GA–A23549

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This is a preprint of a paper presented at the 14th Topical Meeting on the Technology of Fusion Energy, October 15–19, 2000 in Park City, Utah and to be published in *Fusion Technology.*

Work performed by
U.S. Department of Energy under
Contract No. DE-AC03-99ER54463

GA PROJECT 30033
DECEMBER 2000

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ABSTRACT

As part of the Electron Cyclotron Heating (ECH) Facility upgrade at the DIII–D National Fusion Facility, a regulated AC power supply for the filaments of a 110 GHz Gyrotron was designed, tested and integrated into the new ECH power system.[1] A precision regulated filament power supply is essential for maintaining the stability of the cathode temperature and consequentially the gyrotron beam current and rf production.[2] This paper provides a description of the design of the filament power supply, presentation of test results, and an assessment of its performance.

I. INTRODUCTION

A well regulated AC power supply was needed to power the filaments of the new, high power 110 GHz gyrotrons being installed at the DIII–D National Fusion Facility.[3] The key requirements for the gyrotron filament power were to operate at a typical output voltage of 45 V_{RMS} and output current of 6 A_{RMS}, with the output rms voltage regulated to within ±0.5% for input line voltage variations of ±10%. The filament power also needed to be controlled on command, allowing for controlled ramping over long time scales and to allow rapid “boost” heating during a gyrotron pulse.

Several approaches were considered, including housing the power supply subsystem in the gyrotron high voltage oil tank and floating it at the potential of the gyrotron cathode. The selected approach placed the subsystem inside the high voltage vault of the modulator/regulator (M/R) with its output being fed down the same high voltage cable used to transmit the high voltage pulse to the gyrotron cathode. As a consequence, since the M/R can supply two gyrotrons simultaneously, the filament power supply controller was designed with two independent controller channels.

II. DESIGN DESCRIPTION

The design of the gyrotron filament power supply was based on the principle of AC voltage phase control and transformation with the root-mean-square (rms) value of the voltage as the control parameter of interest. A functional block diagram of the power supply is illustrated in Fig. 1.

The key components of the power supply are the AC phase control module, the high voltage isolating step-down transformer, and the controller circuit board. The 120 V, 60 Hz, single-phase line input to the AC phase control module is from the ground level AC power distribution. The AC phase control module is a linear proportional controller, manufactured by Crydom, and it was chosen for its operational simplicity and good linear transfer characteristic. A control voltage input of 0-10 V corresponds to a proportional firing delay angle of 180°–0° (or 0–100% output). The phase controlled line voltage is applied to the primary of the high voltage isolation transformer, which is manufactured by Stangenes Industries. The transformer has a power rating of 500 VA and the secondary to primary isolation rating is 130 kVdc. The transformer is also designed with low capacitance coupling of the secondary to primary so that negligible displacement current flows during the rising and falling edges of the M/R output pulse. The windings of the transformer are configured to produce a 2:1 voltage step-down transformation ratio.

To achieve the output control and regulation that was required, a controller circuit board was developed. The voltage at the transformer primary is sensed with a resistor divider and input to an instrumentation amplifier that provides signal conditioning and scaling. The primary voltage is used for feedback as a simplification, since sensing the secondary voltage would require high voltage isolation techniques that would add to the complexity of

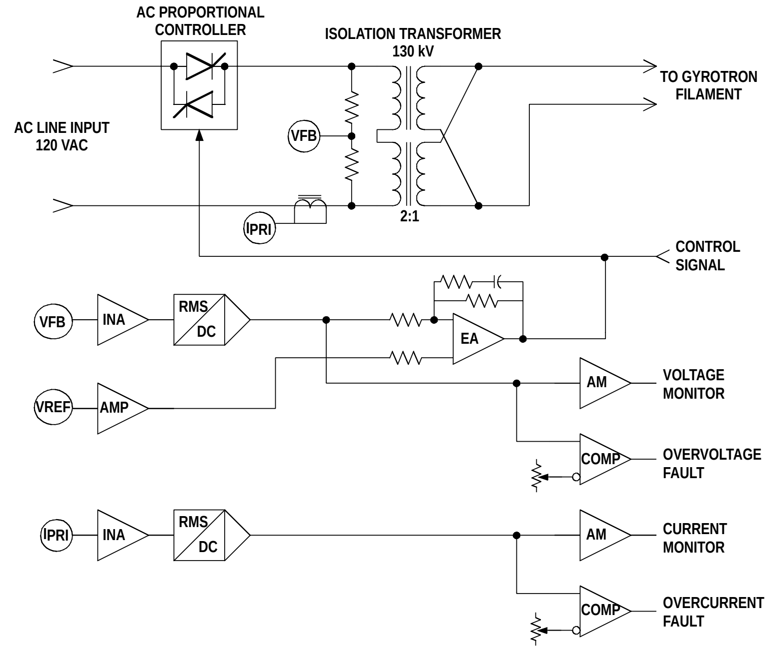

Fig. 1. Functional block diagram of the gyrotron filament power supply system.

the system. This AC feedback signal is then processed with an RMS-to-DC converter circuit (Analog Devices AD637) producing a DC feedback signal that is proportional to the true rms value of the sensed AC signal. A reference voltage command, or setpoint value, is received from a remote control system and is conditioned and scaled with an instrumentation amplifier. The feedback signal and the reference command are compared with a proportional "error" amplifier and a proportional command is generated for control input to the AC phase control module. This circuitry will automatically compensate for variations in line voltage and the load, keeping the output constant about a commanded setpoint. The dynamic response of the system allows for a time and amplitude varying control of the reference command, making possible "programmable" ramping and boosting of the output voltage.

Apart from the closed-loop voltage feedback control circuitry, instrumentation for monitoring and fault processing was also designed. A hall-effect current transducer (LEM) is used to sense the current flowing in the transformer primary. As with the voltage, this AC signal is processed with an RMS-to-DC converter circuit. Both the conditioned voltage and current signals are transmitted to a remote control system for monitoring and data acquisition. The two signals are also fed into comparator circuits that change state if the parameter exceeds a preset level. These over-voltage and over-current signals are latched and used to cut-back and clamp the phase control module to zero output. The fault signals are also transmitted to a remote control system for further use as logical interlocks.

The AC phase control modules, controller circuit board, and other associated components are housed within a fan-ventilated enclosure that is also EMI/RFI shielded. A photograph of the gyrotron filament power supply controller is shown in Fig. 2.

The secondary of the high voltage isolating transformer is connected to the gyrotron filament through a special high voltage interface. A high voltage coaxial cable, manufactured by Dielectric Sciences, and is typically used for x-ray tubes, was chosen for its tri-filar center conductor construction. A voltage graded termination with a field stress control shell was designed and allowed for breakout of the tri-filar cable core. Two of the three wires are connected as the supply and return from the transformer secondary to the terminals of the gyrotron filament. The third wire is connected to the M/R output and transmits the high voltage pulse to the gyrotron cathode. The cathode lead and one of the filament leads are also common. The return path for the high voltage pulse is through the coaxial cable outer conductor. The transformer secondary is fitted with a field stress control shell similar to that on the cable termination. A photograph of the high voltage interface structure and the high voltage isolating transformer is shown in Fig. 3.

III. TESTING AND PERFORMANCE

The gyrotron filament power supply controller was first tested with a 6 Ω resistive dummy load. The basic operation was verified and this is shown in the oscilloscope photograph in Fig. 4. Channel 1 displays the

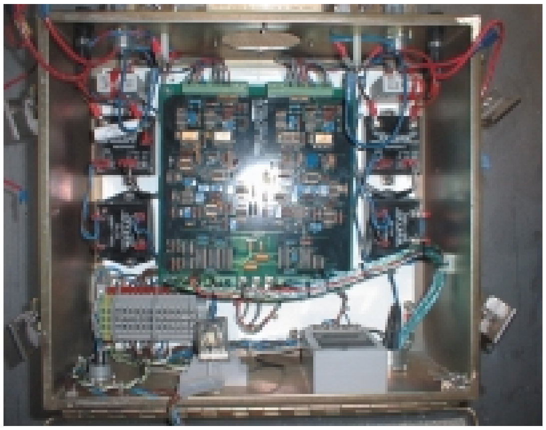

Fig. 2. Gyrotron filament power supply controller showing the controller circuit board, the 2 phase control modules, and associated components.

input line voltage (full sine wave) at a level of 115 Vrms. The load voltage is displayed on Channel 2 and its value is 23 Vrms. The reference setpoint was 6 V (or 60% of full scale) in this test. The expected output for this setpoint and load was 34 V_{RMS}.

It was found that the transformer impedance, namely the resistance of the secondary windings was higher than expected, accounting for the 33% reduction in output voltage. With an increase in the input line voltage to 120 Vrms, the output range was considered acceptable and the power supply was put into service with a gyrotron.

Initial testing with the power supply connected to the gyrotron filament indicated good linearity within the low power operating range of the gyrotron filament. A sample of the transfer characteristic is shown in Fig. 5.

Despite the reduced output capability due to the transformer impedance, the power supply responded true

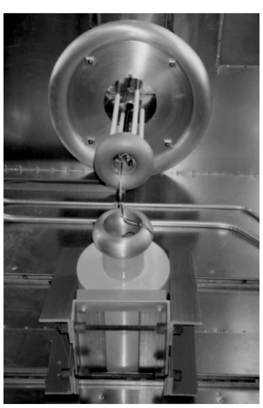

Fig. 3. High voltage isolating transformer and the high voltage interface and output cable.

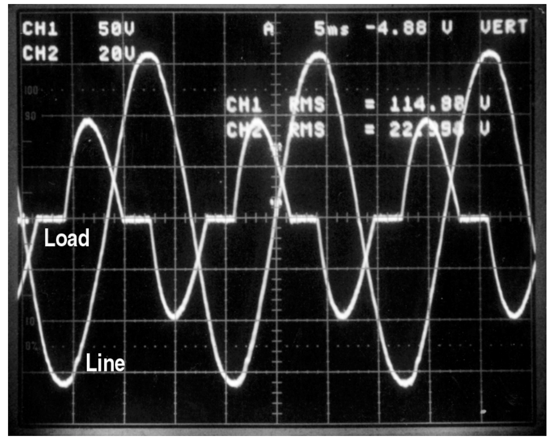

Fig. 4. Oscilloscope photograph of the input line voltage (Channel 1) and the load voltage (Channel 2) at a 6 V reference setpoint.

and stable to voltage ramp commands and could regulate to within 1% of the setpoint command. As the gyrotron output power and pulse length were increased, the demand on the filament power supply began to exceed the capability of the transformer and the regulation degrade to within 10%. To meet the immediate needs of gyrotron operation, two transformers were wired in parallel to effectively halve the source impedance. A new transformer specification was developed with a transformater ratio and maximum impedance limit that will match more closely the range of operation required by the gyrotron filaments. The new transformers will be installed and placed into service for the year 2001 operational campaign.

IV. OTHER APPLICATIONS

Owing to the simple and generic nature of the power supply controller design, the controller is being

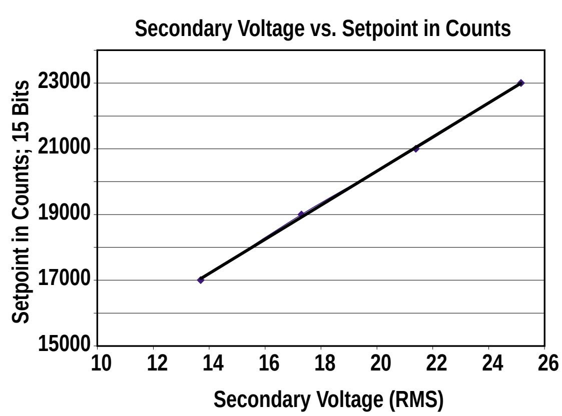

Fig. 5. Transfer characteristic of the output voltage (secondary) versus the reference setpoint (units are in PLC counts) into the gyrotron filament.

implemented in other systems being developed for the DIII–D tokamak. In addition to being used in several other gyrotron systems, an interesting implementation is with a new diagnostic system. The Edge Current Density Diagnostic System makes use of a small lithium ion (Li+) accelerator.[4] The two-channel controller is being used to power both the filament (AC) and the bias (rectified for DC) in the ion source section of the accelerator. Both elements are regulated on their respective output currents. Recent bench testing on the DC closed-loop current mode configuration indicate output regulation to within ±1%.

V. SUMMARY

A power supply system for powering the filaments of a high power gyrotron was designed, fabricated, tested, and placed into operation. While the overall form, fit, and function of the power supply met the requirements, it was found that an improved specification of the step-down transformer was needed to completely satisfy the output capability and regulation in the high power operating regime of the gyrotron. It was also learned that the design simplification of primary voltage feedback masks the effect of the transformer impedance. This problem is overcome by specifying the transformer to have an impedance (leakage reactance and winding resistance) that is very much less than the load impedance. As is seen with other applications, including DC output and current feedback mode, the power supply controller can meet <1% output regulation performance and has demonstrated its flexibility in a variety of configurations.

ACKNOWLEDGEMENT

This work was supported by the U.S. Department of Energy under Contract No. DE-AC03-99ER54463.

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