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A New Overcurrent Protection System for the DIII-D Field Shaping Coils

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Abstract*—A new system has been developed to protect the 18 field shaping coils (F-coils) of the DIII-D tokamak from excessive currents. The new system removes the limitations of the original system and improves reliability. Coil currents are sensed in the new system by Rogowski coils wrapped around conductors feeding the F-coils. The Rogowski coil signals are routed to a remote electronics rack where the signals are integrated to yield voltages proportional to the F-coil currents. Comparators monitor the F-coil current signals and command the coil power supplies to turn off in the event of excessive currents. The F-coil current signals are also sampled by a dedicated data acquisition system for comparison to signals acquired elsewhere. The integrating electronics are interfaced to the DIII-D Integrator Calibration System, which verifies proper integrator operation once daily (typically) or on demand. The new over-current system also features a "self-test" function, which ensures that the Rogowski coils and their signal paths have not open-circuited. The test is performed during the preparatory "get ready" procedure of each DIII-D experiment "shot". A test voltage is momentarily applied to each sensor circuit (Rogowski coil and signal cable) to produce a simulated current signal, which is measured and integrated. The resulting signal is checked by a window comparator circuit to verify that the sensor circuit has continuity, that the integrator has the proper time constant, and that the test signal disconnects when the test is complete. If all these conditions are met (for all 18 F-coils), the "get-ready" procedure is allowed to continue. Otherwise, the procedure is halted and warnings are generated. LED lamps on the system's modules indicate statuses and results of the tests for each of the 18 channels. Design details of this new system are presented.

I. INTRODUCTION

The 18 field shaping coils (F-coils) of the DIII-D tokamak have administrative current limits ranging from 5.5 to 12.5 kA, well below the stress and thermal limits of the coils. Various events can arise during the operation of the F-coil power supplies that can result in F-coil currents exceeding these limits. To keep coil currents within these limits, an overcurrent protection system was originally developed to monitor the currents. The original system utilized biased Hall-effect current sensors and comparators to detect excessive current in any of the 18 F-coils, and produced a single "abort" signal which terminated the DIII-D experiment "shot" and turned off the power supplies feeding the coils. Over time the original system became less reliable, especially as experiments called for larger currents in the F-coils where the signals started to saturate.

A new overcurrent protection system (OPS) was subsequently developed with the goal of providing greater reliability and accuracy (Fig. 1). To meet this goal, new current sensors, independent of those used for acquiring coil current data, were to be used for each F-coil. In addition, the system was required to detect the failure of a current sensor and consequently prevent energization of the F-coils. This is critical for protection because a failed sensor might not provide any current signal, in which case excessive current could escape detection. Finally, overall calibration of the system had to be readily maintainable and verifiable.

II. CHOOSING A CURRENT SENSOR

Several devices were considered for sensing the high current DC feeding the F-coils:

A. Hall Effect Devices

These small devices, which require a bias current, produce a voltage proportional to conductor current when properly positioned in the magnetic field resulting from the current flow. Hall effect devices were used in the original overcurrent protection system, surrounded by cores to intensify local fields and desensitize the devices to stray fields. However, non-linearity of the signals resulted from core saturation at higher currents, making the overcurrent detector more sensitive to noise at these current levels, where the saturation reduced signal resolution.

B. Shunts

These simple, resistive devices are rugged, maintenance-free and require no bias. Their installation in series with the F-coil circuits, however, would require difficult reconfiguration of buswork and cables. In addition, their resistance in the circuit might not be tolerable.

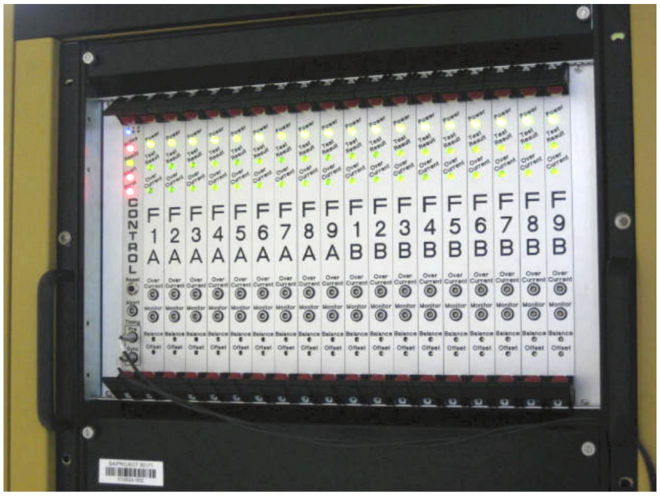

Fig. 1. The new overcurrent protection system (OPS).

C. Hall Effect Current Transducers

These commercially available products develop a small compensating current to null the effects in a Hall effect device of the larger current being measured. The compensating current mirrors the measured current. These transducers are easy to use and very reliable, but like shunts, their size and configuration make them difficult to fit into existing buswork. They also require power supplies, and the cost for transducers of appropriate current range and their power supplies is prohibitive.

D. Rogowski Coils

These flexible, small-diameter solenoid coils, when wrapped around current carrying conductors, produce small voltage signals in response to changing currents in the conductors. Rogowski coils require no bias current or power supplies, and can be easily installed around existing buswork or cables. They do, however, require integrator circuits to provide signals proportional to measured currents.

Rogowski coils are already used to measure F-coil and other large currents at DIII-D [1]. Their signals feed into banks of integrator modules and the resulting current signals are recorded by data acquisition systems. Years of experience with these current monitoring systems at DIII-D, combined with recent integrator design upgrades, led to the decision to utilize Rogowski coils as current sensors for the new OPS. Rogowski coils can be installed without disconnecting, modifying or altering the resistance of the F-coil buswork, and they are electrically isolated from the actual F-coil currents. Since they don't need bias current or power supplies, their instrumentation (integrators, etc.) can be located away from the F-coil buswork and its significant electromagnetic interference (EMI).

III. DESIGN CONSIDERATIONS

The choice to use Rogowski coils as current sensors necessitated some specific design requirements. Of first concern was the need to use integrators. Rogowski coils produce very small voltage signals. DIII-D operations require that the F-coils be energized for up to 10 seconds. During this time the Rogowski coil signals need to be integrated to provide real-time signals replicating the coil currents. Any offset in the integrator circuitry or EMI picked up by the circuit input will also be integrated, and could accumulate as a significant error in the signal. It was therefore necessary to utilize highly-stable integrators and techniques that minimized EMI pickup. Fortunately, the development of the new OPS coincided with the commissioning of newly redesigned integrator circuits of improved stability for magnetics diagnostics at DIII-D. This integrator design was a perfect candidate for use in the new OPS. Furthermore, the design was compatible with the existing DIII-D Integrator Calibration System, so a method was already in place for monitoring integrator calibration and stability.

Another concern was how to verify the integrity of the current sensors. The Rogowski coils in use at DIII-D are essentially long, flexible, single-layer solenoid coils wound with fine wire and covered with protective plastic. Although fairly trouble-free, the most likely failure would be an open-circuit due to a break in the Rogowski coil wire, its connections, or in the wiring between the Rogowski coil and the integrator. Such a failure would cause a loss of the Rogowski signal and possibly the introduction of noise. Considering the simple, passive nature of Rogowski coils, an effective method to check for such a failure would be a continuity test. A voltage could be injected into one leg of the Rogowski coil circuit and measured at the other leg; failure to read the return voltage could be interpreted as a failure. Automated continuity checking could be built into the OPS, and tests could be performed before every DIII-D experiment shot.

IV. IMPLEMENTATION

The new OPS was built in the VME form factor. A single powered crate contains one "control card" and 18 "coil cards". Inter-card communication occurs via the backplane bus, and interface connectors are installed on "I/O" boards behind the backplane. The front panels contain indicator lamps and monitor points, as well as access to balance and offset adjustments. For proximity to the Integrator Calibration System and to avoid areas of high EMI, the entire crate is installed in the DIII-D Control Room Instrumentation Annex, far from the F-coil cables and power supplies. To acquire the F-coil current signals developed in the new OPS, a commercially available 96-channel Ethernet-addressable waveform capture digitizer is installed in a powered crate nearby and connected to analog signals from the 18 Coil Cards. Digital status signals from the Coil Cards and the Control Card are also fed to the digitizer. The digitizer is set up to acquire data during DIII-D operations. The acquired data is uploaded to a nearby rack-mount computer, which serves the data as part of the DIII-D Data Acquisition System. A block diagram of the new OPS is shown in Fig. 2.

The 18 Coil Cards were designed as identical units, one per F-coil. Each card contains an integrator circuit, along with the relays necessary for automated calibration, sensor continuity checks and for integrator reset. Also included are window comparators, latches and indicator lamps for both the overcurrent and continuity check functions. The overcurrent comparator trip points are adjustable so each card can be set to the current limits of its respective F-coil. Voltage monitors verify that the cards receive appropriate power, and various buffers are included as needed. Lamps indicate statuses of power checks, overcurrent faults and sensor tests.

The Control Card contains a Complex Programmable Logic Device (CPLD) which coordinates all functions of the system. This device receives triggers and commands from the Integrator Calibration System and from the DIII-D Timing System. Processes are initiated which then control the functions of the Coil Cards via the backplane bus. Results of the various tests and functions return on the bus to the CPLD, where logic determines whether to send READY or ABORT signals to the DIII-D Control System (lamps indicate these statuses). The Control Card also contains signal buffers and output relays, generates a precision voltage signal for the sensor continuity checks, and interrogates statuses of the Coil Card voltage monitors. Panel lamps indicate various process and test statuses.

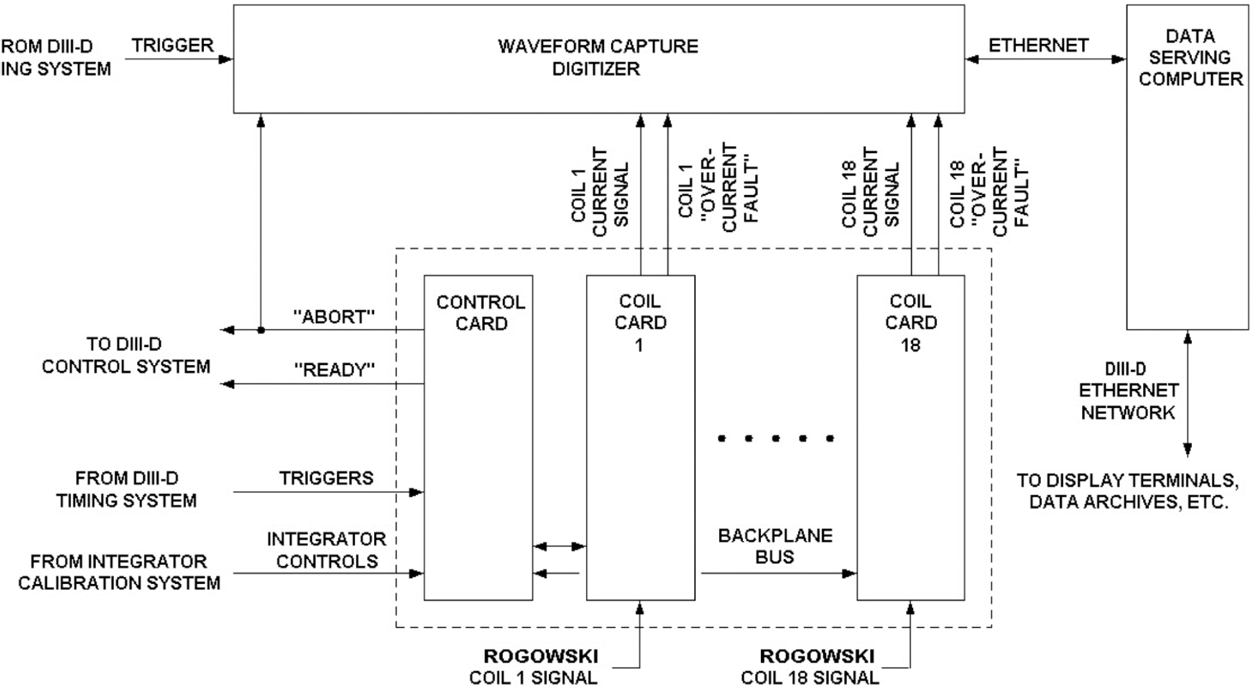

Fig. 2. Block diagram of the OPS.

V. OPERATION

Typical operation of the OPS involves three distinct processes: integrator calibration, sensor continuity check, and overcurrent detection.

A. Integrator Calibration

At the beginning of each DIII-D operations day integrator calibration checks are performed. An automated system is triggered which switches a test signal to the inputs of all integrators while digitizers acquire the resulting outputs. The acquired data is uploaded to computers in which analyses are performed to check the accuracy of the integrated signals. The results are logged, and flags are set to indicate discrepancies from the expected waveforms.

The OPS is fully interfaced to the Integrator Calibration System. As with other DIII-D integrators, relays disconnect integrator inputs on the Coil Cards from sensor signal wires and connect the inputs to the test signals from the calibration system. Additional relays switch the integrators from a "reset" state to an "integrate" state while the calibration check is in progress. Once the process is complete, the relays reconnect the inputs to the sensors and reset the integrators. Discrepancies found in the acquired data are flagged and operators are alerted.

B. Sensor Continuity Check

Before each DIII-D experiment shot is fired, a "get ready" procedure is initiated that gets all systems ready for the shot. Early in the procedure the OPS is triggered to initiate a sensor continuity check. The Control Card terminates a "ready" interlock to the DIII-D control computer, and sends a command to the Coil Cards to start the check. Relays set the Coil Card integrators to the "integrate" state. Other relays disconnect the grounded ends of the Rogowski coil circuits and inject a precise DC voltage signal through the Rogowski coils and back to the integrator inputs. After a set period of time the relays disconnect the DC signal from the Rogowski coils and reconnect the Rogowski coils to ground, while the integrators are kept in the "integrate" state. During this process the integrated signal from a Rogowski coil should resemble a constant rate voltage ramp-up to a specific value and then a hold at this value (Fig. 3). At the moment of disconnection of the DC signal, a window comparator begins monitoring the integrator output for a period of time. If the integrator output voltage remains for the entire test period within the window defined by the comparator's upper and lower trip points, then that Coil Card latches the result that continuity was detected in the sensor circuit. A lack of continuity would result in the test voltage not returning to the integrator input, so the output would not ramp into the window. If all 18 sensor circuits pass the continuity test, then the Control Card latches and restores the "ready" interlock to the DIII-D control computer. The control computer checks the "ready" interlock later in the "get ready" procedure, and halts the procedure if the "ready" is not present.

This check actually verifies more than just sensor circuit continuity. First, the fact that an integrator signal ramps into the window by the time the comparator test begins also verifies that the integrator works properly and that its time constant is correct. A time constant too low or too high would result in an incorrect ramp rate, and the integrator output would either exceed the higher trip point or not traverse the lower trip point of the window comparator before the test signal was disconnected. As mentioned before, the integrators are thoroughly tested by the Integrator Calibration System at the beginning of the operations day. However, the OPS continuity check reverifies integrator function before every DIII-D shot.

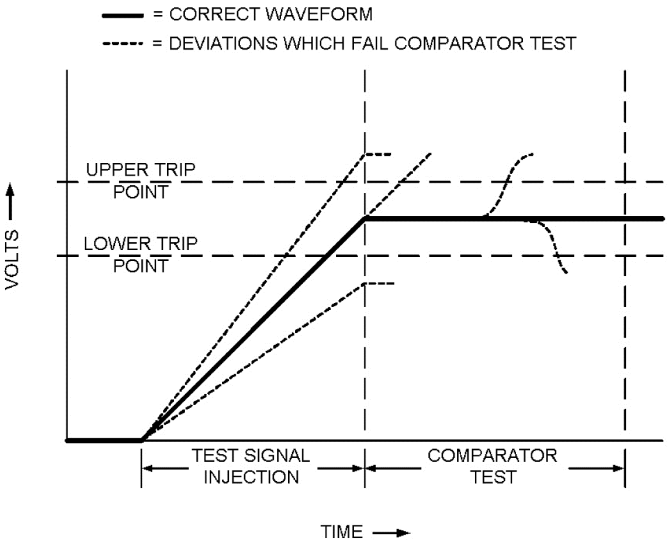

Fig. 3. Integrator output during sensor continuity check.

Second, the time period of the comparator test was chosen such that the system also checks that the test completes properly and that the system removes the test voltage and reconnects the sensor circuit to ground. If the test does not terminate at the proper time (for example, if sticking relay contacts cause the test signal to stay connected), then the integrator output would continue ramping upward, exceeding the comparator upper trip point and resulting in a failed test. Excessive integrator drift would also result in a failed test as the output signal passes beyond the upper or lower trip points during the test period. By checking comparator voltage at the moment of test signal disconnection and for a period of time after, the system verifies sensor continuity, integrator integrity and proper test completion.

Finally, if for some reason the continuity check does not run when commanded, then the "ready" signal, which was terminated at the beginning of the check process, remains off at the end of the process, as if a sensor did not pass the continuity check. The DIII-D "get-ready" procedure checks this status and halts, awaiting intervention. In summary, once a trigger is received to start the continuity check, the "ready" interlock is only provided if the check process completes and positively identifies continuity in all 18 sensor circuits.

C. Overcurrent Detection

Assuming that the sensor continuity check is successful and the DIII-D "get-ready" procedure completes, the OPS is ready to protect against F-coil overcurrent faults as a DIII-D experiment shot is fired. Each Coil Card window comparator has a positive and a negative voltage trip point. For any particular F-coil, the two trip points are set with on-board potentiometers to the same magnitude (to detect excessive current in either direction through the coil). As current in the F-coil begins to flow, the integrator output provides a voltage signal to the window comparator proportional to the coil's current. If this signal value exceeds either the positive or negative trip point, the comparator detects and latches an overcurrent fault for that coil. The fault signal is sent to the Control Card, which also latches that an overcurrent has been detected in the F-coils. An "abort" signal is sent to the DIII-D control system, and the F-coil power supplies are turned off as the experiment shot is terminated. The faults detected in the OPS remain latched until reset during the next "get-ready" procedure. Latched fault indications, as well as coil current signals, are acquired by the waveform capture digitizer.

VI. CONCLUSIONS

The new overcurrent protection system prevents excessive currents in the DIII-D field shaping coils with improvements over the original protection system. The new system's Rogowski coil current sensors were installed without disturbing the F-coil buswork. The sensors do not saturate, resulting in greater accuracy and improved noise immunity at higher coil currents. The new OPS checks sensor circuits and integrators before each DIII-D shot, and prevents the shot from starting if a failure is detected or if the sensor check fails to run or complete properly. An integrator design with improved stability was incorporated in the OPS. The integrators fully interface with the existing Integrator Calibration System, providing for daily checking of integrator accuracy. The OPS includes its own data acquisition system for redundant measurements of coil currents and for recording the detection of overcurrent events. The improved protection provided by this system allows greater utilization of the full capability of the DIII-D tokamak.

ACKNOWLEDGMENT

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