GA–A23524

CIRCUIT MODELING AND FEEDBACK CONTROLLER DEVELOPMENT OF THE 8.4 MW MODULATOR/REGULATOR POWER SYSTEM FOR THE ELECTRON CYCLOTRON HEATING FACILITY UPGRADE AT DIII–D

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A. NEREM, D.H. KELLMAN, S.G.E. PRONKO, and J.R. VALENTINE

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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 DIII–D an 8.4 MW Modulator/Regulator Power System was designed and constructed using acquired hardware from the Mirror Fusion Test Facility (MFTF) at Lawrence Livermore National Laboratory (LLNL) program as a foundation.[1] Design changes in the feedback control of the modulator/regulator (M/R) was motivated by the need for improved output voltage regulation and improved capability to modulate the output voltage consistent with reference command signals containing modulation patterns (typically square wave). The regulation characteristics of the old ECH M/R power system had previously constrained gyrotron operation due to marginal voltage control loop stability and slow response to voltage step changes. The technical approach was to develop models of the circuit functions of the M/R controller from the circuit diagrams, and then examine the control characteristics using circuit analysis software. MATLAB® Simulink® and Intusoft IsSPICE4® (SPICE) codes were used to examine the control issues. These analysis software tools were used to simulate the controller functions and yielded identical results. The SPICE circuit model was selected as a baseline for future maintenance by the engineering staff. The analysis of the controller model blocks provided the needed information to modify the controller circuits. Changes made to the controller included addition of a voltage feedback loop around the grid driver amplifier for the power tetrode control grid in the M/R, and changes to the feedback loop compensation of the main error amplifier. The implemented revised controller performance matches the model performance predictions remarkably well. This paper describes the circuit models, implementation of the revisions to the controller, and recent operational results.

I. BACKGROUND

The ECH system had initially utilized a M/R power system acquired from the MFTF program in one 110 GHz gyrotron system. The MFTF M/R was originally designed for ion-source operation and had been converted to negative polarity output for use in ECH operation. The M/R operates from -105 kV dc voltage power and uses a high voltage power tetrode as means to regulate its output voltage to nominally –80 kV. The regulated output voltage is applied to the ECH gyrotron cathode element. A new M/R power supply was recently constructed and placed in service. The need for precise regulation and output voltage response from the new ECH M/R power system required revisions to the original controller in the acquired hardware from the MFTF program. Specifically, the original controller was marginally stable when the M/R was operated into a gyrotron load, and its dynamic response to voltage command signals was too slow.

II. DESIGN REQUIREMENTS

The target specifications for the new controller were ±0.25% voltage regulation accuracy, and a regulation bandwidth sufficient to accommodate 20 kHz square wave modulation of the output voltage with 15% amplitude capability.

III. CONTROLLER DESIGN

The controller circuit consists of an error amplifier, lead compensation network, fiber-optic coupler and grid-driver, regulator tetrode, output RLC network, and a voltage-divider used for voltage feedback to the error amplifier. The circuit arrangement of these blocks with the final circuit values is shown in Fig. 1.

The controller design focused initially on implementing proper dynamic range and gain for the individual blocks. Simulation analysis was then used to optimize the controller performance.

Gain and phase measurement data from the original MFTF M/R grid-driver amplifier and fiber-optic link are

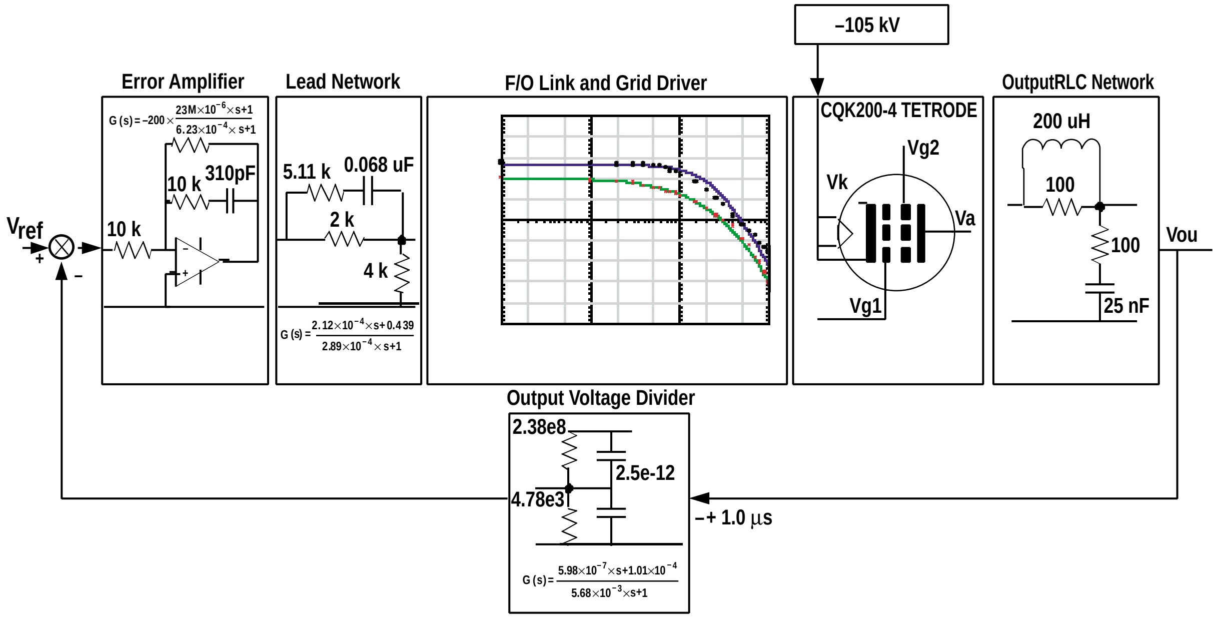

Fig. 1. Schematic block diagram of the M/R controller.

shown in Figure 2. This grid-driver was not well matched in gain and dynamic range to the new control circuit. The addition of a voltage feedback loop to the grid-driver allowed utilization of the full dynamic range of the error-amplifier and fiber-optic link, and substantially improved the control bandwidth of this block [2]. This revision proved to be key in achieving the voltage response bandwidth of the M/R. The transfer function for the grid driver was obtained from a curve-fit to the actual measurement data obtained from the modified grid driver, and includes a 1 µs delay inherent in the Dymec fiber-optic link between the error amplifier and the grid driver. The modified grid-driver circuit is shown in Fig. 3. Figure 4 shows the measured gain and phase characteristics of the modified grid-driver. Figure 5 shows the measured gain and phase data for the modified grid-driver compared to the gain and phase plots of the derived (fitted) Laplace function for this block. The dots in this chart represent the measured gain and phase of the grid driver.

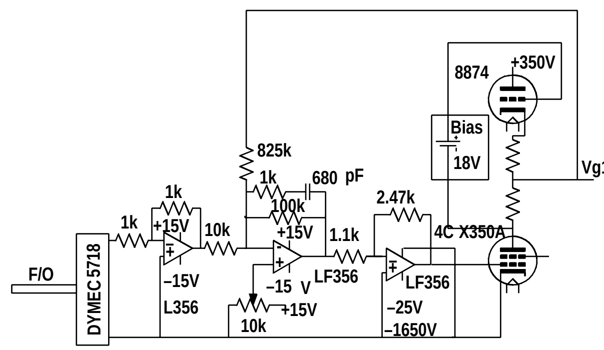

Fig. 3. Closed-loop ECHPS grid-driver circuit (simplified).

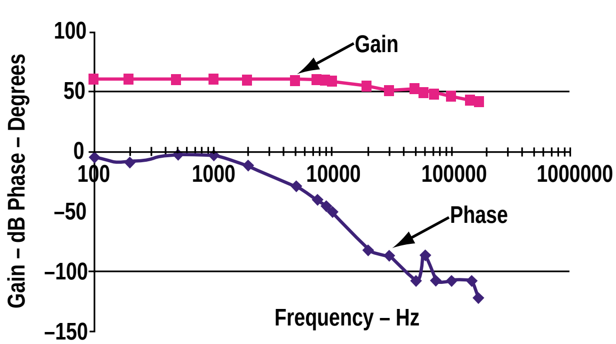

Fig. 2. Gain and phase characteristics of the original ECHPS grid-driver.

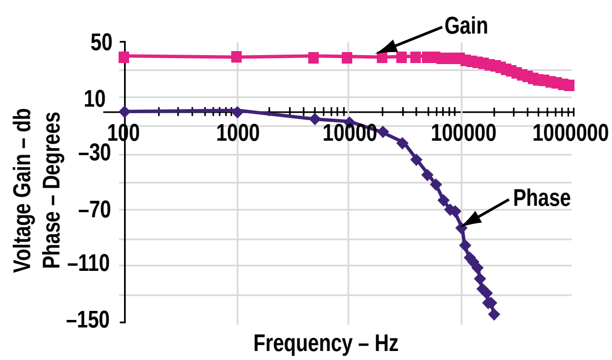

Fig. 4. Gain and phase characteristics of the modified ECHPS grid-driver.

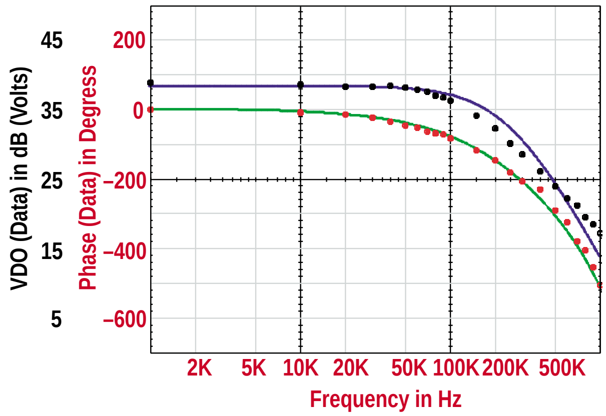

Fig. 5. Curve-fit to measured data for the modified grid-drive and fiber-optic link.

IV. SIMULATION MODELS

Laplace function blocks were used for faster simulation analysis. The individual transfer function blocks were derived from the circuit diagrams. MathCad® was used to do the algebra involved in simplifying the resulting expressions. The CQK200-4 tetrode model is a non-linear function script derived from the manufacturers' data sheet for this tube. This tetrode model assumes a nominal load resistance of 888.9 ohms that is consistent with the desired voltage response. A fixed 2000 V screen grid bias is used in the tetrode model script. The Laplace function blocks for the controller sub-circuits are summarized in Table 1. The simulation models include saturation limit blocks with appropriate maximum and minimum voltage settings for the error amplifier and the grid driver functions in order to maintain realistic bounds for the voltages in the circuit. The Laplace function blocks for the grid-driver, tetrode, output RLC network, and voltage-divider were then adopted as realistic representations of these circuit functions in the simulation model that form the basis for the controller design

V. SIMULATION RESULTS

Optimization of the M/R controller with respect to gain and frequency response was then achieved through the selection of the circuit component values in the error amplifier and the lead network blocks. Aside from the minor difference in format, the simulation models in SPICE and MATLAB/Simulink were identical with one minor exception. The MATLAB/Simulink model used a fixed gain term in place of the tetrode model. The SPICE model was run with the tetrode model script implemented. Both software simulation tools provided essentially identical results. The SPICE simulation model for the M/R controller is shown in Fig. 6.

Table 1. Controller Function Blocks

Error Amplifier	$G(s) = -200 \cdot \frac{3 \cdot 10^{-6} \cdot s + 1}{6.23 \cdot 10^{-4} \cdot s + 1}$
Lead Network	$G(s) = \frac{2.12 \cdot 10^{-4} \cdot s + 0.439}{2.89 \cdot 10^{-4} \cdot s + 1}$
Grid Driver + F/O link	$G(s) = \frac{-82}{4.0.5 \cdot 10^{-13} \cdot s^2 + 1.27 \cdot 10^{-6} \cdot s + 1}$ + 1.0 μ sec TD
Power Tetrode CQK200-4	$Va = -888.9 \cdot 5.5 \cdot 10^{-3} \cdot \left(Vg1 + \frac{Vg2}{3.3} + \frac{Vak}{122}\right)^{1.5}$ Va = anode voltage, Vg1 = control grid voltage, Vg2 = screen grid voltage, Vak = anode-cathode voltage
Output RLC (snubber)	$G(2) = \frac{5.0 \cdot 10^{-12} \cdot s^2 + 4.5 \cdot 10^{-6} \cdot s + 1}{1.0 \cdot 10^{-11} \cdot s^2 + 4.5 \cdot 10^{-6} \cdot s + 1}$
Voltage-divider	$G(s) = \frac{5.98 \cdot 10^{-7} \cdot s + 1.0 \cdot 10^{-4}}{5.68 \cdot 10^{-3} \cdot s + 1}$

The simulation results are shown in Figs. 7 and 8. Figure 7 shows the gain and phase characteristics of the M/R controller from this simulation, and Fig. 8 shows the simulated square wave response.

VI. DATA FROM M/R OPERATION

The experimental data from research operations with the ECH 110 GHz gyrotron system shows that the M/R performance is remarkably close to the simulation results. Figure 9 shows a M/R pulse with 2 kHz square wave modulation with the M/R operating into a resistive dummy load. The upper trace shows the M/R output voltage (20 kV/div), the middle trace shows the M/R output current (50 A/div), and the bottom trace shows the voltage reference command signal (10 kV/volt). An expanded view examines a smaller time portion of the waveforms in Fig. 10, allowing a closer look at the square wave modulation effect. The 20 KHz modulation capability has not yet been tested, but is anticipated to meet the requirements. Figure 11 shows a regulation measurement from the M/R operating with a gyrotron load at –80 kV. The top trace in Fig. 11 is again the M/R output voltage offset with an external precision voltage source in order to allow the precise measurement of regulation

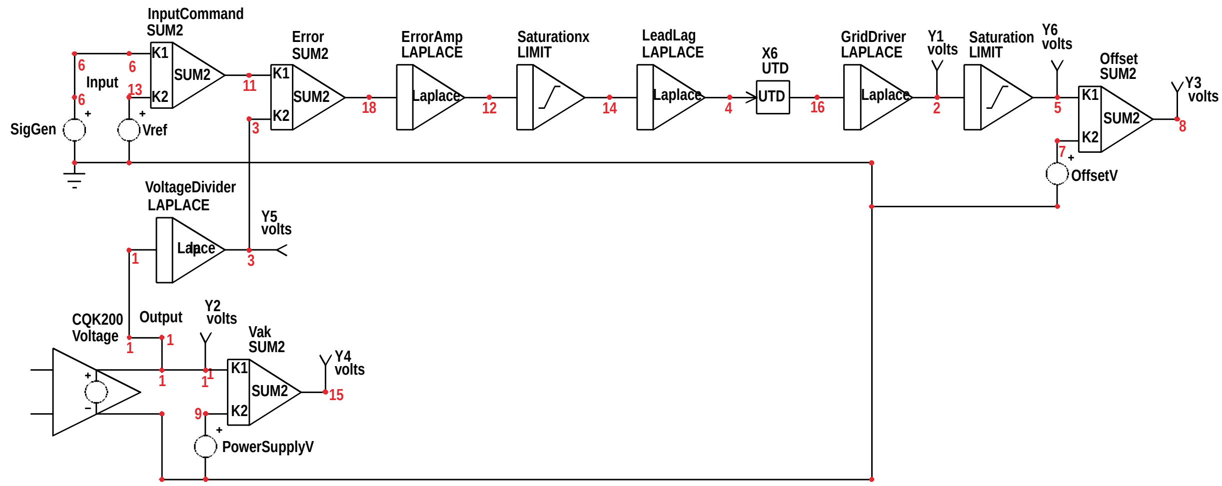

Fig. 6. SPICE model of the Mod/Reg controller.

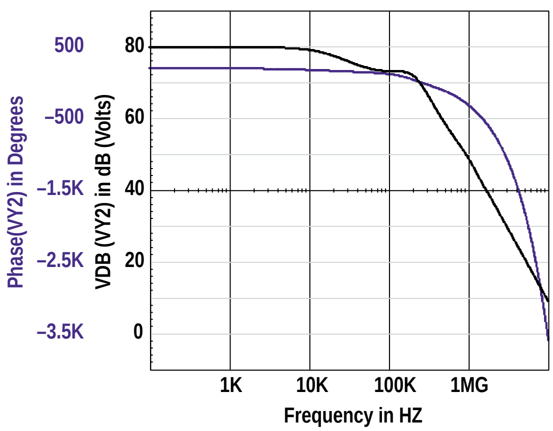

Fig. 7. Gain and phase response of the M/R controller.

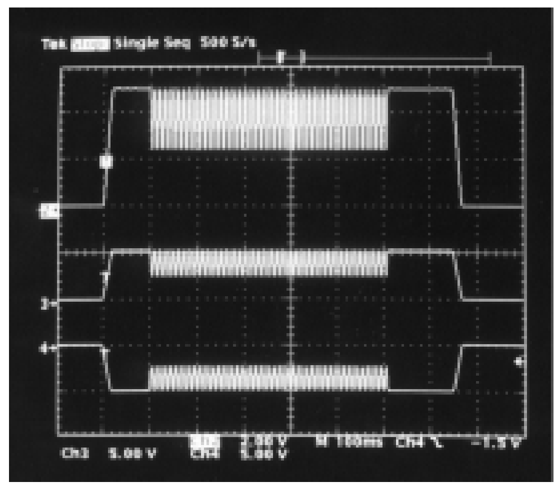

Fig. 9. M/R output waveform with 2 kHz square wave modulation.

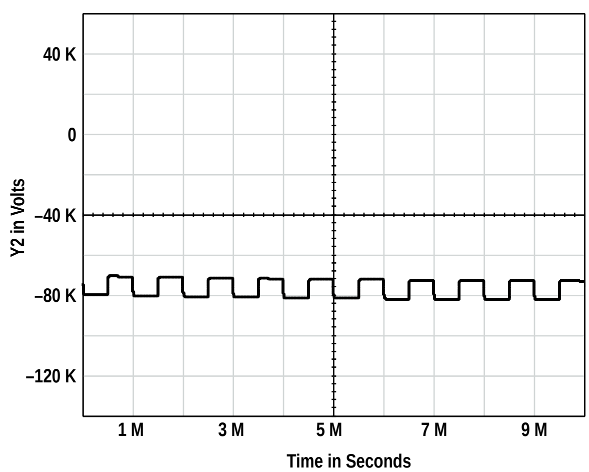

Fig. 8. Simulation step response of the M/R controller.

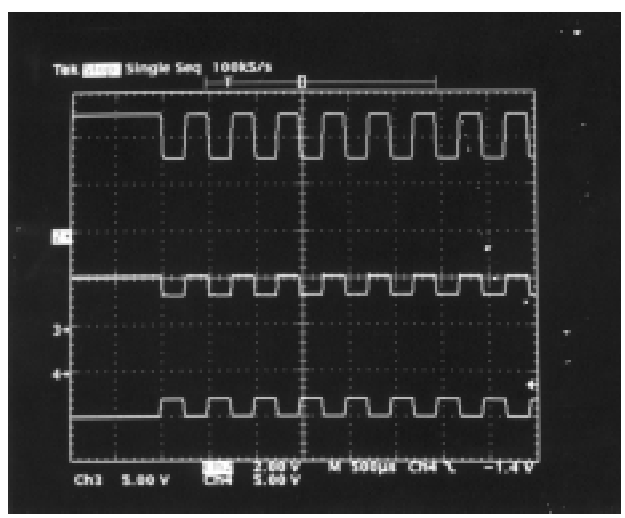

Fig. 10. M/R output waveform expanded shows the 2 kHz modulation waveform details.

accuracy. This measurement shows a 44 V peak-peak regulation, and this performance actually meets and exceeds the specification requirement. The middle trace in

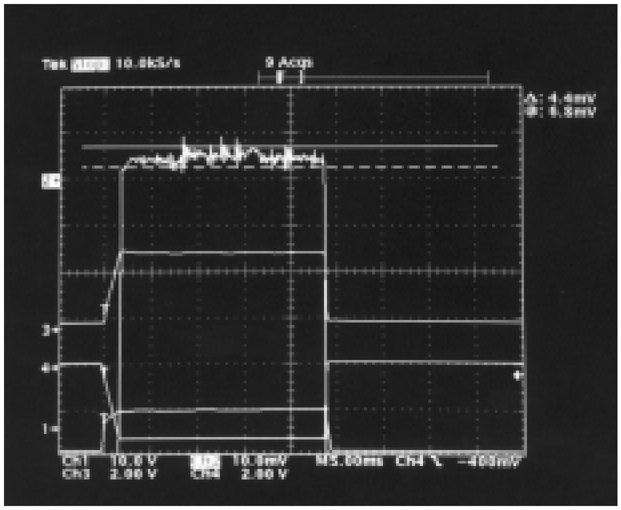

Fig. 11. M/R regulation measurement.

Fig. 11 is the M/R output current into the gyrotron load (20 A/div). The next lower trace is the voltage command reference to the M/R controller. The bottom trace is the error signal. The M/R is now being used in ECH operations at DIII–D.

Experiments are being planned that will utilize the M/R regulation and modulation capabilities to modulate ECH power for electron transport physics experiments.

ACKNOWLEDGMENT

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

REFERENCES

1. S.G.E. Pronko, *et al.*, “Performance of the 8.4 MW Modulator/Regulator Power System for the Electron Cyclotron Heating Facility Upgrade at DIII–D,” this conference.

2. S.G.E. Pronko, and D. Baggest, “The 8.4 MW Modulator/Regulator Power systems for the Electron Cyclotron Heating Facility Upgrade at DIII–D,” IEEE/NPSS Symp. on Fusion Engineering, Albuquerque, New Mexico (1999).