FAULT MONITOR FOR MULTI-MEGAWATT AVERAGE POWER PULSERS

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Summary

Fast-acting, interactive fault monitoring system used to protect an ERADCOM resonantly charged 50 kilojoule, 6 megawatt average power pulser will be discussed as to its design. construction and history of operating performance.

Introduction

Multi-megawatt average power repetitively operated pulsers using multiple switches requires fault protection to prevent damage to the pulser or its associated load. The pulser itself has to be protected against unequal current sharing through the multiple switches and against load or internal arcing. Furthermore, when a fault does occur, the fault protection must signal the system power supply to cease operation.

The fault logic described in this report was designed for the six megawatt average power pulser schematically shown in Figure 1. The design resulted from an earlier, single thyratron fault detector, Reference 1. The multi-megawatt version is similar to a previously reported design, Reference 2. There are six MAPS-40 thyratrons, Reference 3, (EG&G model HY7) that discharge 20 microsecond (μs) pulse forming networks (PFNs) into the primary of a step-up pulse transfromer. The pulser is capable of delivering 50 kilojoules per pulse to a matched load. The pulser was resonantly charged from a direct current (dc) power supply. Each of the six modules making up the pulser consist of two lumped element PFNs, each with its own end-of-line clipper, Reference 4. The two PFNs operate in parallel, discharging through one thyratron per module. A Hall effect current sensor monitors the charging current feeding the pulser. Current transformers are used to sense tube current, end-of-line clipper current and load current. An uncompensated voltage divider is used to monitor the anode charging waveform. In addition to these pulser sensors, the fault monitor generates six isolated trigger signals in sync with a system command signal. Each of the six trigger signals feeds into a EG&G TM-30 thyratron trigger unit. If a fault is detected, then the fault monitor generates a shut-down signal to prevent damage to either the pulser or the load.

Logic Design Principles

The logic guidelines evolved from major system considerations, which include factors such as the problem of protecting expensive pulser and system user components and the adverse impact of system down-time on scheduling and manpower. In order to protect key components, the logic design was guided by the objective of detecting all faults even at the expense of a small number of false alarms. To maintain a high degree of reliability, and at the same time, a low number of false alarms required logic with the highest degree of noise immunity. Any damage sustained by the fault monitor should not jeopardize the monitor's ability to generate its shut-down sequence. The logic should be flexible to the extent that it could be made to operate with any number of pulser modules. It was essential that the logic incorporate a self-check feature to assure fault monitor operability. To minimize down-time the fault monitor should include the identification of the specific fault condition. The fault monitor circuit should be designed so that those components subject to failure under extreme fault conditions could be easily replaced as plug-in units. Further, the damage should be limited to only those plug-in units and not propagate beyond them.

Simplicity was a key guideline in the fault logic design. The types of faults and the number of inputs were chosen on the basis that a detected fault would result in system damage if left uncorrected. The logic display was designed to only show key information. A logic fault simulator was constructed as a separate unit to verify the operability of the fault logic rather than having it made part of the fault logic. The fault logic was designed to "lock-up" on the first fault detected and to ignore the consequent faults. The "1st fault" performance feature was essential to the fault monitor to provide diagnostic capabilities as well as system protection. The fault monitor detects, stores and displays a specific malfunction when it occurs greatly enhancing system maintenance procedures and reducing down-time. Subsequent to a fault, the signals from all sensors can no longer be relied upon to provide an accurate assessment of failure.

CMOS logic was selected primarily because of its superior noise immunity. This family of logic can operate at comparatively high voltages, up to 20 volts and because of its complementary structure, CMOS rejects noise which is less than 30 percent of the supply voltage. It ignores noise common to both the input and power supply lines. Built-in diodes protect the CMOS gates shunting larger input signals to the supply line, within limits. Another important aspect of CMOS logic performance is the low current required for logic operation. This feature proves to be extremely valuable in reducing the shielding requirements for the logic package. Since adequate test data was not available on CMOS operation in very high pulsed field environment, an experimental battery operated test circuit (a timer) was constructed using CMOS logic. The circuit was packaged in a commercial aluminum small chassis box. A thin aluminum blank plate covered the open side of the box and was secured to the box with sheet metal screws. No additional shielding was used. This box was placed in a pulsed 0.3 Tesla field generated at the open end of the solenoid of a high energy PFN. The timer was operated in this pulsed field for three hours without error. The conclusion was that CMOS logic is relatively insensitive to even very high magnetic fields. This verified our original supposition that only electro-static shielding was required for the fault monitor.

Flexibility was built into the logic design by providing adjustable threshold detection limits and adjustable timing signals to allow for varying pulser repetition rates. The fault monitor, as built, could operate from one to six pulser modules, and with additional sensor input boards, could be made to operate with more than six pulser modules. Additional flexibility allows the operator to select whether to shut down the system if one switch failed to fire, or if two consecutive failures to fire were detected.

Minimal stand-by power consumed by the CMOS logic allowed the fault monitor to operate from internal

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14. ABSTRACT

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D cell batteries. However, the bipolar threshold circuits, the LED display unit and the bipolar Darlington driver circuits had to be designed to conserve power.

To protect the logic, all inputs from all sensors were provided with isolation and shaping circuitry. The system command trigger was transformer isolated, as was the output triggers to the six thyratron trigger (TM-30) units. The output shut-down signals were also transformer isolated.

Fault Conditions

Table 1 lists the types of faults that initiate system shut-down. Prefires refer to one or more switches firing out of sequence (switch firing without a trigger signal). This can result in system malfunctions and thyratron switch damage caused by dumping all the pulser stored energy through one switch. The fault logic is designed to internally generate six thyratron trigger signals when a prefire is detected to insure that any switch does not pass more than its share of the total energy. The logic also generates a 10 volt (V) fault signal back to the system command console. This fault signal was used to trigger a crowbar across the load and to shut down the power supply.

Misfire refers to the failure of one or more thyratron switches to fire when triggered. This will result in increased dissipation in the thyratrons that fire, however, this is not considered to be as serious a fault as prefire. The logic has a provision which allows the operator to choose whether shutdown should be initiated by one misfire or by two consecutive misfires of the same switch, or by two other switches. Misfiring of a thyratron is usually symptomatic of a need for hydrogen reservoir adjustment, or switch replacement.

Continuous conduction refers to the inability of any switch to recover its voltage hold-off capability. The logic senses continuous conduction by looking at the anode charging waveform some time after the switches have fired. If the signal from the voltage divider senses an anode voltage below a predicted minimum, then the logic will register a continuous conduction fault. Continuous conduction can also result from capacitor failure, or a breakdown somewhere in the system. Whenever continuous conduction occurs, the system must shut-down.

Load fault is sensed as an unusually large end-of-line clipper current, Reference 5. It can result from a load arc, step-up transformer breakdown or a faulty load crowbar. Since all networks are connected in parallel when the thyratron switches are fired, only one end-of-line clipper current transformer output is connected to the logic. Improved system reliability would be achieved if the actual load current were used as the load fault input signal, as it would be available regardless where the load fault occurred in time relative to the pulser firing. The logic detects load fault as an input signal exceeding a preset voltage threshold.

Overcurrent refers to excessive charging current averaged over a period equal to the inverse of the repetition rate. The overcurrent sensor will detect current levels in excess of the integrated charging current. This condition could result from a damaged charging choke or from a leaky capacitor. Like the load fault, the overcurrent condition is sensed by an input signal exceeding a preset voltage threshold.

Logic Operation

Table 2 lists the major features of the fault logic circuit. Common to all inputs in this figure are the isolation and shaping circuits. The isolation has been provided by the current transformers, which are electrically isolated from the pulser frame. The RG-58 C/U coaxial leads from the current transformers terminate onto chassis BNC connectors. The exception is the continuous conduction sensor which is a voltage divider and cannot be transformer isolated. Until recently, when optoisolators were incorporated into the input isolation stages, the voltage divider input had not been effectively isolated from the pulser. Optoisolators were added to effectively limit damage to the fault monitor, to a single plug-in component. Thus, extensive damage throughout the fault monitor, as a result of extremely high signal input levels, is eliminated.

The shaping circuit is a Schmitt trigger, which embodies a 15 V zener as an input protection element. The Schmitt trigger switches start when the signal level exceeds 6 V and has a hysteresis of approximately 1 V. At full power, each pulsed MAPS-40 switch current reaches 40,000 amperes (A). With the thyratron current transformer ratio of 10,000 A per volt, the optoisolator input for each of the thyratron current signals will reach 40 V. The optoisolators have approximately unity voltage gain so the fault monitor will respond to thyratron pulsed currents greater than 6,000 A. Lowering the Schmitt trigger threshold below 6 V to sense lower thyratron currents increases the susceptability of the fault monitor to noise spikes. The selected threshold represents a good compromise between range of operation and noise immunity.

Timing of the prefire, misfire and continuous conduction faults is shown in Figure 2. The timing zone diagram refers to the command trigger as its reference point in time. All MAPS-40 switches must fire within a 5 μs valid fire zone beginning at the leading edge of the command trigger. Failure of any thyratron switch to fire within the valid fire zone constitutes a misfire. The 5 μs chosen includes various triggering delays in the logic and in the pulser, plus variation in thyratron switch firing times. For the next 600 μs when system noise is the greatest and input information is of little consequence, the logic is inhibited to prevent unwanted noise spikes from falsely triggering the logic. The logic is sensitive to prefires at any time other than the valid fire zone and logic inhibit zone. The continuous conduction signal is proportional to the anode charging voltage, and is sampled 8 milliseconds into the pulse for 100 Hertz operation, 80 percent of the interpulse period. Threshold detection circuits use a zener for absolute voltage reference. A pair of NPN and PNP transistors are used in a ON-ON/OFF-OFF configuration in the threshold circuit to conserve battery power. The circuit draws current only when the signal exceeds the threshold limit. The threshold setting for continuous conduction was chosen as 25 percent of the value expected at 80 percent into the interpulse period.

The logic lock-up circuit inhibits the logic registers when a fault is detected. The lock-up circuit ensures capturing the first fault only of a fault sequence. All subsequent fault data has no real value. For that rare event when two or more independent simultaneous faults occur, the logic will record and display all the simultaneous faults.

The simplified diagram of the fault monitor logic is shown in Figure 3. To understand the logic operation requires tracing each of the input signals through the logic. Each thyratron current transformer input passes through an isolation and shaping circuit and enters a thyratron switch identification storage register. This register stores the status of each of the MAPS-40 thyratrons as a function of time. The logic examines the register in accordance with the timing diagram, Figure 2, in order to determine if a fault condition has occurred, and the nature of the fault. The identified fault is stored in a fault register.

The continuous conduction signal upon shaping enters the continuous conduction threshold detector. When the continuous conduction gate signal reaches the detector, the threshold circuit examines the input signal to determine if the anode charging voltage exceeds the threshold. If it does not, then a signal is sent to its fault storage register. The load fault signal, once shaped, is examined by its threshold detector circuit. If the threshold is exceeded, a signal is sent to the appropriate fault storage register. The overcurrent signal upon passing through the shaping circuit, is integrated and then compared to a predetermined threshold. If the threshold is exceeded, a signal is sent to the appropriate fault storage register.

Once a fault is registered, then two actions occur simultaneously. A shut-down signal is generated and logic lock-up is initiated. The outputs of the switch identification storage register for the prefire and misfire conditions are sent to the display circuit along with the type of fault from the fault storage register. If a prefire condition is recorded, then another signal is sent to the thyratron trigger generator. This generator provides a firing signal amplified by the trigger booster circuit, to fire all switches.

Not shown in the logic flow diagram is the provision for selecting whether one misfire or two consecutive misfires are required to generate shut-down. The two consecutive misfires could be from the same switch, or from two different switches. The selection is made by setting a 2-position toggle switch located on one of the logic boards located inside the logic enclosure. If two switches misfire simultaneously, then both switch positions will be displayed. If the same switch misfires twice, then only one position will be displayed. A picture of the logic display is shown in Figure 4, and the complete fault monitor logic circuit is shown in Figure 5.

Results

The fault logic was first tested with the compact megawatt module pulser in a open-loop configuration. The logic was monitored as the pulser operated at the megawatt average power condition for runs of 10 to 21 seconds duration at repetition rate of 100 Hertz. Once the threshold detector levels were set, the fault logic operated as expected. Simulated faults were properly detected. Later, the fault logic was operated with five of the six modules of the ABEL brassboard modulator, again in an open-loop configuration (shut-down output signal is not used to terminate system operation) for evaluation purposes. The fault monitor successfully demonstrated the full detection capability, which is required. In fact, it proved to be very useful in the open-loop configuration, as a test instrument for aligning individual thyratrons to achieve coincidence of firing times. Once all switches were aligned, the logic operated as designed. There was one serious logic failure when a switch prefired at full voltage and simultaneously its end-of-line clipper shorted to ground. The switch current transformer experienced approximately ten times the normal peak current. The signal from the current transformer destroyed the protective zener circuit and subsequently damaged many of the CMOS integrated circuits on the input board. To avoid further incidents of this type and to improve input isolation, the logic input signals have been optically isolated. If such a rare event occurs again, then damage will be confined to the optoisolator which can easily be replaced.

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TABLE 1

FAULTS REQUIRING SYSTEM SHUT-DOWN

1. Prefires
2. Misfires
3. Continuous Conduction
4. Load Faults
5. Over Current

TABLE 2

MAJOR FEATURES OF FAULT LOGIC CIRCUIT

1. Isolation/Shaping
2. Timing
3. Threshold Detection
4. Logic Lock-Up

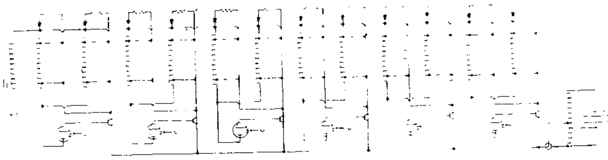

Figure 1. Six megawatt average power pulser schematic.

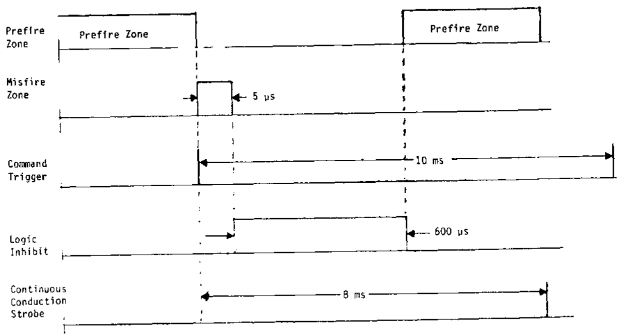

Figure 2. Fault logic zone timing diagram.

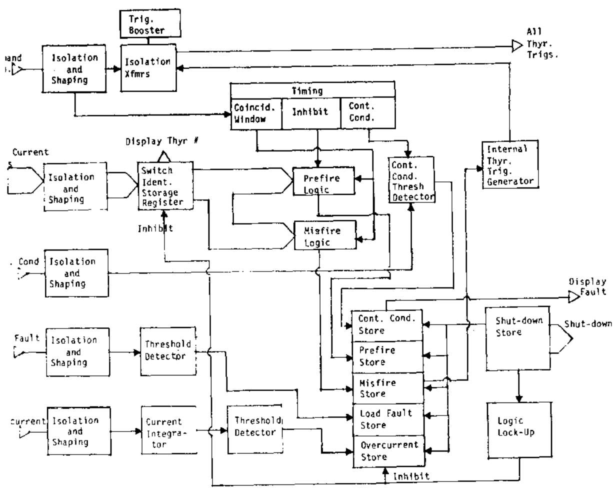

Figure 3. Simplified fault monitor logic diagram.

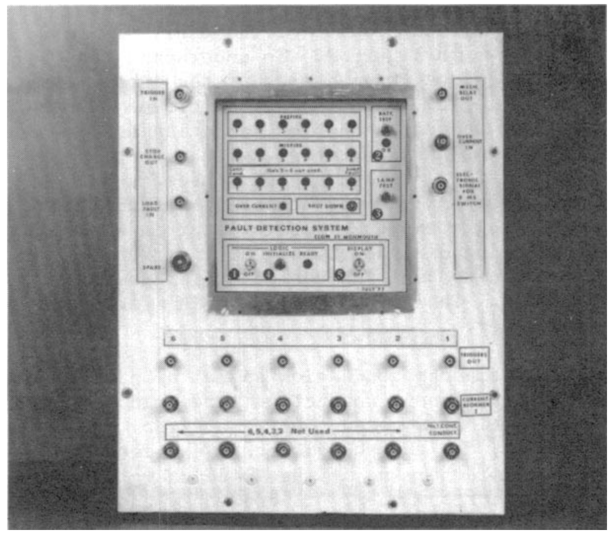

Figure 4. Fault monitor display.

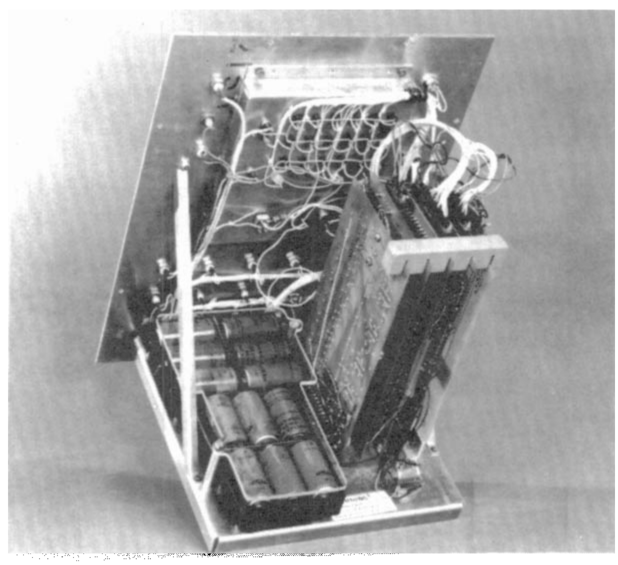

Figure 5. Fault monitor logic prototype.