IEEE Transactions on Nuclear Science, Vol. NS-30, No. 4, August 1983

PROTOTYPE PHASE AND AMPLITUDE FEEDBACK-CONTROL SYSTEMS FOR THE FMIT ACCELERATOR*

M. V. Fazio and R. D. Patton, AT-5, MS H827
Los Alamos National Laboratory, Los Alamos, NM 87545

Summary

The phase and amplitude feedback-control systems for the Fusion Materials Irradiation Test (FMIT) accelerator have been successfully prototyped and tested. The testing was performed at low power with two 100-W rf sytems driving a high-Q resonant cavity at 80 MHz. The control systems can maintain the cavity field amplitude to within ±1% and the phase to within ±1° of the set-point values. When there are multiple rf systems independently driving a resonant cavity through individual drive loops, amplitude matching and proper phasing between the outputs of each rf system are essential for proper system operation. Experimental results are presented.

Introduction

For normal operation, the FMIT accelerator requires, simultaneously, as many as six high-power rf systems to drive a single Alvarez structure at full beam current. Each amplifier is designed to produce 600 kW, cw at 80 MHz.[1] All of these amplifiers must be phase and amplitude controlled to within ±1° and ±1%, respectively, of the set-point values for proper accelerator operation. These tolerances are maintained with analog feedback-control systems. The complete analog feedback-control system and low-power rf system was tested in the configuration depicted in Fig. 1.

An experiment was breadboarded in the laboratory to test viability of the multiple rf-drive concept. The experiment consisted of two rf amplifier chains, each with 100-W output, driving a resonant load with a Q_0 of 8000. The resonant load was a coaxial, half-wavelength, capacitively end-loaded cavity.

The rf system is driven by a frequency synthesizer at 80 MHz. The synthesizer is followed by the cavity phase shifter module. Beyond this point, the rf signal is split and distributed to two identical rf amplifier chains. Chain 1 is designated the master chain, and Chain 2 is the slave.

The cavity and the chain phase-shifter modules are alike. The phase shifters are of the varactor-tuned circulator type.[1] The actual phase shifting is done at 400 MHz because of the unavailability of circulators at 80 MHz and the physical size of the strip-line circuitry at that frequency. Each phase-shifter package includes an active up-converter to mix the 80-MHz input with a 320-MHz source to reach the 400 MHz required by the circulator/varactor part of the circuit, which is followed by an active down-converter to get back to 80 MHz. Phase information is preserved by using the same 320-MHz signal for both up and down conversion. The phase-shifter module includes an automatic-level control (ALC) amplifier whose output is held constant to compensate for the phase-shifter's insertion-loss variation with phase shift.

The phase shifter is followed by a 30-dB, 100-mW drive-level control (DLC) amplifier whose output power depends on a dc control voltage. Because of unavailability of 80-MHz isolators, a 10-dB pad is included between the ALC and DLC amplifiers to provide some isolation between stages. The final stage is a 100-W rf amplifier, loop coupled into the cavity resonator. In the FMIT system, the 100-W amplifier will be followed by a three-stage, 600-kW linear amplifier[2] with an EIMAC 8973 final.

Control Philosophy

The basic control philosophy accomplishes a dual purpose. The first is to maintain the cavity field's required phase and amplitude. The second is (1) to establish zero phase shift between both chain's rf outputs and (2) to maintain the slave chain's power output equal to that of the master chain. Phase and amplitude tracking between the two rf chains is important to achieve good overall system stability. It will become even more important in the case of FMIT with six 600-kW chains.

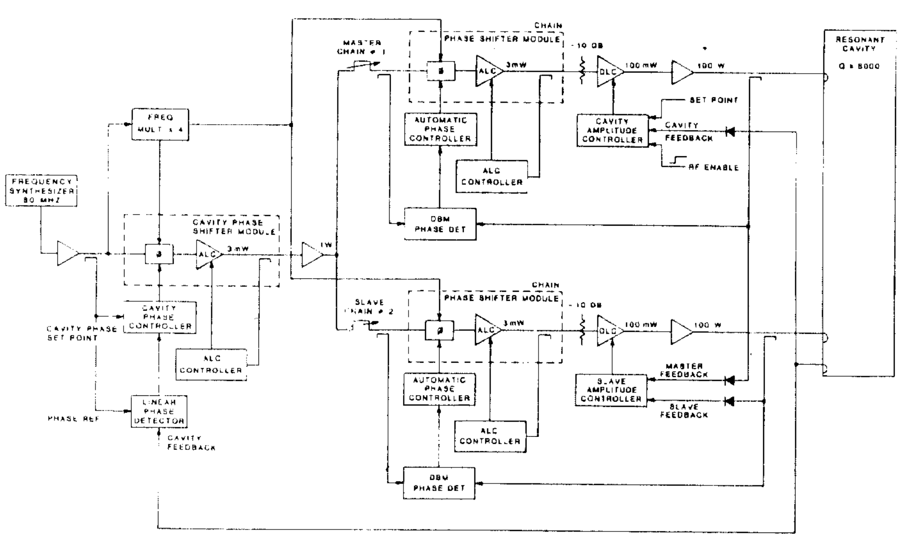

Fig. 1.
Simplified schematic for rf control-system experiments.

*Work supported by the US Department of Energy

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To achieve phase tracking, each chain has an automatic phase-control loop that maintains a constant phase shift across the chain regardless of operating conditions. The chain phase detectors are double-balanced mixers. The cavity phase detector is a device designed by Los Alamos that has a linear output over a 360° range and a 100-kHz bandwidth.[3]

Amplitude tracking is accomplished by making the slave chain match the master chain in output power by using an amplitude controller. The cavity phase and cavity amplitude control loops have a 20-kHz bandwidth, determined primarily by the cavity bandwidth. The automatic phase control and the slave amplitude control loops were designed for a 100-kHz bandwidth.

The basic configuration for the feedback controllers is shown in Fig. 2. It consists of an error amplifier; proportional, integral, and derivative stages; and an output driver. All the controllers are basically alike, although the gains in the various stages depend on the specific application and typically are not the same from unit to unit.

Control System Operation

In normal operation of the rf amplifier chains, the following sequence occurs:

(1) An "RF Enable" signal to the cavity amplitude controller tells Chain 1 to turn on. Inputs to this controller are a detected cavity feedback signal and a set point corresponding to the desired cavity rf field amplitude.

(2) As Chain 1 turns on, Chain 2 tracks it in output power. The ~10-μs response time of Chain 2 is much faster than the cavity's 50-μs rise time; thus, both rf systems essentially are driving the cavity simultaneously.

(3) The automatic phase-control loop around each chain holds the phase shift across each chain to a constant value, regardless of operating conditions. This assures that both amplifiers are driving the cavity in phase.

(4) As soon as the cavity amplitude-loop locks, the cavity phase controller locks and maintains the cavity field's proper phase.

Experimental Tests

Several tests were performed on the complete system to assure proper system performance over a wide range of system disturbances. Step disturbances were introduced through the "External Demand" inputs to the various controllers.

The following tests are some of those successfully performed:

(1) Chain 1 output was varied from 0 to 100% in a cw mode. Phase and amplitude tracking of Chain 2 was within the ±1°/±1% tolerance.

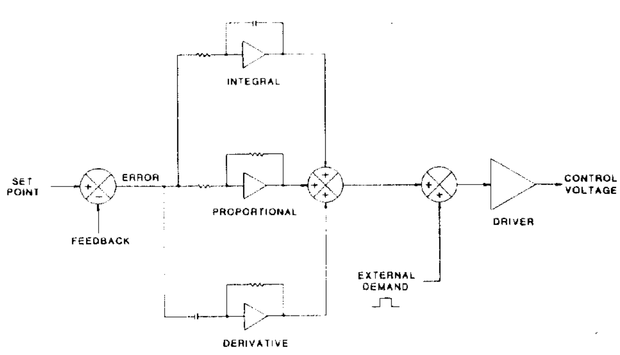

Fig. 2. Basic configuration of feedback controllers.

(2) With both chains operating at half-maximum power, an External Demand was applied to the slave amplitude controller of sufficient level to drive it from 10 to 90% of full output if the control loop were open. The controller held the cavity amplitude constant to ±1%. Figure 3a shows the 10 to 90% External Demand input. Figures 3b and 3c show the slave error and cavity (master) error signals. Figure 3d is the vertically expanded cavity rf field that is being controlled to ±2.8% on the initial under- and overshoot and to considerably <1% after the transient has damped away. Figures 3e and 3f show the tops of the master and slave rf output envelopes on an expanded time and voltage scale.

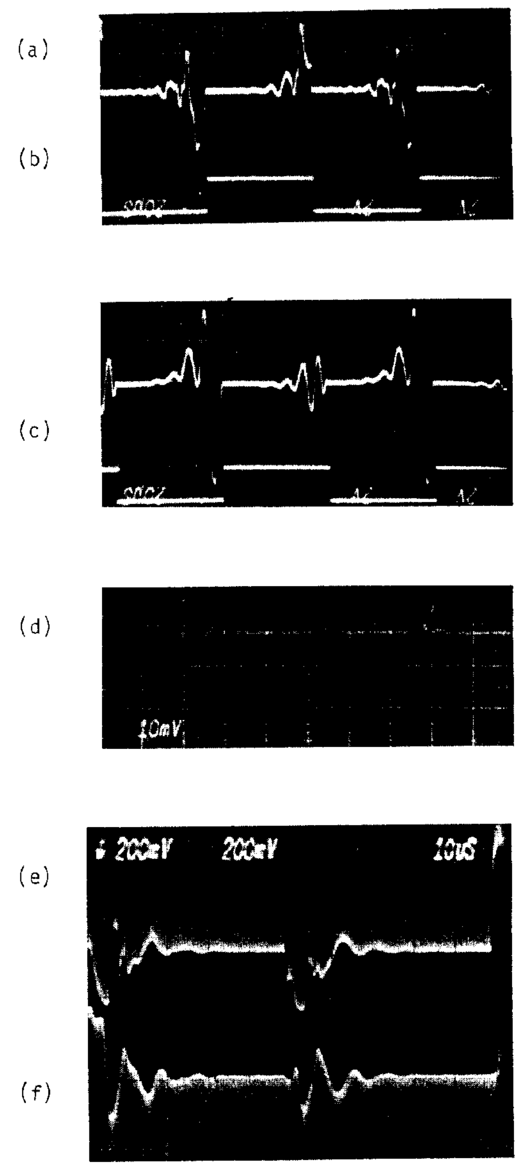

Fig. 3. (a) External demand on slave controller (2 V, 20 μs/div). (b) Slave amplitude error signal (100 mV, 20 μs/div). (c) Cavity amplitude error signal (100 mV, 20 μs/div). (d) Cavity rf field (10 mV, 20 μs/div). (e) Vertically expanded rf envelope of master chain. Full envelope is 2V P-P. (200 mV, 10 μs/div). (f) Vertically expanded rf envelope of slave chain. Full envelope is 2V P-P. (200 mV, 10 μs/div).

(3) An External Demand was applied to the automatic phase-control loop sufficient to drive the phase of the chain ±90°, if it were open loop. The controller maintained the loop phase shift across the chain to less than ±1°.

(4) With the cavity field amplitude set so that each amplifier was delivering one-third full power, the cavity-amplitude feedback signal was modulated to simulate a 200% beam loading [where per cent beam loading = $(P_{beam}/P_{copper}) \times 100$].

The cavity field amplitude was maintained at ±1%. See Fig. 4 for transient response.

(5) With the cavity phase set to the set-point value, a ±90° phase disturbance was applied through External Demand on the cavity phase controller. Tank phase was held to ±1°. See Fig. 5 for transient response.

In gaining experience with the multiple-drive configuration, it became obvious that very tight tracking was required between the output phase and amplitude of each chain to maintain a low VSWR in each output drive line. Detailed measurements have not been made yet, but as a general rule of thumb a phase difference between chains >10° and an amplitude difference >10% led to drive-line VSWRs and cavity field instabilities that would not be acceptable in an operating accelerator system. In an operating accelerator, final amplifier gain depends strongly on load VSWR; thus, every possible effort must be made to get the VSWR to behave in a controlled manner during transient conditions. Because our system successfully held phase and amplitude differences to less than ±1° and ±1% between chains, at this time detailed measurements were not made on the effects of large phase and amplitude tracking errors between chains.

Another control-system configuration had been tried previously, where instead of a master/slave arrangement, each rf chain had an automatic gain control (AGC) around it to keep the gain constant under a variety of operating conditions and system disturbances.[1] It proved impossible to develop an AGC loop with enough dynamic range to maintain a constant gain over the rf output range of 20 to 100% of full power. Because of the lack of success in trying to stabilize this configuration, we opted to go with the first configuration discussed.

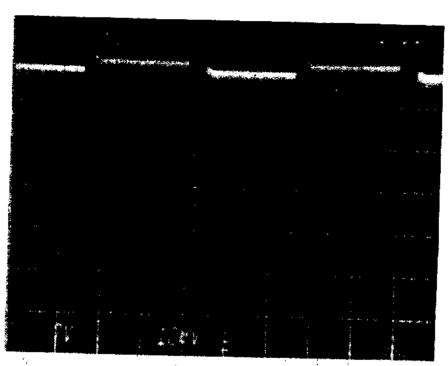

Fig. 4. Vertically expanded cavity field with simulated 200% beam loading. Full signal is 240 mV P-P. (10 mV, 100 μs/div).

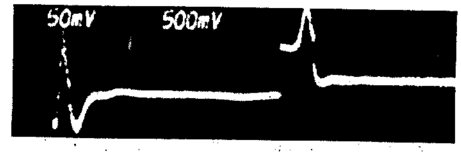

Fig. 5. Cavity phase error 50 mV/deg. (50 mV, 200 μs/div).

Conclusion

When multiple rf sources are required for driving single rf accelerator cavity, very tight phase and amplitude tracking is needed between the source's outputs. The master/slave configuration for amplitude control, coupled with automatic phasecontrol loops around each chain, proved to be a very stable design in the laboratory, maintaining the cavity field to within ±1° in phase and ±1% in amplitude, in spite of a variety of imposed system disturbances. Based on these results, a similar control philosophy is being implemented on the FMIT accelerator and currently is under test at high power.

References

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