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A New Crowbar System for the Protection of High Power Gridded Tubes and Microwave Devices

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ABSTRACT

As part of the electron cyclotron heating (ECH) facility upgrade at the DIII-D National Fusion Facility, two 8.4 MW modulator/regulator power systems were designed and constructed (Ref. 1). Each power system uses a high power tetrode to modulate and regulate the cathode voltage for two 1 MW-class 110 GHz gyrotrons (Ref. 2). A critical element in the power system is the fault energy divertor, or crowbar switch, that protects the tetrode and the gyrotrons in the event of an arc fault. Traditionally, mercury filled ignitron switches are used for this application, but it was desired to eliminate hazardous materials and improve overall switching performance. The new crowbar switch system was required to meet the following requirements:

- Operating voltage: –105 kVdc
- Peak current (750 ms e-fold): 1.6 kA
- Follow-on current: <1 kA (25 ms)
- Charge transfer per shot: <15 Cb
- Turn-on time: <1 μs

The switch that was chosen for the new design is a low pressure deuterium filled device, called a metal-arc thyratron, manufactured by Marconi Applied Technologies (Ref. 3). In addition to the new crowbar switch assembly, improved fault signal processing circuitry was developed. This new circuitry uses fiber-optics for signal and trigger transmission and a complex programmable logic device for high speed signal and logic processing.

Two generations of metal-arc thyratrons have been commissioned in the two ECH power systems constructed at DIII-D. In the first, the crowbar system performed extremely well, meeting all of the operating requirements and demonstrating its ability to protect a 36 gauge copper wire from fusing (energy let-through <10 J). However, after accumulating over 500 shots, the metal-arc thyratrons lost their ability to reliably hold-off voltage. This problem was solved by Marconi with a design modification of the thyratron electrodes. The second generation tubes were installed in the second ECH power system. The crowbar system was fully commissioned and all of the performance requirements were satisfactorily achieved.

The design of the crowbar switch and the fault signal processing system and their performance will be presented in this paper.

1. INTRODUCTION

High voltage, high power amplifier, regulator, and rf/microwave tubes are prone to internal arc faults and can become severely damaged if too much energy is deposited in the fault. To protect these usually expensive devices it is required to interrupt or divert the source electrical energy from the fault. The classical method by which to accomplish this is to use a switch to rapidly short the terminals of the input power supply and then to de-energize it. The shorting of the power supply terminals, or crowbarring, diverts the source energy from the fault, minimizing the deposited amount of energy and allowing the fault to clear. The crowbar switch continues to conduct the power supply current until the supply is de-energized, usually by the opening of the main circuit breaker. Interruption of the fault current can also be accomplished by use of a fast opening switch. However, mature switch technology that can interrupt high current at high speed and reliably block voltage greater than 100 kV is only recently beginning to become available. For this reason, the lower risk, traditional shunt divertor topology was chosen for the new DIII-D ECH crowbar system design. The overall ECH modulator/regulator power system is illustrated in figure 1 with an emphasis on the crowbar circuit.

A conventional transformer and rectifier are used for the conversion of the ac three-phase line power into the high voltage dc power required for the gyrotron loads. The power system can be rapidly disconnected from the main ac lines, within 1.5 cycles or 25 ms, by a fast-interrupting circuit breaker that is also backed up by current-limiting fuses. Within the modulator/regulator (M/R) vault is located the crowbar switch assembly, filter capacitor bank, and the M/R tetrode hot deck. The gyrotrons reside in a different location and are

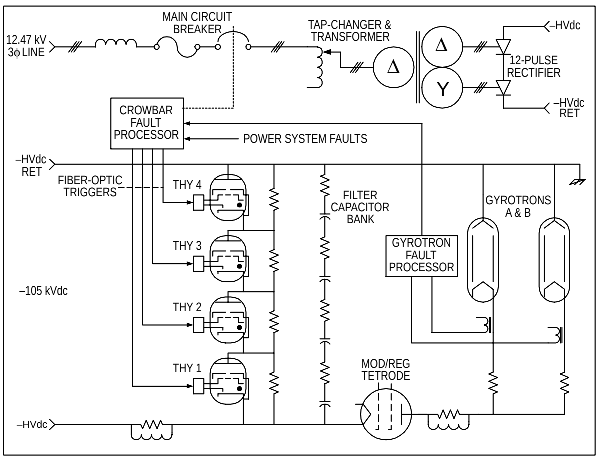

Figure 1. Simplified circuit diagram of the ECH modulator/regulator power system emphasizing the crowbar circuit.

connected to the M/R via coaxial transmission lines. The gyrotron fault processing electronics are also located remotely from the power system.

2. DESIGN & SYSTEM DESCRIPTION

In a protective crowbar system design, the key element is the crowbar switch. To be effective, the switch must: (1) have a high speed response, (2) reliably fire when commanded, (3) indefinitely hold-off high voltage without spurious self-breakdown, (4) reliably conduct with a low starting voltage and have a low conduction voltage drop, and (5) be able to transfer large amounts of electron charge without damage. Mercury filled ignitrons, if used in a circuit designed with substantial voltage margins and special heating and cooling equipment, would meet the criteria. It was desirable to avoid the presence of hazardous materials in new designs.

2.1 The Switching Device

The switch that was chosen for the new DIII-D design is a relatively new, low pressure deuterium filled device manufactured by Marconi Applied Technologies (Ref. 3). The device is referred to as a metal-arc thyratron. It operates in a regime to the extreme left of the Paschen minimum and relies on metal-arc vapor from a cold cathode as the principle conduction mechanism. Designated the HX-2500 (Ref. 4), the switch has combined characteristics similar to a hydrogen thyratron and a triggered vacuum gap. The thyratron-like triggering characteristics and high-speed response combined with high charge transfer capability and a wide operating voltage range, make the HX-2500 an appropriate choice for crowbar service. With an operating voltage rating of 30 kVdc, four switches would need to be connected in series to provide appropriate margin at the highest operating voltage of –105 kVdc. The series arrangement is illustrated in figure 1. A photograph of a single stage of the crowbar switch assembly with an HX-2500 installed is shown in figure 2.

The current and electron charge handling capabilities of the switch are important considerations. The highest peak current produced in the DIII-D system is that due to the discharge of the capacitor filter and the high voltage transmission cables when the crowbar switch is fired. At the maximum voltage, the peak current is 1.6 kA and is well within the rated 7.5 kA of the thyratrons. The more important parameter is the amount of electron charge that is transferred through the switch during each shot. While the capacitor filter and the cables produce a high peak current, it is of short duration and does not contain significant electron charge (~1 Cb). It is the conduction of the power supply follow-through current that supplies the large portion of charge. Since the main circuit breaker reliably interrupts within 25 ms, the total transferred charge during a crowbar event is ~13 Cb. The source impedance of the power supply limits the follow-through to peak values that are less than 1 kA. The HX-2500 thyratron is rated to transfer 40 Cb of charge on a per shot basis as long as the follow-through current is about an order of magnitude less than the peak current rating.

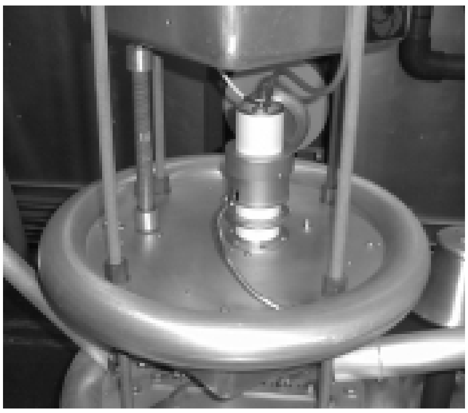

Figure 2. Photograph of a single stage of the crowbar switch assembly.

2.2 Controls and Fault Processing

A protective crowbar system not only involves a highly specialized switching device, but also includes sensors and electronics to detect and process faults into firing commands and other indicators. Ancillary circuitry for the thyratrons such as grid drivers and heater power supplies are also required.

The control and fault processing circuitry incorporates both “hard-wired” discrete and programmable logic. A simplified circuit diagram of the crowbar fault processor is illustrated in figure 3. The “hard-wired” discrete circuitry provides the primary firing function. There are four fiber-optic command inputs transmitted from the gyrotron system fault processor and the power system fault processor. A fifth input is derived from the crowbar discharge current transformer and is used to detect a self-breakdown of the switches. A manual push-button input is also provided for crowbar test firing. These inputs are summed together through isolating diodes and in turn set a latch circuit if any of them make a transition to the faulted state. The latch has two outputs; one drives a pulse generator with four fiber-optic output triggers and the other provides a command to open the main circuit breaker. The individual output triggers are

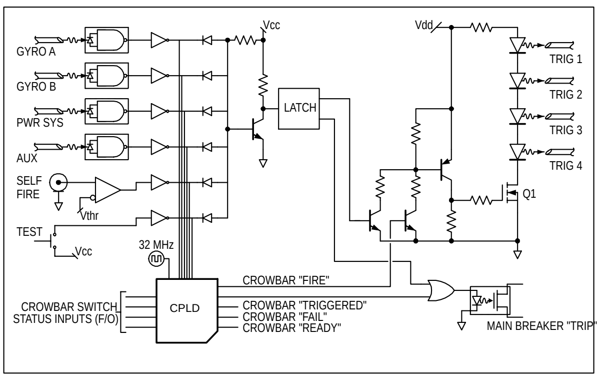

Figure 3. Control, fault processing, and firing circuitry.

transmitted to fiber-optic receivers in each of the crowbar switch stages.

The programmable logic is contained within a complex programmable logic device (CPLD). This device, and its associated circuitry, performs three functions. It replicates the hardwired logic circuit for redundancy; latches the first fault command and indicates it for diagnostic purposes; and monitors the status of each crowbar switch stage. One feature of the programmable logic is a firmware technique to improve the noise immunity of the chip-level circuits. Written in VHDL code, incoming command signals are compared against the 32 MHz clock for three cycles (~100 ns). If the faulted state persists beyond this point, then the decision is made to latch the signal, fire the crowbar, and open the main circuit breaker. Should the signal only be a noise glitch, it is ignored and a spurious crowbar firing is avoided. This circuit also improves the accuracy of the discrimination of the first occurring fault.

2.3. The Switch Assembly and Ancillary Circuitry

Each stage of the crowbar switch assembly is comprised of a thyratron mounted on a deck that provides a Faraday enclosure for the thyratron's ancillary circuitry. Also mounted on the deck is a 25 MΩ high voltage resistor connected in parallel with the thyratron for voltage grading. Four decks are stacked vertically; supported from the floor on porcelain insulators and supported off of each other with fiber-glass threaded rods. The structure of each deck is shaped with toroidal contours for electric field stress control as can be seen in the photograph of figure 2. Electrostatic field analysis software tools were used to guide the design of the crowbar switch assembly structure. The resulting contours, spacing, and grading minimize electric field enhancements such that no detectable corona discharge is produced.

The ancillary circuitry for the thyratron includes heater power supplies for the cathode filament and the deuterium reservoir, a power supply for the auxiliary, or "keep-alive", discharge circuit, the grid drive trigger circuit, and subsystem status monitoring circuitry. A simplified schematic is illustrated in figure 4. Each deck is supplied line power through a low coupling capacitance isolation transformer.

2.4 The Firing Sequence and Thyratron Triggering

The crowbar firing sequence begins with the sensing of a fault. While there are several different types of faults that can occur, the most common are overcurrent faults that are indicative of a tube arc or loss of control of the tetrode. Typically, a current transformer or resistive shunt is the sensor used for detecting the fault. The sensor signal is conditioned and compared to a trip threshold on a fault comparator. If the signal represents a fault, the comparator changes state and a signal is transmitted (via fiber-optic) to the crowbar fault processing circuitry. A "FIRE" command is generated,

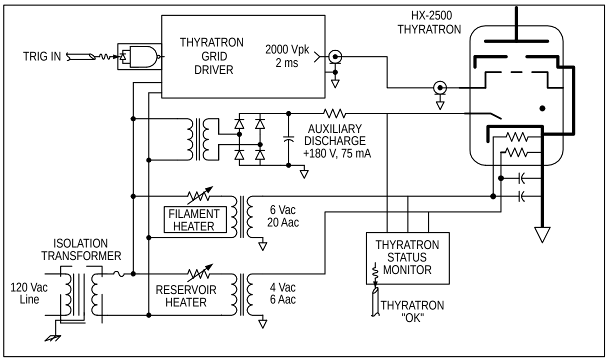

Figure 4. Thyratron ancillary circuitry showing the grid driver, auxiliary discharge circuit, filament heater power supply, and the reservoir heater power supply, and the isolation transformer.

driving the four thyratron trigger outputs and commanding the main circuit breaker to open. This sequence involves several subsystems that may be separated by hundreds of feet and each contributing time delay to the overall system response.

Triggering of the thyratrons is the most critical phase of the crowbar firing sequence with respect to minimizing the system response time and maximizing the protective reliability. As a design goal, an allocation of 1 μs was provided for triggering the thyratrons into conduction. The firing sequence elements that are included in the 1 μs allocation are: processing of a received "FIRE" command; generation of the fiber-optic trigger outputs; transit of the trigger signals via fiber to the thyratrons; generation of the thyratron grid drive pulse; evolution of the discharge in the thyratrons and start of conduction. This sequence is shown on the oscillascope display in figure 5. The thyratron grid drive trigger example shown here is that of the latest firing tube. The through-put delay from receipt of command to the initiation of the thyratron discharge is less than 700 ns.

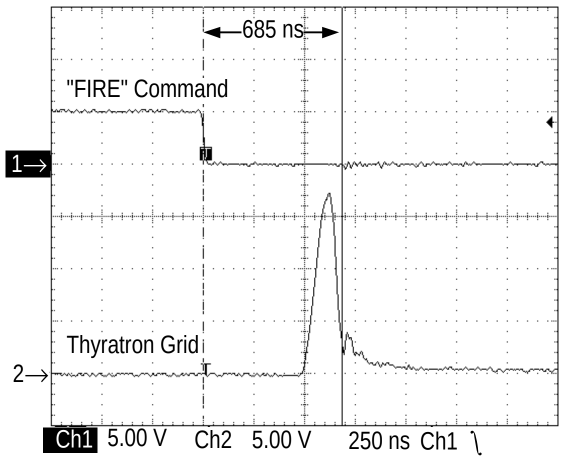

Figure 5. Comparison of the "FIRE" command signal (5 V/div) to a thyratron grid drive trigger pulse (500 V/div). The delay from receipt of command to crowbar switch turn-on is <700 ns.

The portion of this sequence with the greatest variability is the evolution of the discharge and start of conduction in the thyratrons; further complicated by the requirement to drive four tubes simultaneously with close synchronization. The timing relationship of the four thyratron triggers is shown in figure 6. Each individual pulse is highly repeatable and the temporal spread from the earliest to the latest firing is <50 ns. The tightness and repeatability of this synchronization is important since it ensures that the discharge formation in each tube occurs simultaneously and not as a result of severe over voltage. The mechanisms by which the low turn-on delay, tight synchronism, and repeatability are achieved are through a combination of thyratron grid drive parameters. The grid drive pulse, the auxiliary discharge, and the internal tube deuterium pressure all play a role in optimizing the response of the tube. The grid drive pulse has a fast rising voltage (+2 kV in 100 ns) to ensure rapid initiation of the grid to cathode discharge. An optimized tube will breakdown at a grid voltage of 1.5-1.8 kV. Once the discharge starts, the drive pulse must be able to supply a fast rising current (40 A in 100 ns) to generate a strong trigger plasma. Within the first 100 ns following grid breakdown, a strong trigger plasma will have diffused through the aperture of the cold cathode into the main gap of the thyratron. The current drive must sustain the trigger plasma for 1-2 µs while the discharge in the main gap is forming. At this point, the discharge current development is limited entirely by the external circuit. The auxiliary discharge provides a ready supply of electrons that speeds up and reduces the variability the trigger plasma initiation process. The deuterium pressure in the tube is controlled by the reservoir heater temperature. The optimum pressure will allow the grid to cathode breakdown to occur with energetic electrons (1.5-1.8 kV) and will then provide enough gas to be ionized and form a strong trigger plasma. However, the setting of the deuterium pressure must be coordinated such that the voltage hold-off integrity of the main gap is not compromised.

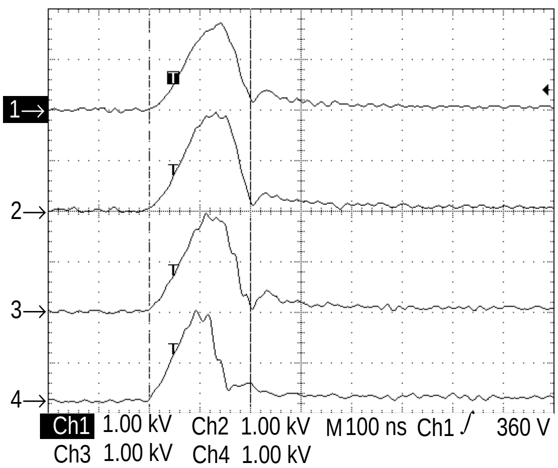

Figure 6. Trigger pulses measured at the grids of all four thyratrons (1000 V/div) showing the timing precision. The temporal spread from the earliest to latest firing is <50 ns.

3. CROWBAR SYSTEM PERFORMANCE

Crowbar system performance is gauged by the following tests and operations that allow evaluation of the system against the design and performance criteria:

- High potential test for long time period voltage hold off integrity
- Wire survivability test for energy deposition limit and overall system response
- Operational experience under real conditions.

High potential testing allows for the evaluation of the high voltage integrity of the crowbar switches, the supporting structures, isolation transformers, and insulators. A high impedance, current limited, high voltage power supply is used to impress a voltage across the terminals of the system. Both of the power systems in service at the DIII-D facility were designed for operation at –105 kVdc and to withstand a -120 kVdc high potential test. During the tests of both systems, the only leakage currents that were measurable were those due to the voltage grading resistors and the high voltage divider. Even at –120 kV, there was no detectable corona discharge and no evidence of ozone production.

The ultimate test of the protective capability of a crowbar system is the wire survivability test. This is a simulated fault test in which a thin copper wire is substituted for the gyrotron. The wire provides an approximately calibrated measure of energy deposition. If the wire fuses during the simulated fault, the energy absorbed is known from the wire diameter, length, and the current flowing during the fault. From this one can determine the fusing action of the wire. For a 36 AWG copper wire, the fusing action is 12.9 Joules/W (or A^2-s) (Ref. 5). For a piece of 36 AWG wire with resistance that is about 1 W (at 20°C), the actual energy to fuse it will be much less than 12.9 Joules. Empirical results from tests performed using a 6 in. long, 36 AWG copper wire indicate that the energy deposition for fusing is 8.7 Joules (Ref. 6) Since the gyrotron manufacturer requires the energy deposition to be less than 10 Joules, passing the survivability test with a 36 AWG copper wire is considered acceptable.

To conduct the test, a high voltage relay is connected in series with the wire and the power system output terminal and is used to initiate the fault. With the power system energized to operating levels, the relay is closed and current will flow in the wire and in turn be sensed by the gyrotron fault diagnostics. The signal travels through the fault processing circuits, as described previously, and the crowbar switches are fired and the main circuit breaker is opened. If the crowbar fires in time and presents a more favorable path for the fault current to flow, then the fault energy is diverted and the wire will survive. It should be noted that the wire test is very stringent in that the voltage drop on the fault is much lower than a typical arc fault and unlike arc faults, it will not extinguish. An example of this wire test is illustrated with the waveforms shown on the oscilloscope display in figure 7. The fault current and the voltage collapse as the crowbar current increases. The total response of this particular system is shown to be less than 4 µs where most of the delay resides in the gyrotron fault processor electronics and the long signal cables. With this test, the crowbar system is considered qualified to be placed into service with a gyrotron load.

There is never a better test of a system's overall performance than the accumulation of operational experience under real conditions. Real conditions include normal operation, occurrence of system faults, externally generated noise, internally generated noise, and even operator errors. A typical crowbar event is characterized by the waveform shown on the oscilloscope display in figure 8. Upon firing, the high and fast peak current appears and then decays to the power supply follow-through current. The double hump wave shape is a characteristic of the power supply complex source impedance. The main circuit breaker opens at ~28 ms. The total charge transferred during this event is ~13 Cb.

In the following sections, some operational experiences with the two systems that were constructed at DIII-D are described.

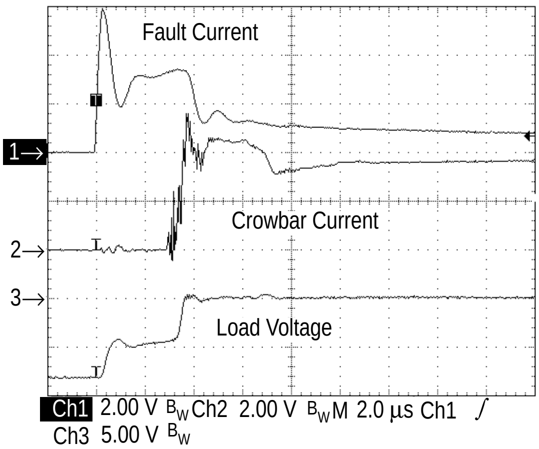

Figure 7 Results of the crowbar wire test in which a 36 gauge wire survived five repeated trials. The top trace is the fault (wire) current (400 A/div), the middle trace is the crowbar current (400 A/div), and the bottom trace is the power supply (load) voltage (50 kV/div).

2.5 First Generation Thyratron

Initially, the first crowbar system performed extremely well, meeting all of the operating requirements and demonstrating its ability to protect a 36 AWG copper wire from fusing (energy let-through <10 J). The turn-on time of all four switches was <800 ns with a temporal spread of <50 ns. The total delay time from start of the sensed fault current to the peak of the fully diverted crowbar current was <1.5 µs. In this particular system, the gyrotron fault processing electronics are of a newer generation design and the signal cable lengths are not as long as in other systems.

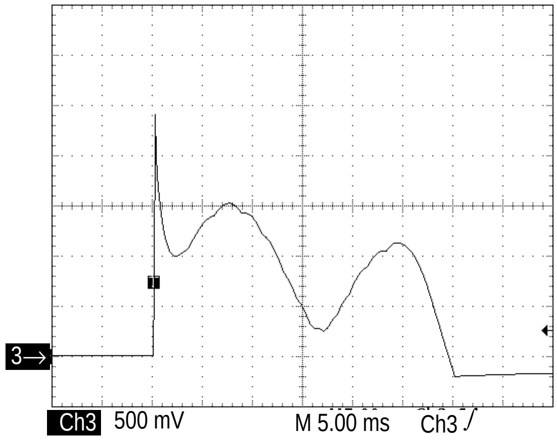

Figure 8. A typical crowbar event during a pulse. Shown is the crowbar current (200 A/div).

After approximately 400 hours of system operation, that included more than 500 crowbar events, the voltage hold-off capability of the tubes had degraded. High voltage, low energy conditioning of the tubes would restore hold-off, but it would degrade after only a few high coulomb crowbar events. It was determined by Marconi engineers that copper electrode material had unexpectedly deposited on the main insulator in a region where the highest electric fields existed. It is most likely that the copper migrated to that region due to the relatively high follow-through current that persists for long time scales. This is in spite of the fact that the conducted current and transferred electron charge was well within the design specifications of the tube. Marconi engineers recognized the problem and to achieve proper performance when operating in this current-time regime, designed new electrodes. The new electrodes were configured in a reentrant, nested cup geometry as opposed to the original planar design. The new design featured greatly improved electric field stress control and a much longer and obstructed path through which the metal vapor would have to travel in order to deposit on an insulator.

2.6 Second Generation Thyratron

The improved design metal-arc thyratrons were installed in the crowbar switch assembly for the second of the two power systems constructed at the DIII-D facility. As in the case of the first system, the second was commissioned without any problems and began operations. The wire survivability test for the second generation system was shown in figure 7.

The system had been operating very well until a multitude of control system and noise problems caused a rash of erroneous crowbar events. Approximately 100 events were accumulated over a several day period. At this point the tubes developed a problem with reliably holding off voltage. It was found that the tubes could support nearly the rated voltage but had extremely high leakage current. This suggested that a sustained discharge was occurring within the tubes indicating that the deuterium gas pressure was too high and not properly regulated. Marconi indicated that the reservoir and gettering system used in this tube could become poisoned under severe conduction circumstances (albeit within the device specifications); especially when the tubes are new (Ref. 7). Poisoning of the getter and reservoir forces the gas pressure to be higher and the reservoir cannot properly regulate this. A rejuvenation technique was applied where the filament and reservoir temperatures are raised well above normal operating levels and then cycled on and off per a prescribed time interval and number of cycles. The leakage current of the rejuvenated tubes was measured and found to be substantially lower and constant over the range of high potential test voltages. The tubes were reinstalled and had no problems holding off full operating voltage. Since the rejuvenation process, the tubes have recovered from every crowbar event in a normal manner.

4. SUMMARY AND CONCLUSIONS

Over the course of the design, fabrication, and testing of two multi-megawatt power systems, the design, testing, and development of the protective crowbar system became the most significant challenge of the project. The overall concept and the detailed design of the crowbar switch assembly and control and fault processing electronics has proven to be sound. All of the operational requirements have been met or even surpassed. In particular, the system response time and protective reliability as demonstrated by the wire test and operational experience has significantly outperformed systems previously in use at DIII-D and other facilities.

Two major challenges, both associated with the new metal-arc thyratrons and both very different, were encountered and subsequently overcome. The first challenge involved an unexpected shortcoming in the electrode design of the HX-2500. An elegant solution to this problem was found. This created the second generation HX-2500 in which manifested the second challenge. Although not a catastrophic failure, the poisoning of the reservoir and gettering system and the rejuvenation process create a maintenance task that was otherwise not planned. It is expected that a third generation HX-2500 will feature an improved reservoir and gettering system.

5. ACKNOWLEDGMENTS

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