Bates South Hall Ring RF Control System[1]

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Abstract

A system designed to control the 2856 MHz RF voltage in a 10 kW, CW standing-wave cavity is described. In-phase/Quadrature (I/Q) down/up frequency conversion is used within a cavity-voltage feedback loop, permitting integral as well as proportional gain. I/Q down conversion is also used to produce an amplitude-insensitive resonance controller. Separate gain and phase feedback loops around the klystron maintain transmission characteristics. Thus, the cavity-voltage loop, open-loop gain is controlled and the loop is stable over a wide range of operating conditions. The design provides input points and monitoring for AM (amplitude modulation), PM (phase modulation), and pulse modulation. Supervisory control and monitoring is achieved through multi-channel Bitbus cards.

1. INTRODUCTION

The design and implementation of a low-level RF control system are described. The system is comprised of four feedback loops listed in Table 1. Support for AM, PM, and pulse modulation is provided as well as monitoring of power levels and loop error signals. General system and performance specifications are given in Table 2.

Table 1: Loop Function

Loop	Regulated Variable
Voltage:	cavity voltage (amplitude and phase)
Resonance:	cavity resonant frequency
Gain:	klystron transmission gain
Phase:	klystron transmission phase

Table 2: General Specifications

f_{rf}:	2856 MHz
harmonic number:	1812 (f_0 = 1.576 MHz)
cavity Q_0:	18 000
coupling:	$1 \leq \beta \leq 10$
cavity power:	100 W to 10 kW
resonance regulation:	± 0.5°
cavity voltage regulation:	± 1%, ± 1° rms
AM rate and depth:	100 Hz to 100 kHz, 100%
PM rate and range:	10 kHz to 1 MHz, ± 180°
pulse modulation:	0 to 1 kHz, ≥ 500 ns

1 This work performed under US Department of Energy contract number DE-AC02-76ER03069.

Following an overview of the control package, the design of each feedback loop is discussed. Overall control system performance, including the cavity, is reported in a companion paper [1].

2. OVERVIEW

The control loop configuration is shown in Fig. 1. Klystron gain is regulated by the innermost loop that compares the power level at the klystron output with the input. A PIN diode modulator is used to correct for gain changes. A digital phase shifter is adjusted by the phase loop to regulate transmission-phase across the klystron. Together, these loops regulate complex klystron gain so that the stability and performance of the cavity voltage loop is not degraded as cathode voltage is changed or power levels are manipulated.

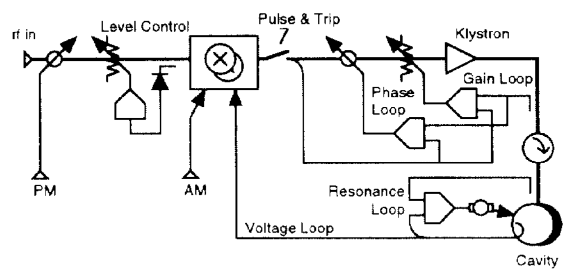

Figure 1: Overview of Control Loops

Resonance is controlled by measuring the phase between the rf drive into the cavity and the cavity voltage. A cavity tuning plunger is then positioned to zero this phase difference.

Cavity voltage is down-converted by a quadrature mixer and a 2856 MHz reference signal. The resulting in-phase (I) and quadrature (Q) signals are processed by video bandwidth electronics, up-converted by the 2856 MHz reference and applied to the rf drive line. Sensitivity of the down/up conversion process to variations in reference level is avoided by using an automatic level control (ALC) upstream of the mixers.

Phase modulation is effected by a digital phase shifter on the 2856 MHz reference signal. Use of ALC prevents use of an amplitude modulator in line with the reference; therefore, AM is achieved by varying the setpoint for the I component of the down-converted cavity voltage.

Pulse modulation is provided for cavity conditioning. A fast-acting PIN diode switch is used for fast rf shutoff as well as pulse modulation. In addition to front-panel, manual, and (Bitbus) computer activation, the switch can be triggered by excess reverse power at either the input or output of the klystron. Four spare inputs are provided for other "trip" signals.

Two chassis pairs house the control system. Each pair consists of an rf chassis and an electronics chassis. One pair contains circuits for the gain, phase, and modulation control; the other holds the voltage and resonance loops. All rf components are "connectorized" and mounted within the rf chassis. Circuits for signal conditioning and control dynamics are constructed on 6U VME cards and contained in a card frame with a multi-channel Bitbus node, built by MIT-Bates. Operation is by a local Bitbus-equipped computer or by the Bates supervisory-Bitbus system.

3. VOLTAGE

Quadrature (I/Q) frequency shifting has proven useful for: avoiding the non-linear cross-coupling of amplitude and phase loops [2, 3], creating a modular control system [4], and allowing feedback with swept frequency systems [5]. In this instance, I/Q feedback is used because of the large transit time (> 200 ns) around the voltage loop that severely limits proportional gain. However, the significant ripple at frequencies up to 720 Hz present in the klystron output must be suppressed. This requires high gain over a frequency band centred on f_{rf} with bandwidth less than that of the cavity. Such bandwidth is very difficult to achieve at 2856 MHz; however, after shifting to 0 Hz (i.e., baseband), a simple integrator of the type shown in Fig. 2 meets our requirements.

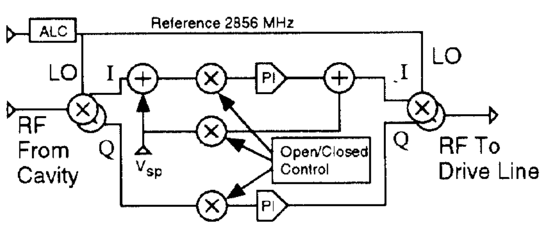

Figure 2: Voltage Loop Control Block

A setpoint of zero is implied for the Q arm of the controller; hence, phase-angle changes must be made on the reference rf. Open-loop operation is provided by by-passing, and removing the input to, the PI controller. A smooth transition between open- and closed-loop modes is realized by continuous control over the relative gains of the closed- and open-loop paths.

Design challenges were the variable coupling into the cavity (β) and the wide dynamic range. Variable β presents the controller with a variable bandwidth, variable-gain load. Gains were selected for stability at the worst case of $\beta = 1$ (with a phase margin of 35°) and unity-gain bandwidth of $\geq$ 300 kHz over the whole range of β. For the case of $\beta = 4.5$ and gains of 1.2 V/V and 3.3 MV/(V-s) the effect of feedback on $\Re\{\mathbf{Z}_{cavity}\}$ is shown in Fig. 3. With feedback, cavity impedance is given by:

$$\mathbf{Z} = \frac{\mathbf{C}}{1 + \mathbf{HC}} \tag{1}$$

where **C** is the loaded cavity impedance
H is the feedback circuit impedance

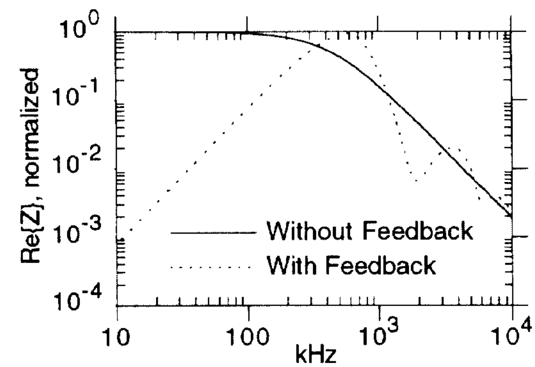

Figure 3: $\Re\{\mathbf{Z}_{cavity}\}$ With and Without Feedback

Impedance is improved over the unity-gain bandwidth of the loop. Then, due to delay-induced phase rotation, impedance is worsened until 1 MHz. The result is good regulation against power supply ripple, reduction of cavity impedance near f_{rf}, and little effect at the revolution sidebands.

The dynamic range of mixers are limited due to offsets, asymmetries and variations in response that dominate at low signal levels. Mixers had to be characterized to get the best match possible; then, careful biasing was required to get a 30 dB range. Transmission phase through the closed-loop system gave the most sensitive indicator of balance. A ±0.5° variation over 30 dB was achieved during bench testing.

4. RESONANCE

In this application, detuning for average beam-loading compensation will be small; therefore, techniques for linearizing detection of frequency error [6, 7] are not required, particularly when the nonlinear tuning action and the rate limit of the stepping motor are considered. The 1.6 MHz range is covered in 10 mm of travel, with a maximun sensitivity of 400 kHz/mm. Plunger speed is limited to 1 mm/s. Consequently, the design emphasizes wide dynamic range with stable phase measurement. A dual tracking ALC is used to maintain power levels and avoid phase shifts between arms of the detector (see Fig. 4). Use of an I/Q mixer followed by division further extends dynamic range. The result is ± 2° variation over 30 dB range on both inputs.

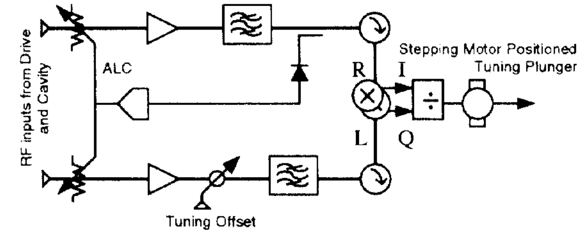

Figure 4: Resonance Phase Detector

Provisions are included for manual and remote position and phase control as well as smooth, controlled, loop closure.

5. KLYSTRON

5.1 Klystron Gain

Identical detector circuits measure the input and output power level of the klystron. The difference of these detected levels drives a PI controller. Non-linear detector response is largely compensated by modulator non-linearities, and linearization circuits are not required. Changes to the gain setpoint are made by rf attenuators located prior to the detectors.

The PIN modulator has significant phase shift as a function of attenuation. Gain-loop response has been set to < 100 Hz so that it is slower than the phase loop, which can then correct for this AM to PM effect without unstable interactions between these loops.

The integral controller term passes through a successive-approximation ADC that provides an output of its internal DAC. Thus, if the ADC conversions are halted, the integral term is held indefinitely. Conversions are conditioned on a minimum input to the klystron. Accordingly, the gain setting is maintained between applications of rf power.

5.2 Klystron Phase

Phase measurement is done using a quadrature mixer and division of the Q output by the I output (as in the resonance circuit) to give a phase error-signal independent of power level. To maintain the phase setting between applications of rf power, the phase error is converted to a digital clock signal using a voltage to frequency ($V \rightarrow F$) converter. This clock is then conditioned on power level and used to increment/decrement an 8-bit counter that sets the phase of a digital shifter. This architecture has limited bandwidth due to the time delay imposed by the $V \rightarrow F$ converter and its maximum frequency of 1 MHz. A 1 kHz unity gain was achieved, and hence the 100 Hz setting for the gain loop.

A deadband is included to prevent chatter. With this deadband set to $< \pm 0.5°$ the phase-error signal is as shown in Fig. 5. With an eight-bit shifter the minimum phase error would be 2.8° p-p. The additional 1.2° observed results from loop-response rate and deadband.

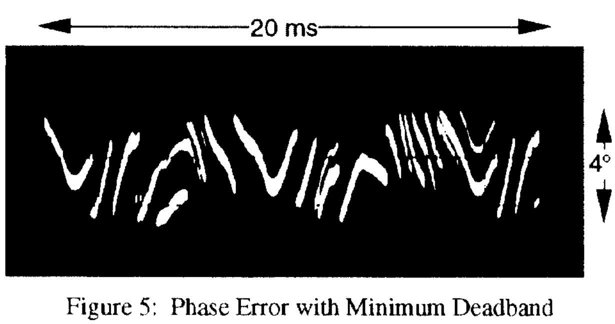

Figure 5: Phase Error with Minimum Deadband

In addition to the discrete phase steps seen in Fig.5, large phase transients exist for 60 ns on each phase step. Rather than allow the loop to constantly generate this phase "hash", the deadband is set so that the typical 13° p-p ripple of the klystron is allowed. At the cavity, this ripple is effectively removed by the voltage loop.

6. MODULATION

Amplitude modulation cannot pass through the input ALC; hence, AM is implemented by modulating the I-channel setpoint for the voltage loop. Loop-gain amplifiers are situated after the down-conversion mixer; hence, harmonics generated by this mixer are not suppressed and overall harmonic performance will be between that of a single mixer and a series pair. Performance should degrade as the harmonics extend outside the bandwidth of the voltage loop.

Phase modulation is applied to the rf reference source using an eight-bit shifter driven at an 8 MHz update rate. The 1.5 dB PM to AM conversion and phase discretization of the shifter is the limiting factor for PM quality.

7. CONCLUSIONS

Complex frequency shifting has permitted high-gain integral control of cavity voltage that is effective for suppressing narrow band disturbances, such as power supply ripple, and reducing cavity impedance to the beam over a ± 300 kHz bandwidth.

Use of a dual-tracking ALC and an I/Q mixer for phase measurement produced consistent, accurate resonance control over a wide dynamic range. A similar technique was used to produce an amplitude-insensitive klystron-phase regulator. When used in conjunction with a klystron-gain regulator, the stability of the cavity-voltage control loop is maintained over a wide dynamic range.

8. REFERENCES

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