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ABSTRACT

The DIII-D National Fusion Facility at General Atomics is completing the upgrade of its electron cyclotron heating (ECH) capability from the previous 3 MW at 110 GHz to 6 MW of generated microwave power.[1] An 8.4 MW modulator/regulator (M/R) power system has been designed and constructed.[2] Surplus hardware that was acquired from the Lawrence Livermore National Laboratory (LLNL) Mirror Fusion Test Facility (MFTF program) was used as part of the design foundation. The power system, with a nominal output of -80 kV and 80 A, can supply a pair of gyrotrons with up to 10 second long pulses that may or may not be modulated.

The modulator/regulator was designed about the BBC CKQ200-4 tetrode, which was the key component acquired from the LLNL program. In order to meet the performance goals of the program, substantial design modifications were needed to be made on the grid driver amplifier and the closed-loop feedback regulator circuits.[3] Also, a newly designed crowbar switch system, featuring a high speed, thyratron-like triggered gas switch, was implemented. The modulator/regulator performance to date has been demonstrated as having <0.06% peak-to-peak ripple and square wave modulation of 50% amplitude at 2 kHz. The key features of the design of the power system and its performance will be presented in this paper.

I. INTRODUCTION AND SYSTEM OVERVIEW

The upgrade of the DIII-D ECH capability from 3 MW to 6 MW[1] of generated microwave power requires the addition of new power systems to supply the new gyrotrons as well as replace legacy hardware. The availability of surplus hardware from LLNL, developed for the MFTF, provided a basis for the new power system design. The power systems from MFTF were originally designed for neutral beam injectors and contained much hardware that would not be required for gyrotron service. In addition to the elimination of the superfluous components, some design changes would be necessary in order to meet the DIII-D ECH performance requirements. In 1989, one of these surplus power systems was converted for use as a gyrotron power system at DIII-D. From that operational experience, the following key points were learned: (1) the rectifier transformer had limited ability to mechanically withstand repeated crowbar events; (2) the voltage ratings of the crowbar switch and the filter capacitor bank were marginal, leading to unpredictable self-breakdown of the ignitron switches and partial discharges within the capacitors; (3) the bandwidth and stability of the grid driver amplifier and the feedback loop were insufficient to meet the desired regulation and modulation goals; (4) the control system contained much obsolete and unsupportable hardware and was complicated with neutral beam injector specific requirements.

The planned use of each new power system is the operation of two diode gun gyrotrons in parallel. The terminal requirements of the gyrotrons are:

Cathode voltage:	(-)70–86 kV
Cathode current (2 gyrotrons):	70-80A
Pulse length (max):	10 s
Cathode voltage dc regulation:	<0.5%
Cathode voltage modulation:	15% at 20 kHz
Response to load fault:	<<10 μs

Shown in Fig. 1 is a simplified schematic diagram of the overall power system. The essential design is of the classic hard-tube topology. Following the flow of power, the 12.47 kV 60 Hz 3ϕ mains are connected through current-limiting line reactors to the protective switchgear. The switchgear consists of a line contactor, current-limiting fuses, and a fast interrupting circuit breaker.

Following the switchgear is the ac/dc power supply which converts the 60 Hz 3ϕ power into dc voltage. Coarse adjustment of the power supply is accomplished by tap-changing in the step-regulator. The negative high voltage dc output of the rectifier is transmitted through approximately 600 feet of coaxial cable (Kerite EPR, 120 kVdc) to the input section of the modulator/regulator vault. The M/R vault is located within the facility building in close proximity to the gyrotrons. Within the M/R vault the power flows through an input L/R network, through the M/R tetrode, then through an output L/R network and out to the gyrotron loads. Shunting the input of the M/R is the protective crowbar switch and the filter capacitor bank.

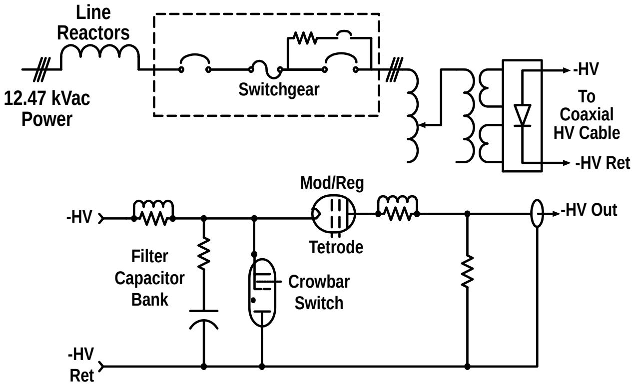

Fig. 1. A single-line diagram of the ECH Modulator/Regulator Power System.

Over a period of six months of testing and operations, key accomplishments and the achievement of some major performance goals were experienced:

- High potential testing of the integrated system to a level of –120 kVdc with no detectable corona discharge.
- Successful demonstration of the Crowbar System protecting a 36 gauge wire and exhibiting a total throughput delay of <1.5 μs.
- Stable, oscillation-free, operation of the tetrode over its entire operating range.
- Output modulation of 50% amplitude with a 2 kHz square wave (into dummy load).
- Output voltage peak-to-peak ripple of <±0.06% against a 10% droop of the input high voltage (gyrotron load).
- Simultaneous operation of two gyrotron loads.

Also experienced during this period:

- Degradation of voltage hold-off capability of the crowbar switches.
- Various noise and susceptibility issues manifested in the interface between the gyrotron control system and the control system of the high voltage power supply.
- Lessons learned that are leading to incremental design improvements.

Since much of the detailed design and construction descriptions were treated in a previous writing,[2] the remainder of this paper will focus on key performance achievements, interesting problems and their solutions, and the next steps in this power system upgrade project.

II. THE MODULATOR/REGULATOR

The principal control element of the power system is the modulator/regulator. At the core of the M/R is the high power tetrode (BBC CQK200-4) vacuum tube. The tetrode is seated in a socket that is mounted to the M/R hot deck. The hot deck structure houses the grid driver amplifier, the screen grid subsystem, and the hot deck control interface. The structure is connected to the cathode potential of the tetrode and acts as a Faraday cage for the components it encloses. Two isolation transformers provide power for the tetrode filament (21 V, 450 A) and power for the M/R subsystems (480 V, 12 kVA, 3ϕ).

Two other elements are combined with the M/R tetrode and the hot deck to complete the functionality of the M/R system. A precision voltage divider connected between the output terminal and the zero-volt reference provides a proportional voltage feedback signal to an error amplifier. The error amplifier is located in the ground level controls system. An input voltage reference signal is compared to the output voltage feedback by the error amplifier and an error signal is generated. This signal is transmitted to the grid driver amplifier on the M/R hot deck via a fiber-optic link using voltage-to-frequency conversion.

The original grid driver amplifier was analyzed and modeled, and from this a new design was developed to meet the project requirements.[3] By creating a feedback loop within the grid driver amplifier itself, the gain of the circuit was lowered, increasing the bandwidth and improving the phase margin. Also, by increasing the input dynamic range by 20 dB, no penalty is paid for lowering the gain and the signal to noise ratio is greatly improved. The operation of the modified circuit was observed to be much more stable, precise, and robust than the previous system. The stability, precision, and robustness of the M/R system is demonstrated with Figs. 2 and 3.

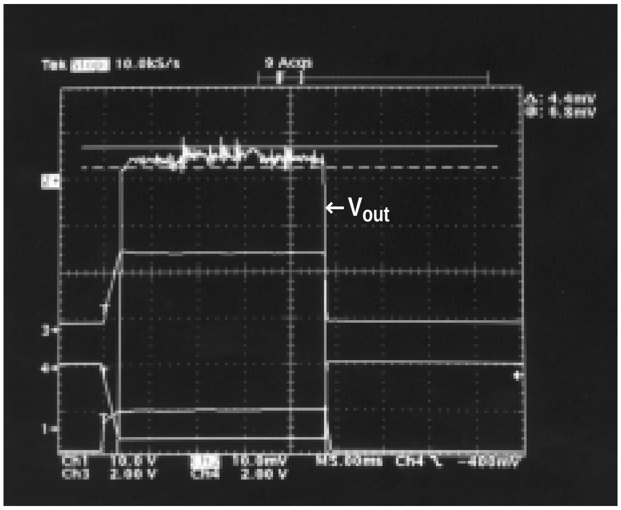

Fig. 2. The M/R output showing the pulse flat-top ripple to be <44 Vp-p at a nominal output of –80 kV into a gyrotron load.

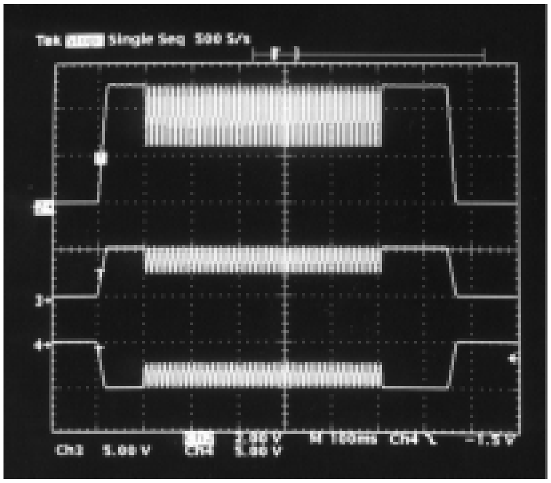

Fig. 3. The M/R output square wave modulated to 50% amplitude at 2 kHz into a resistive dummy load.

The pulse flat-top ripple is indicated in the trace labeled V_{out} in Fig. 2. The zero baseline has been depressed and the vertical scale expanded to amplify the flat-top structure. The horizontal cursor lines bound the ripple which is measured to be 44 Vp-p or <0.06% at a nominal level of –80 kV. This is well within the requirement of <0.5%. The other traces, respectively from top to bottom, are the output current into the gyrotron, the reference command voltage, and the error signal to drive the tetrode grid amplifier.

The waveforms in Fig. 3, respectively from top to bottom, are the output voltage (50 kV/div), the output current (50 A/div) into a resistive dummy load, and the reference command voltage (5 V/div). This data clearly displays the ability to gate the M/R with a modulation signal. In this case the amplitude was modulated to 50% with a 2 kHz square wave.

III. THE CROWBAR SYSTEM AND THE FILTER CAPACITOR BANK

The main protective element in the power system is the energy diverter, or crowbar switch. In the event of a load fault, the crowbar switch is fired which effectively shunts the input terminals to the M/R. Energy that is stored in the filter capacitor bank and energy that continues to be delivered by the dc high voltage power supply is diverted back to the source. This action limits the amount of energy absorbed by the fault, typically an arc of the gyrotron cathode. To be effective, a crowbar switch must: (1) have a high speed response, (2) reliably fire when commanded, (3) indefinitely hold-off high voltage without spurious self-breakdown or triggering, (4) reliably conduct with a low starting voltage, and (5) transfer large amounts of electron charge. Criteria 1–3 provided much of the motivation for deciding to design a completely new crowbar switch system as opposed to using the original MFTF hardware. In addition, it was desired to eliminate the mercury filled ignitron switches from the system design. The new crowbar switch system needs to meet the following requirements:

Operating voltage (max):	105 kV dc
Peak current (750 µs e-fold):	1.2 kA
Follow-on current:	<1 kA (25 ms)
Charge transfer per shot:	<15 Cb
Turn-on time and jitter:	<1 µs/50 ns

The switch that was chosen for the new design is a low pressure deuterium filled device manufactured by Marconi Applied Technologies (formerly English Electric Valve). The switch is referred to as a metal arc thyratron (MAT) and has combined characteristics similar to a hydrogen thyratron and a triggered vacuum gap. The thyratron-like triggerability and high speed response combined with high charge transfer capability and a wide operating voltage range make the MAT an appropriate choice for crowbar service.

In order to qualify the crowbar as a protective system for the gyrotron, a wire survivability test was performed. The test simulates a gyrotron arc fault by switching the M/R output into a 36 gauge copper wire connected in place of the gyrotron device. The fault detectors in the gyrotron control system respond to this fault current and transmit a “fire” command to the crowbar trigger system. The crowbar then conducts and diverts the energy away from the load and continues to conduct until the main circuit breaker opens on command. If the test is successful, then the energy absorbed by the 36 gauge wire will be no more than 8 J. The waveforms in Fig. 4 show the fifteenth shot of a series of fifteen where the wire survived each shot. The complete system throughput delay (from peak of fault current to peak of crowbar current) is <1.5 μs.

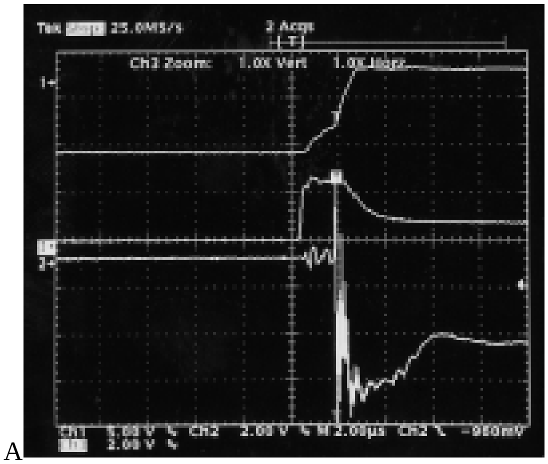

Fig. 4. Results of the crowbar wire test in which a 36 gauge wire survived repeated trials. The middle trace is the wire current (400 A/div), the bottom trace is the crowbar current (400 A/div), and the top trace is the M/R output voltage (50 kV/div).

The crowbar system performed extremely well until after over 500 full energy shots had been accumulated. A degradation in the switch tubes ability to reliably hold-off voltage had manifested. It was found that application of very low energy pulses would recondition the MAT tubes to normal hold-off levels. However, the poor hold-off would return after a few full energy shots. At first, the problem was not understood and this launched a collaborative effort with the tube manufacturer to solve the problem. Despite the fact that the tubes were operated well within their specifications for voltage, peak current, and charge transfer, it was later found that the long conduction times made it possible for metal vapor to unexpectedly migrate into the main insulator region of the tube. A design change to the tube’s internal structure will serve to mitigate this problem in the future. In the meantime, the system availability and reliability needed to be improved. An alternate, although slower, switching device was used to augment the MAT tube temporarily in a manner that preserved the high speed response of the MAT tube while minimizing the conducted charge with the alternate device passing the vast majority of the current. This concept was implemented and with the exception of a response delay increase of about 1μs, it has operated satisfactorily. Replacement MAT tubes of the improved design will become available in the early part of year 2001 and it is expected that the new design will restore the original performance and achieve the required lifetime.

The filter capacitor bank is used to smooth out the rectified power supply ripple and to provide passive transient compensation. The original capacitor bank was composed of obsolete capacitors and at the maximum operating voltage, the energy stored was 132.3 kJ. The selection of the new capacitor and the damping resistance values would involve trade-offs among available components, stored energy, ripple reduction, and circuit dynamics (damping and transient compensation). Through a combination of circuit analysis and working with capacitor manufacturers, a capacitance value of 5 μF was chosen. In anticipation of future performance requirements, the provision for doubling the filter capacitance was designed into the capacitor bank structure. The unit capacitor, manufactured by General Atomics Energy Products Division (formerly of Maxwell Technologies), is rated at 20 μF and 35 kVdc so that a series connection of 4 stages results in an overall voltage rating of 140 kVdc. This provides for copious margin at the operating voltage level. The maximum stored energy under normal operating conditions is only 27.5 kJ.

Early in the conditioning phase of the gyrotrons, typical operation involves the repetitive application of fast rise-time, short pulses (500 μs/5 ms). Under these conditions, the 5 μF capacitance was not adequate to support the rising edge of the output pulse. Taking advantage of the designed feature for increasing capacitance, the transient compensation for the fast rise-time, short pulses was made adequate. Also, at a capacity of 10 μF, the system becomes critically damped.

IV. THE CONTROL SYSTEM

The original MFTF control system was based on the CAMAC platform and included many custom designed circuit modules. Many of the modules, both custom and CAMAC, contained obsolete components. A decision was made to completely redesign the control system around a modern platform and to make the system as simple as possible.

The combination of a programmable logic controller (PLC) and state-of-the-art programmable logic devices was chosen as the new platform. A simple block diagram of the control system architecture is illustrated in Fig. 5. The PLC is a GE-FANUC 90-30 series and is used as the overall controller. It executes the operational sequences, conducts continuous interlock monitoring, and provides status indication. Another key feature of the PLC is its communications capability. The CPU364 provides both ethernet and RS-232 data communications. As the ECH facility at DIII-D expands, the subsystems will be linked, monitored, and controlled through a local area network.

The Hardware Interlock and the Fault Handler subsystems are based on high speed complex programmable logic devices (CPLD) manufactured by Xilinx. The hardware interlock serves as the master combinatorial logic of the system. All interlock, system, and fault status is processed in this subsystem. A key function of the hardware interlock is to supervise the operation of the PLC, preventing errant system operation due to a software anomaly or programming error. The fault handler processes all of the critical faults that require high speed response. It also captures and identifies the first fault in any given event. The major advantage of the PLC/CPLD architecture is that the control logic and sequences are contained in software and firmware. Revisions to the system control and troubleshooting are accomplished with relative ease and speed and at very low cost.

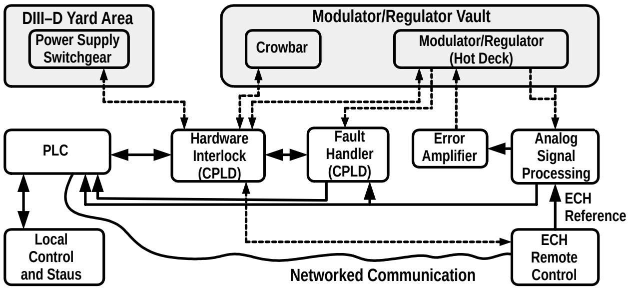

Fig. 5. The ECH power system controls architecture. The dashed lines indicate signals transmitted over fiber-optic links.

Throughout the operational period, the Hardware Interlock and the Fault Handler subsystems remained inoperable due to continued development of the high-speed logic circuitry and firmware. Control of the system was accomplished via the PLC and manual execution by skilled operators. Critical fault channels were hardwired into the system. While this allowed safe operation of the power system, the lack of automation and remote control capability reduced overall productivity and required substantial manpower. The complete control system is expected to be implemented and tested in the early part of the year 2001 operational campaign.

V. SUMMARY

Making judicious use of the surplus MFTF hardware made available from LLNL, a new 8.4 MW power system for high power gyrotrons has been designed, fabricated, tested, and placed into operation at the DIII-D National Fusion Facility. A second power system of identical design is presently under construction and will become operational for the year 2001 experimental campaign.

Over a six month period of testing and operation, a substantial body of work was completed. Safe, stable, and precision operation of a multi-megawatt high voltage power system was achieved. An advanced, very high-speed protective crowbar system was developed. All of the technical challenges encountered during this project have been carefully analyzed, resulting in solutions, some of which are yet to be implemented, that have lead to establishing a world-class facility.

ACKNOWLEDGEMENTS

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