Between Magnet 2 and Segment of Magnet 1	M_{a2}	M_{b2}	M_{c2}	M_{d2}	M_{e2}	M_{f2}	M_{g2}	M_{h2}	M_{12}
	0.1702	0.1662	0.1618	0.1572	0.1526	0.1484	0.1442	0.1400	1.24

(b) Mutual Inductance Table⁷

FIGURE 3-1. ELECTRICAL REPRESENTATION AND INDUCTANCE VALUES

passive resistor bridge could be used to buck out the inductive voltage across the tap. A quench in the segment would appear as a voltage unbalance in the bridge proportional to the size of the normal region. Because of the coupling M_{a2} from Magnet 2, quench detection techniques that use only parameters associated with magnet 1 are not adequate. Compensation due to $\dot{i}_2$ effects must be made in order to unscramble the quench signal.

The magnitude of the $\dot{i}_2$ effect is worst during ramping and can be estimated from the mutual inductance calculations made at LLL shown in Figure 3-1.

The voltage offset induced by magnet 2 into quench detector Q1A central tap (using Figure 3-1) is

$$\Delta V_{1A} = (M_{a2} + M_{b2} - M_{c2} - M_{d2}) \dot{i}_2$$

$$\Delta V_{1A} = 17.4 \text{ mv}$$

assuming magnet 2 is being charged at 12 volts which corresponds to current rate of 1 amp/sec.

For quench detector Q_{1c}, the induced voltage offset is

$$\Delta V_{1c} = (M_{a2} + M_{b2} + M_{c2} + M_{d2} - M_{e2} - M_{f2} - M_{g2} - M_{h2}) \dot{i}_2$$

$$\Delta V_{1c} = 70.2 \text{ mv}$$

By comparison, Q_{1B} has an induced voltage comparable to Q_{1A} .

$$\Delta V_{1B} = (M_{e2} + M_{f2} - M_{g2} - M_{h2}) \dot{I}_2$$

$$\Delta V_{1B} = 16.8 \text{ mv}$$

For quench detectors such as Q_{1D} that examine the voltage across the entire coil, the effect is more dramatic. Here the induced voltage is

$$\Delta V = (M_{a2} + M_{b2} + \dots + M_{h2}) \dot{I}_2 = 1.24 \text{ volts}$$

The quenched conductor will develop a voltage drop 27 mv/meter according to Section 2.2. In order to resolve one meter, as recommended, the quench detectors must subtract out or compensate for the induced voltage. A credible algorithm will require knowledge of the mutual inductances which should be measured in initial tests.

3.1.4 Inductance Changes in the Magnet

In a large structure like MFTF, the magnet windings are expected to expand and contract during charging and discharging. This will cause inductance changes as the magnet is ramped. Inductance changes could be misinterpreted as a section of the conductor going normal. One method of monitoring inductance changes would be to sense deviation of linearity of the magnetic field as a function of current. A pickup coil around the magnet would also be able to detect a change in inductance. Although pickup coils or field sensors are not foreseen as being required for quench protection since the voltage thresholds are very high, such sensors would be recommended as diagnostic tools.

Inductance changes may occur rapidly due to conductor slippage causing large voltage spikes in the magnet. Quench detectors should be capable of filtering out large voltage spikes. Inductance changes will probably be less than 1% based upon allowable thermal and magnetic stresses. This corresponds to approximately 120 mv shift (1% of 12V ramp rate) which corresponds to less than $\frac{1}{2}$ turn being normal. Precautions should be taken in the quench detector to compensate for these changes if they happen to become larger than expected.

3.1.5 MFTF Quench Detector Requirements

In Table 3-1 is a summary of parameters associated with MFTF quench protection. Any quench detector must be compatible with these parameters. Because of the difficulty in predicting the exact behavior of such a large magnet as MFTF, the quench detector should be as flexible as possible. Parameters, such as voltage thresholds and quench detector response time; should be programmable.

Two methods of quench detection are recommended. The first method, the balanced bridge approach, has been used successfully in the past with large magnet systems and is being used currently with IGC magnets.² The current rate method has been used at ORNL and has been found to be quite effective.⁸ MFTF requires some modification of these basic techniques because of the coupling between the two large magnets.

TABLE 3-1

MFTF Quench Detector Requirements Summary

Magnet Energy	220 MJ
Max Voltage Across Magnet	1000 V
Max Magnet to Cryostat Voltage	500 V
Magnet Inductance	12 Henries
Mutual Inductance Between Magnets	1 Henry
Maximum Charging Voltage	≈ 12 volts
Magnet Voltage (RMS)	≈ 12 volts
Induced Voltage from Other Magnet	≈ 1.5 volts RMS
Breaker Activation Time	< 100 ms
Quench Normal Zone Length	$\approx$ one turn = 15.75 meters
Quench Normal Resistance	15.75 meters $\times$ 46 n Ω /cm = 72 $\mu\Omega$
Quench Voltage (1 meter)	0.435 volts @ 6000 amps
Quench Velocity	≈ 1 meter/sec or 27.6 mv/sec @ 6000 amps
Resolution Recommended	27 mv @ 6000 amps
Max Tolerable Noise	≈ 3 mv for S/N = 10
Recommended Bandwidth	10 Hz
Recommended Stability of Quench Detector (no mutual)	< 27.6 mv/12V = 0.23%
Degree of Balance Required to Cancel Mutual	< 27.6 mv/1.5 V = 1.8%
Available Time from Onset of Quench to Dump	Programmable (1 - 15 seconds)
Quench Detection Time from Onset	Programmable in increments of 100 ms

3.2 Balanced Bridge Method

3.2.1 Discussion of the Principle

A model of the balanced bridge method used for quench detection is shown in Figure 3-2. The method involves comparing the voltage across taps in the magnet to voltage drops across resistors which are arranged in a bridge circuit. In the diagram ΔV is the unbalance signal processed by the quench detector. When the bridge is initially balanced R_1 and R_2 are adjusted so that ΔV is nulled. Note at balance, if V_a and V_b are zero, the null point is independent of the charging voltage V_1 .

The balanced bridge works as follows. If the rate of change of I_2 is assumed to be zero, V_a and V_b represent the resistive voltage drops in the respective segments L_a and L_b . (For a superconductor, V_a and V_b should be zero.) If a normal zone propagates equally in segments L_a and L_b , then $V_a = V_b$ and the normal zone would not be detected. If, on the other hand, the normal zone only appeared in segment L_b , the unbalance signal ΔV would be one half of the voltage drop across the normal zone, i.e. $\Delta V = \frac{1}{2} V_b$.

NOTE:
$$V_R \approx \frac{R_b}{R_a + R_b} V$$

Using Laplace Transforms

$$V - V_a - V_b = SI_1 (L_a + L_b)$$

$$V_T = SL_2 I_1 + V_b$$

$$V_T = \frac{SL_2}{SL_1 + SL_2} (V - V_a - V_b) + V_b$$

$$\Delta V = V_T - V_R = \frac{L_2}{L_1 + L_2} (-V_a - V_b) + V_b$$

For equal arms

$$\Delta V = \frac{1}{2} (V_b - V_a)$$

FIGURE 3-2. BALANCED BRIDGE MODEL

For the real case when magnet 2 has current changing, the voltage seen at V_a due to mutual inductance will be

$$V_{a(\text{induced})} = M_{a2} \dot{I}_2$$

and $V_{b(\text{induced})} = M_{b2} \dot{I}_2$

so that the total effect is

$$\Delta V_{(\text{induced})} = \frac{1}{2} (M_{b2} - M_{a2}) \dot{I}_2$$

The inductive signal must be anticipated by the quench detector and subtracted out from the unbalanced signal in order to accurately detect a quench forming.

3.2.2 Algorithm Including Mutual Inductance Effects

Once a technique for generating a signal proportional to the length of the normal zone has been established, such as the balanced bridge method, some signal processing is required to test whether or not the quench has progressed far enough to warrant a fast dump. In this section, some ground rules are established in terms of the parameters required and the type of calculations that need to be performed.

Below is a list of parameters that are required for an algorithm for quench detection in magnet 1 of MFTF.

V1	Low threshold above which indicates the onset of normal zone formation.
V2	Middle threshold above which indicates dangerously high normal zone formation.
V3	High threshold above which indicates a critical normal zone which warrants an immediate dump.
t_1	Maximum time available from the onset of a normal zone above the second threshold to complete breaker activation.
t_2	The maximum time a steady state normal zone is allowed to exist without ramping down.
t_B	Opening time of the breaker from energization to current interruption.
t_d	Time available from the onset of a normal zone to quench recognition.
t_s	Sample time between points.
N_s	Number of samples.
t_p	Processing time allotted to recognize a quench.
V_B	Continuously averaged baseline.

V_{BL}	Maximum baseline drift tolerated without warning the operator.
ΔV	Unbalanced signal averaged over N_s samples minus the baseline.
$\dot{\Delta V}$	First derivative of ΔV averaged over N_s samples.
$\ddot{\Delta V}$	Second derivative of ΔV averaged over N_s samples.
M_{12}	Mutual inductance of segment monitored due to other magnet (magnet 2).
L_1	Self inductance of section monitored (for Q. D. 1D that would be the entire magnet 1).
$\dot{I}_1$	Rate of current change in magnet 1.
$\dot{I}_2$	Rate of current change in magnet 2.
M_{12}^U	Mutual inductance between magnet 2 and the upper part of the section monitored in a balanced bridge arrangement.
M_{12}^L	Mutual inductance between magnet 2 and the lower part of the section monitored in a balanced bridge arrangement.
$\Delta M_{12} = M_{12}^U - M_{12}^L$	Differential mutual inductance between the upper section and the lower section and magnet 2.

The quench detector should continuously calculate the baseline V_B , the resistive voltage signal ΔV , the voltage derivatives $\dot{\Delta V}$ and $\ddot{\Delta V}$. The total processing time is dependent on the complete detection algorithm and the analog-to-digital converter rates.

In a balanced bridge quench detector such as Q. D. 1A in Figure 3-1, the induced voltage from magnet 2 is continuously subtracted from the raw input signal so that

$$\Delta V = V_{\text{bridge}} - \Delta M_{12} \dot{I}_2 - V_{\text{Baseline.}}$$

For a current rate quench detector, which will be discussed in section 3.3, such as Q. D. 1D in Figure 3-3, the induced voltage from magnet 1 and magnet 2 is subtracted from the total voltage across the magnet so that

$$\Delta V = V_{\text{magnet}} - M_{12} \dot{I}_2 - L_1 \dot{I}_1 - V_{\text{baseline}}$$

Once the quench detector processes the resistive signal ΔV , a series of decisions must be made as to whether protective action should be initiated.

Below is an example of the type of algorithm a quench detector must execute in order to protect the magnet.

<u>Conditions</u>	<u>Response</u>
$\Delta V > V_3$	Initiates a dump at 1000 volt rate
$\Delta V > V_2$ for $N_s t_s$ time and ΔV monotonically increasing	Initiates a dump at 1000 volt rate
$V_1 < \Delta V < V_3$ for a time t_2	Instructs magnet protection microprocessor to decrease currents until normal zone disappears

3.2.3 Description of Balanced Bridge Module

In order to meet the requirements listed in sections 3.2.3 and 3.1.5, a programmable quench detector should be used. Such a unit is commercially available from IGC. A block diagram of the unit is shown in section 3.2.4.

The heart of the quench detector is a small microprocessor which is used for signal averaging, buffering, computation, and communication. The users algorithm is contained in 4K bytes of read-only memory (ROM) with 4K bytes of random-access-memory (RAM) for scratch pad memory and data storage.

Below is a summary of components and features contained in the module:

- Input Section - All balancing networks, signal amplifiers, and test circuits appear in this section. The test circuits check voltage tap continuity and exercises the input isolation amplifier and ADC under program control.
- Slow ADC - This is the primary ADC used for digitizing the quench signal.
- Fast ADC - This board contains a secondary ADC used to cross check the slow ADC and also monitors ambient temperature for compensation.
- Interface - This board contains all microprocessor interfaces and logic for the quench detector.
- Microprocessor - Controls all testing, computations and communication.
- Fast Dump Bus - This output bus contains two lines (one for redundancy) capable of activating the 6000 A fast dump breakers. The bus is optically coupled for noise isolation and is fail proof.

- Communication Bus - This is an I/O bus for communication between quench detectors and the main microprocessor. It also contains inhibit signals which lock up the quench detector in case of a fault. The communication bus is normally a 20 ma TTY compatible serial bus. For MFTF an IEEE-488 bus may be more appropriate.
- I_1 , I_2 Bus - This input bus is used for transmitting the rate of change of current to other quench detectors for processing. This is necessary in a two-magnet environment. The current rate bus is separate from the communication bus for extra reliability and speed.
- Watchdog Timer - This circuit latches up the quench detector if the microprocessor fails to respond every second.
- Front Panel Controls - The quench detector is capable of displaying all the parameters involved with quench detection. Thresholds and times will be fixed and contained in read-only-memory and cannot be set from front panel except during initial installation tests. During normal operation, the quench detector runs unattended. In the event of a quench, data is recorded in each quench detector to examine the status of the magnet at quench.
- Noise Isolation - The module is especially designed for noisy environments. The input amplifier is an isolation amplifier with a common mode rejection ratio greater than 120 db. In addition, there is 60 Hz and 360 Hz prefiltering before the signal is averaged and processed.

3.2.4 BLOCK DIAGRAM OF MFTF BALANCED BRIDGE QUENCH DETECTOR

3.2.5 Software Flow Chart: Balanced Bridge Quench Detector

3.2.6 Front Panel

BALANCED BRIDGE METHOD

3.3 Current Rate Method

3.3.1 Discussion of the Principle

For a pure inductor the rate of change of current is directly proportional to the voltage across the inductor. This basic relationship can be used to detect a quench. In Figure 3-3 a model for the current rate method is outlined. The resultant signal for Q_{1D} includes the mutual inductive voltage term $M_{12}\dot{i}_2$, which was computed earlier in Section 3.1.3. This of course must be subtracted from ΔV to give the true quench signal.

The method requires a transducer which gives an output proportioned to the current rate $\dot{i}_1$. Current rate transducers can be either a current transformer or a current monitor with a differentiator. The multiplying and subtraction required for this technique can either be done with analog or digital components. Since the signal processing required for ΔV will be done in software, the scaling and subtraction required for forming ΔV is efficiently done with software.

3.3.2 Description of the Module

The current rate quench detector module is very similar to the balanced bridge quench detector described in Section 3.2. The primary difference is that the current rate module requires an additional input channel from the current rate transducer and eliminates the need for the voltage tap balance network. The current rate transducer is assumed to be an air core transformer. The module also has an additional output, the current rate it measures and sends to other quench detectors. A block diagram of the module is shown in the next section. The front panel is similar to the balanced bridge in section 3.2.6.

The signal processing algorithm has been described in Section 3.2.3. It essentially requires that $M_{12}\dot{i}_2$ be subtracted from the raw quench signal ΔV . M_{12} is a parameter established by analysis and later verified by experiment before it is burned into ROM.

Note: In QD_{1D} V_O is compared to V_1 . At balance A is adjusted so that $V_O = V_1$. Assuming the system was balanced when $V_n = 0$, $A = L_1$. When an unbalance occurs

$$V_1 = V_n + L_1 \dot{I}_1$$

so the signal ΔV becomes

$$\begin{aligned} \Delta V &= V_{\text{quench}} + M_{12} \dot{I}_2 + L_1 \dot{I}_1 - L_1 \dot{I}_1 \\ &= V_{\text{quench}} + M_{12} \dot{I}_2 \end{aligned}$$

FIGURE 3-3 MODEL FOR THE CURRENT RATE METHOD

3.3.3 BLOCK DIAGRAM OF MFTF CURRENT RATE QUENCH DETECTOR

3.3.4 Flow Chart: Current Rate Quench Detector

The components and features are almost identical with the balanced bridge quench detector except for the additional output bus carrying the current rate data.

3.4 Quench Detector Connection

Fig. 3-4 shows the arrangement recommended for MFTF. In most cases, this arrangement is redundant to three levels. For example, if Q.D. 1A fails, Q.D. 1C and Q.D. 1D will be able to detect a normal zone. Of course, if Q.D. 1D or an $\dot{I}$ sensor fails, other quench detectors which rely on $\dot{I}$ information will be handicapped. This situation could be backed up by a redundant $\dot{I}$ detector or by the magnet protection microprocessor computing $\dot{I}$ from current readings from the power supply shunt. Current rate information is also available at the current controller in the current rate set point buffer but the actual current rate may differ (See Section 4.8). The correction due to the current rate ($\dot{I}$) is not large enough to cause a quench in most quench detectors except Q_{1D}. This can be prevented by adequate quench detector voting logic.

3.5 Quench Voting

Additional reliability may be gained by passing fast dump requests from quench detectors through some decision logic before activating the breakers. The decision logic cannot be too restrictive else if a quench detector fails, a quench would be missed. There is enough redundancy in the proposed connection (Section 3.4) that even if a single quench detector fails, the magnet would survive. Below is a voting table, Table 3-2, that accommodates single quench detector malfunction without adversely effecting the magnet. By making the decision logic programmable, even multiple quench failures could be tolerated without endangering the magnet.

FIGURE 3-4. MFTF QUENCH DETECTOR CONNECTIONS

Table 3-2
Proposed Quench Voting Table

Q _{1A}	Q _{1B}	Q _{1C}	Q _{1D}	Output of Voting Table	
FD	X	FD	FD	FD	
X	FD	FD	FD	FD	
X	X	FD	FD	FD	
X	X	X	FD	SD	Q _{1D} probably bad
X	X	FD	X	SD	Q _{1D} or Q _{1C} probably bad

FD = Fast Dump

ND = No dump

X = ND or Quench Missed

SD = Slow Dump and Alarm

4.0 MAGNET PROTECTION SYSTEM

4.1 Overview

4.1.1 System Diagram and Instrumentation List

Figure 4-1 shows a preliminary drawing of the MFTF magnet electronic instrumentation and control system. The drawing includes all equipment required for monitoring and protecting the magnet.

All critical monitors funnel into the central control cabinet which contains the quench detectors, current controllers and protection modules. Control signals, such as the fast dump busses and power supply current demand signal, fan out from central control cabinet.

Some typical inputs to protection modules include relay position indicators, dump resistor thermostats, vacuum pressure switch contacts, and single threshold outputs from signal conditioners such as the lead voltage monitor. The status of the inputs are indicated on the front panel of the central control console.

The voltage taps from the magnet enter the central console in the quench detector input relay modules which disconnect the taps in the event of a fast dump. In the relay box, the taps are routed to each quench detector. The balanced bridge quench detectors require three taps, a center tap and two outside taps. This connection is shown in Figure 3-1. The current rate quench detectors require two taps and a separate input from the $\dot{I}$ transducer. The magnet taps into the current rate quench detector originate at the extreme ends of the magnet as shown in Figure 3-3 processor module. There are two separate fast dump output busses from each quench detector that feed into the quench detector voting logic module. Fast dump signals are passed through the voting logic module and are sent to the breaker driver interface module which controls all of high current circuit breakers. In the breaker driver module, additional fast dump and slow dump command signals from the input indicators merge with those from the quench detector voting logic and determine the combination of

FIGURE 4-1 MFTF Electronics Subsystem

TABLE 4-1

TABLE 4-1. EFFECTS OF OPERATING CONDITIONS
ON THE PERFORMANCE OF THE SYSTEM

System Element	Failure Mode	Failure Mechanism (Initiation, Growth, Propagation, Failure)	Criticality Index	Rem. Code	Effect Type	Impact Level	Indicator	Effect Location	Impact Symptoms	Indicating Equipment
Magnet 1 & 2	Quench	Quench (Initiation, Growth, Propagation, Failure)	H	L	A	A	A	Quench detector initiates fast dump	Magnet off line, Alarm - Quench detector - Initiation - Initiated	Quench detector channel that detected a quench will have Quench indicator.
	Small steady state normal loss	Normal (Initiation, Growth, Propagation, Failure)	H	L	B	B	B	Quench detector initiates slow dump	Magnet off line temporarily.	Regular checks & message.
High Current Leads	Lead helium flow rate low	He gas flow insufficient to cool lead	H	L	B	B	B	Initiates slow dump	Magnet off line temporarily.	Lead that was being cooled rate will be displayed and alarmed.
	Lead over- temperature	Lead self-heating due to insufficient lead cooling	H	L	B	B	B	Initiates slow dump	Magnet off line temporarily.	Lead that exhibits an over- temperature will be displayed and alarmed.
	Lead over- voltage surge	Lead voltage drop in excess of normal operating value	H	L	B	B	B	Initiates slow dump	Magnet off line temporarily.	Lead that exhibits an over-voltage will be displayed at the lead voltage monitor.
	Lead over- voltage critical	Lead voltage drop above critical operating region	H	L	A	A	A	Initiates fast steady dump	Magnet off line and possibly with Initiation Intermittent.	Lead that exhibits a critically high voltage will be alarmed and displayed at the lead voltage monitor.
Cryostat	Cryostat pressure high	Pressure within cryostat exceeding operational limit	H	H	B	B	B	Initiates slow dump Helium gas valve closed Vent valve opened.	Magnet off line temporarily.	Cryostat emergency shutdown and alarmed.
	Helium level low	Helium level below operational limit in magnet cryostat	H	H	B	B	B	Initiates slow dump	Magnet off line temporarily.	Helium low (alarmed) and alarmed.
	Main vacuum low	Main vacuum above normal vacuum operational limit	H	L	A	A	A	Initiates fast dump	Magnet off line temporarily.	Main vacuum low alarmed and alarmed.
	12 ₂ level low	12 ₂ level below operational limit	L	H	-	-	-	Helium level was drop rapidly.	No 12 ₂ valve impact, however, loss of 12 ₂ from cable can magnet off line.	12 ₂ controller will register low.
6000 A Power Supply	Power supply output overvoltage	Output voltage in excess of rated limit (6000 V)	H	L	C	B	B	Power supply shuts down (Event)	Magnet off line temporarily.	Overvoltage condition will be alarmed at the affected power supply.
	Power supply output overcurrent	Output current in excess of rated limit (6000 A)	H	L	C	B	B	Power supply shuts down (Event)	Magnet off line temporarily.	Overcurrent condition will be alarmed at the affected power supply.
	Power supply over-temperature	Power supply over-temperature in excess of operational limit	H	L	C	B	B	Power supply shuts down (Event)	Magnet off line temporarily.	Over-temperature condition will be alarmed at the affected power supply.
4000 A Circuit Breaker	Breaker failure during operation	Breaker fails to open or is partially damaged during opening action and results in closed condition	H	L	B	C	B	Alarm - Breaker failure	Breaker failure indicator.	Breaker closed indicating trouble with the dump initiator.

TABLE 4-1 (continued)

FAILURE MODE, EFFECT AND ANALYTICAL ANALYSIS

Page 2

System Element	Failure Mode	Failure Description	Criticality Rating	Prob. Cntr.	Effect Cntr.	Impact Cntr.	Indicator Cntr.	Effect Comments	Impact Comments	Indicator Comments
Dump Resistors	Dump resistor open failure	Dump resistor develops high resistance reaction resulting in open circuit in resistor during use	H	L	A	A	A	Affected magnet unable to fast dump.	Magnet damage possible.	Dump resistor has indicator label on it.
	Dump resistor overtemperature	Dump resistor temperature in excess of all-waste limit for subsequent future dump utilization during quench	H	L	A	B	B	Initiates slow dump.	Magnet off line temporarily.	Dump resistor not indicated and latched.
	Dump resistor coolant low	Dump resistor bath empties due to SSB supply failure	H	L	A	B	B	Initiates slow dump.	Magnet off line temporarily.	Dump resistor coolant empty indicated and latched.
Refrigeration System	Refrigerator off line	Internal refrigeration system failure allows return helium supply source	L	H	A	A	A	He ducting valve closes, no supply source interrupted.	No immediate impact.	Refrigerator off indicated at refrigerator.
	Refrigerator valve closed	Valve closes due to refrigerant system failure allows fail no of valve malfunction	L	L	A	A	A	He ducting valve closes and no source interrupted.	No immediate impact.	Refrigerator off indicated at refrigerator.
Magnet Protection System	Quench protection bus failure	Single bus failure	H	L	B	B	B	Initiates slow dump.	Magnet off line temporarily. Helium not quench, bus will protect magnets.	Quench bus failure indicated and latched.
	With busbar fail		H	L	B	B	B	Initiates slow dump.	Magnet damage possible if a quench occurs during slow dump.	Quench bus failure indicated and latched.
	RODA breaker driver failure	Affected breaker fails to open due to a pullout in driver circuitry	H	L	B	C	C	Affected magnet unable to dump.	Magnet damage possible.	Affected breaker closed indicated and latched.
	Logic Failure	Internal logic is inconsistent or fails to respond to internal tests due to circuit failure	H	L	B	B	B	Initiates slow dump.	Magnet off line temporarily.	Quench logic failure indicated and latched.
	Unit internal power supply failure	Power supplies exceed operational limits	H	L	B	B	B		Magnet off line temporarily.	Power supply indicator on.
Quench Detectors	Microprocessor failure, LCU computer failure.	Microprocessor fails to respond as a result of internal circuit failure	H	L	B	B	B	Initiates slow dump.	Magnet off line temporarily.	Quench logic failure indicated.
	Quench detector failure system	Single quench detector malfunction	H	L	B	B	B	Initiates slow dump. Protection through reducing quench detector.	Magnet off line temporarily.	Quench detector fault indicated at affected quench detector. Message at display.
		Multiple quench detector malfunction	H	L	A	A	A	Initiates fast energy dump.	Magnet off line and possibly warm. Refrigerator off line temporarily.	Quench detector fault indicated at affected quench detector. Message at display.

TABLE 4-1 (Continued)

TABLE 4-1 (Continued)
EFFECT OF LOSS OF UTILITY AND EFFECT OF LOSS OF UTILITY

Page 5

System Element	Failure Mode	Failure Mechanism	Criticality Code	Frequency Code	Effect Code	Impact Code	Indicator Code	Effect Summary	Impact Summary	Indicating Comments
Utility Line Power	440 VAC Power Fail	240 VAC line power not within operational limits	H	M	C	A	B	Power supply shuts down. Indicate slow dump.	Magnets off line temporarily.	440V Fail Indicated and latched.
	120 VAC Power Fail	120 VAC line power not within operational limits (brown out)	H	M	C	A	B	UPS switches down to reserve battery line.	None	120 VAC power fail indicated momentarily.
		120 VAC power off for 6, 1, 5 minutes	H	M	B	B	B	Indicates slow dump.	None	120 VAC power fail 45 minutes indicated.
Uninterruptible Power source	UPS battery weak	UPS battery backup power below maximum acceptable charge	H	L	C	B	B	MFC indicates slow dump.	Magnets off line temporarily.	UPS battery weak indicated and latched.
	UPS battery dead and 120 VAC Power Fail	UPS battery backup power below operational limit and power lost to 120VAC power reference and critical circuits	H	L	A	A	A	Beacon in Reserve station signals station that power reference and power supply is interrupted. Reserve station indicates last energy dump.	Magnets off line and possible warm. Reference power the beacons are interrupted. Reserve station indicates last energy dump.	All beacons off.

EFFECTS:

EFFECT CODE A

- 440V AC line dump breakers open.
- Magnet current transfers from power supplies to the dump resistors.
- Refrigerator valve closes.
- Dump resistors temps rise.
- Helium levels rise drop.
- Appropriate pressure may rise.

EFFECT CODE B

- Magnets temporarily inoperative.
- Affected magnet may be warm if a quench occurred.
- Refrigerator valve is closed.
- Vent valve opened.
- System may need to be cooled down and restarted when the current is zero.

INDICATOR CODE A

- 440V AC breakers open indicated on 120V.
- Audio alarm at Magnet power module.
- Dump resistors hot indication possible.
- Helium low indication possible.
- Circuit over pressure indication possible.

EFFECT CODE B

- Power supply controllers disabled.
- 440V AC slow dump breakers activated for slow discharge through the slow dump resistor.
- Power to magnets is absorbed passively by dump in the series resistors.

EFFECT CODE C

- Magnets temporarily inoperative.
- Power supply controllers force current in magnets to zero.
- System cannot be operated unless fault condition is corrected.

INDICATOR CODE B

- Power supply controllers 120V are disabled state.
- Audio alarm at Magnet power module.

EFFECT CODE C

- Power supply controllers disabled.
- Power supplies AC breakers opened via internal power supply circuitry.
- Breakers activated for slow discharge through slow dump resistor.
- Power to magnets is absorbed passively by dump in the series resistors.

EFFECT CODE C

- Possible magnet damage.
- System should not be operated until thoroughly checked by key operator.

Criticality Code & Frequency Code

H = High
M = Medium
L = Low

relays to be opened or closed. In addition, the breaker driver module contains inhibit gates and front panel controls that allow testing to occur with or without triggering the circuit breakers. The fast dump busses are optically coupled to the breaker driver circuits which activate the coils of the circuit breakers.

All protection modules such as the input indicators, quench voting logic, and breaker driver interface share a common IEEE-488 interface which links them to the microprocessor module.

The central control cabinet also contains the current controllers which are interfaced to the input indicator and to the microprocessor module. The interface to the input indicator module is used as a power supply interlock. If an alarm appears at the input indicator the current controllers are forced to ramp to zero and cannot be operated until the alarm is cleared.

The interface from the LLL computer enters at the control console and interfaces separately to the current controller and microprocessor module. Communication from the LLL computer to the current controller is kept private so that no conflict in control between the microprocessor module and the LLL computer is possible.

4.1.2 Front Panel Layout and List of Modules

Figure 4-2 shows the front panel of the magnet protection control console. On the top of the console is mounted a 32 character display which is used to prompt the operator as to the status of the magnet system. The display is driven by the Microprocessor Module through the IEEE-488 bus.

The current controllers are mounted just below the display within reach of the operator. Under the current controller are mounted a group of modules which together comprise the magnet protection system.

The Microprocessor Module is the hub of the protection system. It controls communication and coordinates testing between modules. The input indicator panels indicate status on alarm conditions. The breaker drivers interface module and quench voting logic module coordinate fast dump requests from the quench detectors. The quench detectors are mounted below the display modules since they are stand alone devices and rarely need attention.

A complete list of protection modules recommended by IGC is given in Table 4-2.

FIGURE 4-2

MFTF MAGNET PROTECTION CONSOLE

TABLE 4-2

LIST OF PROTECTION MODULES RECOMMENDED FOR MFTF

<u>DEVICE TITLE</u>	<u>IGC MODEL</u>
Microprocessor	MP 500
Input Indicator (Master)	II 501
Input Indicator	II 502
Input-Output Indicator	IOI 503
Quench Detector (Voltage Balance)	QD 550
Quench Detector (Current Rate)	QD 551
Quench Detector Voting Logic	QDVL 504
Breaker Driver Interface	BDI 505
Microprocessor Display	MPD 600
Quench Detector Input Relay	QDIR 601
Current Controller	CC 602

4.1.3 System Operation

The magnet protection system works as follows. When the system is first powered up the microprocessor module takes control and locks up the current controller by forcing it to ramp to zero (at power up it will be at zero anyway) and does not allow the operator or the LLL computer to energize the magnet until the system is completely checked out. The microprocessor prompts each quench detector to begin a self test cycle. Upon the completion of each test, the microprocessor expects to receive a "test pass" response from each quench detector. The microprocessor then requests the quench detectors to toggle the individual fast dump busses in all combinations while at the same time inhibiting fast dump circuit breakers from opening. This allows the microprocessor module to test all circuitry up to the breaker driver interface module including the quench detector voting logic. The breaker driver interface module is wired so that only one fast dump bus can be inhibited at a time. (Note that there are two fast dump busses, one for redundancy.) This prevents the microprocessor from inadvertently commanding the breaker driver interface to gate both fast dump busses off, leaving the magnet dangerously unprotected.

If the quench detector passes the initial power up tests, the microprocessor asks the operator if he would like to manually activate the large circuit breakers. If the operator would like to perform a test, he must turn the keylock switch on the face of the breaker driver module to the test position. The microprocessor guides the operator through the test using messages at the display. The test is monitored by the microprocessor and error messages appear if the test malfunctions or if the operator makes a mistake.

If all tests pass, the microprocessor unlocks the current controller

so the power supply may be operated from the console or the computer. Meanwhile, the microprocessor spends most of its time polling the quench detectors to see if they are active.

If a problem exists, the microprocessor switches on the front panel audio and visual alarms to get the operator's attention and sends a message to the LLL computer describing the nature of the problem. In the event of a quench or fast dump, the microprocessor records the current in the magnet as a function of time and other parameters of interest during a quench. These parameters are stored in the microprocessor's memory and may be read out through the front panel display or transmitted to the LLL computer.

Status and alarm conditions in the magnet system are trapped by the input indicator modules. The inputs are wired directly to the dump busses and will cause a dump immediately if an alarm occurs. The microprocessor monitors these inputs but does not react to them. This takes the microprocessor module out of the critical protection path.

For critical paths like the fast dump busses, two busses are carried from the quench detector. As explained before, one bus is for redundancy. The redundancy is maintained in the circuitry as well. The quench detector voting logic module, the breaker driver interface module, and the breaker driver have completely independent circuits, one dedicated to each bus. The fast dump signal propagates down each critical bus through no common components.

A special purpose module, an input/output indicator, is also included in the system. The module's outputs are used to open refrigerator vent valves and close refrigerator return valves during a fast dump.

Finally, the proposed system also reacts to prevent internal module power failure. Some critical modules like the input indicators, breaker driver module, and the quench detector voting logic contain provisions for backup power input in case power to the logic fails due to either a power supply problem or a facility power failure. The input power required is DC and automatically switches in through diodes when the logic voltage drops below an operational level. Voltage threshold monitors which monitor the module power are included in each module and are connected to the slow dump bus. The backup power is provided by batteries and inverters which are monitored by the protection system. If all power fails, including the backup power, the protection system activates a fast dump in a last attempt to protect the magnet.

4.2

Criteria for Dumping and FMECA

The magnets should be under the protective control of supporting electronics. These pieces of equipment provide magnet protection in the form of a slow dump or fast dump of the magnet energy. A slow dump of magnet energy should be initiated for any of the following conditions.

- He Level Low
- Cable Interlocks Open
- Guard Vacuum Low
- Cryostat Pressure High
- Lead A Flow Rate Low
- Lead B Flow Rate Low
- Lead A Temperature High
- Lead B Temperature High
- Lead A Voltage Exceeds a Dangerous Level
- Lead B Voltage Exceeds a Dangerous Level
- Dump Resistor Hot
- 6000 Amp Power Supply Fail
- Uninterruptible Power Source Fail
- Uninterruptible Power Source Battery Weak
- 120 Vac Power Fail
- Breaker Compressed Air Failure
- Main Vacuum Low
- Internal Logic Failure (Logic fails to respond to internal tests.)
- He Reservoir Level Low
- Microprocessor Fail
- Microprocessor Slow Dump (Note: A microprocessor slow dump is initiated by such items as a quench detector failure, quench detector bus failure, or small steady state normal zone -- detected by the quench detector.)
- Internal Power Supply Failure
- Voting Logic Discrepancy

A fast dump of magnet energy should be required if any of the following conditions occur.

- Lead A Exceeds a Critical Voltage
- Lead B Exceeds a Critical Voltage
- Thermal Shield Develops an Overtemperature
- Total Power Fail (120 Vac and UPS)
- Magnet Quench
- Vacuum Failure

In Table 4-1, a complete failure mode and criticality analysis (FMECA) is presented for the MFTF magnet system.

4.3 Microprocessor Module

4.3.1 Description

The microprocessor can be programmed for a variety of functions. Front panel program changes can be made using the keyboard with the address-data display when the keylock switch is in the enter/reset position. Bidirectional communication between the microprocessor and magnet protection system is accomplished via an IEEE-488 bus. Communication between the microprocessor and the LLL computer is through a separate interface bus. The module can be interfaced to an external 32 character alphanumeric display unit through the IEEE-488 bus. A programmable front panel audio/visual alarm can be programmed to alert the operator of potentially harmful conditions.

Specifications

Display:

4 Hex characters, 2 address + 2 data

Keyboard:

Hexadecimal

Input/Output:

I/O IEEE-488 bus

Serial I/O port with 20 ma current loop interface

LLL computer bus

Power:

115 VAC, 1A

12 VDC, 5A Backup

4.3.2 Front Panel

4.3.3
Block Diagram

MICROPROCESSOR MODULE

4.3.4 Software: MFTF Magnet Protection System Flow Chart for Microprocessor Module

4.4 IGC Universal Input Indicator

4.4.1 Description

The general purpose input indicator device is used to display the status or alarm conditions of a magnet system. Outputs are provided for interface to a magnet protection system. The input indicator has provisions for inputting and displaying 16 signals. Display mode is selected with a five-position switch.* The modes are as follows:

- Latched - all incoming signals are stored.
- Continuous - incoming signals are samples once a second.
- Slow Dump Snapshot - input states when the slow dump occurred are latched.
- Fast Dump Snapshot - input states when the fast dump signal occurs are stored.
- The fifth position of the mode selection switch is Computer Control, whereby remote mode selection is allowed through the IEEE-488 bus.

Indicator lights denote the display mode selected either by the external computer control or by manual selection when not in computer control. Outputs are provided for Fast Dump and Slow Dump signals, which are wired to inputs requiring protective action. These outputs can be bussed to additional input indicator modules allowing common connection and operation of all modules. The keylock switch provides selection between normal operation and the reset condition.* A single reset pulse is generated when the reset switch is initially engaged, cancelling all alarms, then resuming normal operation immediately. The keylock switch must be returned to the normal position before a subsequent

* Where multiple input indicator modules are used together, these switches can be housed in one master module only and eliminated from the other modules. All other input indicator modules respond to the master control.

reset is allowed.

The unit is also programmable via hardwire connections. For example, any input may be wired to activate the slow ramp down bus, the fast ramp down bus, or if no action is required, the input can be left without being connected to any bus. All inputs are prewired into the IEEE-488 interface.

A unique feature of the module is its extremely high noise immunity. The signals are optically coupled to the logic providing greater than 20 V/ns common mode transient noise immunity. In addition, each input is sampled only once a second to reduce the possibility of spurious noise activating critical busses.

The front panel of the module is shown in section 4.4.2.

Front Panel

4.4.3 Block Diagram

INPUT/INDICATORS

Specifications

Signal Input: Provisions for inputting 16 normally open or normally closed relay contacts or transistor switches. All inputs are optically coupled for optimum noise immunity and are interfaced to an IEEE-488 bus.

Outputs:

Protection: 3 Busses: Dump A

Dump B

Slow Dump

Internal Buffers

Latch and Hold: store all incoming signals

Continuous: sample incoming signals once per second.

Slow Dump: stores input status when a slow dump occurs.

Fast Dump: stores input status when a fast dump occurs.

Programmable Features (Hardwire Connections)

Invert/Non-invert selection of N.O. and N.C. input sources.

Inputs requiring protective action can be connected to protection busses { Dump A, Dump B, and Slow Dump }.

Inputs not requiring protective action would not be connected to the protection busses, but their status would be indicated and sent to the IEEE-488 bus.

Input Power

115 Vac, 1A

Backup Power Input 12V, 5A

(This may be required for critical application when the input/indicators module must be powered by batteries in the event of a power failure.)

4.5 IGC Breaker Driver Interface Module

4.5.1 Description

The breaker driver interface is used for digital control of the breaker circuitry. The primary function is to permit automatic testing of quench detectors, quench detector voting logic, and fast dump busses. Another function is to permit manual testing of the unit, the breaker drivers, and the breakers from the front panel while the magnet is not in operation. The keylock switch must be in the test position with the ready-to-test light on before one can proceed with manual testing. Slow dump and fast dump inputs from the quench detector voting logic and input indicators are used to control the breaker drivers during magnet operation.

Specifications

Inputs: Fast Dump A
Fast Dump B
Slow Dump

Outputs: TTL Breaker Driver Busses. These signals activate the breaker driver units which open and close the breakers either during tests or in response to alarm conditions.

Computer Interface: IEEE-488 Bus

Power: 115 Vac, 1A - Backup 12 VDC, 5A

4.5.3
Block Diagram

BREAKER DRIVER INTERFACE

4.6 IGC Quench Detector Voting Logic Module

4.6.1 Description

The function of the quench detector voting logic module is to trigger the fast dump busses when a programmed combination of input signals appears on the quench detector busses (indicative of quench detected in the superconducting magnet). Any combination of inputs for four quench detectors can be hardwire programmed in the voting logic section. Inputs for quench detectors are also transferred to the IEEE 488 bus for microprocessor monitoring. This provides the ability for greater system reliability by avoiding hasty response to momentary or false quench conditions.

Specifications:

<u>Inputs:</u>	Quench Detector Fast Dump A, Fast Dump B
<u>Outputs:</u>	Fast Dump Bus A, Fast Dump Bus B
<u>I/O:</u>	IEEE 488 Bus
<u>Power:</u>	115 Vac, 1A - Backup: 12 VDC, 5A

4.6.2 Block Diagram

QUENCH DETECTOR VOTING LOGIC

4.7 Quench Detector Input Relay

4.7.1 Description

The function of the quench detector input relay device is to prevent high magnet voltages from entering the quench detector inputs during a fast dump. Normally closed SPDT high voltage relays open the quench detector inputs including coaxial shields upon command. The relays are normally opened by the breaker driver interface when a fast dump has been initiated. The relays have a rated operating voltage of 8 kvdc. In addition, each output is protected by a zener diode-fuse combination in case the relay fails.

Specifications

Inputs - (1) 24 vdc relay trip line
(5) voltage tap signal lines

Outputs - 5 separate output connectors.
Each output connector contains 3 voltage tap lines, connects up to 5 quench detectors in the configuration described in section 3.4.

Power - 115 VAC, 1 A - Backup: 12 VDC, 5 A

4.8 IGC Current Controller Unit

4.8.1 Description

The controller can be operated by an external computer or through front panel switches. Current level and current rate selection are set by thumbwheel switches on the front panel or by remote computer command. Magnet current and voltage are shown on front panel analog meters and are available to the magnet protection system as digital outputs via the IEEE 488 bus and the LLL computer through a separate interface bus. A front panel switch allows either magnet rate or power supply voltage to be monitored from a front panel analog meter. The setpoints for current and rate are shown on digital displays. Ramp-to-zero, ramp-to-level, and hold functions can be selected from front panel switches/indicator or by remote computer command through the LLL computer interface. Ramp-to-zero and ramp-to-level generate linear current ramp in the magnet at the selected rate. The hold function provides immediate unconditional ramp stop at the existing current. Two controllers can be operated independently or in tandem, where one controller acts as a master controlling both. Controllers are capable of either master or slave operation. The master control is selected from a master pushbutton on the front panel of a designated master unit or by remote computer command through the LLL computer interface. When transitions are made from local, computer or master, the controller(s) are placed in hold to prevent possible undesirable magnet operation. Master, local and computer control functions can be selected from front panel switches/indicators or by remote computer command through the LLL computer interface. An at-level front panel indicator provides verification when the selected level is reached. An interlock input for the slow dump bus is provided so that in the case of an alarm all front panel switches and computer controls are overridden and the current controller is put in a ramp-to-zero state until the alarm or slow dump bus is cleared.

Also, if when in computer control the LLL computer fails to respond every second, the controller goes into an automatic rampdown to zero state.

Front panel pushbuttons are illuminated switches, which light up when depressed unless the controller is under computer control or unless it is locked up by the protection system. The pushbutton lights always indicate the state of the controller.

Specifications

Inputs: Power Supply Analog Current
 Power Supply Analog Voltage
 Coil Analog Voltage
 Slow Dump Bus

Analog Output: Analog current control signal
 0-10 V @ 5 k Ω

Digital Input/Output: I/O IEEE-488 Bus

LLL Computer

I/O Indicator: slowdump

Power: 115 VAC, 1A - Backup: 12 VDC, 5 A

4.8.2 Front Panel

4-32

Power Supply Current

Current Level

Level
Select

CURRENT CONTROLLER

Voltage

Current Rate

Current Rate
Select
Amps/sec

Computer

Local

Master

Ramp-to-Level

Ramp-to-Zero

Hold

At-Level

Power

On

INTERMAGNETICS

MFTF CURRENT CONTROLLER BLOCK DIAGRAM

4.9 Microprocessor Display

4.9.1 Description

The display unit contains a gas discharge 32-character alphanumeric display and interface compatible with the IGC microprocessor module.

Specifications

<u>I/O Interface:</u>	IEEE-488 bus 0.2" x 0.14" character size
<u>Display:</u>	32 alphanumeric .2" x .14" characters
<u>Power:</u>	115 VAC, 1 A

4.9.2 Front Panel

MICROPROCESSOR DISPLAY

5.0 CONCLUSION

Although the recommended protection system appears extremely complicated, if one examines the main critical circuit paths, it is extremely simple. Only a few gates separate a given quench detector from the 6000 A fast dump breakers. The same situation is true for the slow dump breaker. For example, the overpressure switch inputs pass through only a few integrated circuits before activating the slow dump breaker. Much of the overhead in the system relates to the diagnostic capability, test capability and additional reliability added to the system which will pay for itself in saved helium and downtime.

Superconducting magnets are somewhat unpredictable. Some have been known to quench after many hours of flawless operation. The danger is that personnel begin to believe that the magnet is safe and it does not need to be protected. When a small deviation from normal operation occurs, a critical problem can go unnoticed, leaving the magnet open for damage. With a comprehensive protection system such as that recommended, this situation is unlikely to happen.

Other approaches to the protection problem have been considered. A package of any kind should be modular for accessibility and maintenance. Few commercial modular packages are designed for the rugged and noisy environment of a superconducting magnet, rather, most modular packages are slanted toward non-critical experimental process and control applications.

There are other needs such as redundancy, additional inter-module cabling, and self diagnostics that makes the MFTF protection magnet problem difficult to solve with most standard test equipment and computer interface modules.

Modification of equipment not specifically designed for the task may precipitate a host of problems. A more reasonable approach is to use specialized modules such as those described in this study to attack the problem.

Putting the entire protection system together will be a formidable problem. The software and systems integration effort is easy to underestimate. The hardware design and fabrication is more straightforward and can be done in a cost-effective fashion. But if the hardware is not properly integrated it can precipitate an enormous system problem. In this study, we have carefully selected each module to meet the needs of the system which should in the end reduce the magnitude of the problem.

6.0 REFERENCES

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NOTICE

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