BEAM LOADING COMPENSATION FOR 52 MHz RF SYSTEMS

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Abstract

A combination of wide-band feedback, wide-band feedforward, and narrow-band resonance control loops has been implemented for both the PETRA II and HERA 52 MHz proton rf systems. Heavy beam loading, nearly in quadrature to the desired cavity field, produces beam current dependent cross-coupling between cavity field amplitude error and phase error. The effectiveness of separate amplitude and phase feedback controllers would be compromised by the cross-coupling. Direct feedback of the cavity rf field, in a 52 MHz servo loop, has been implemented. This conceptually simple approach is free of the cross-coupling drawback.

The overall design for beam loading compensation is reviewed, then implementation experiences are described. Finally, controller performance is presented.

Introduction

Specifications for the HERA 52 MHz rf system call for ±2% amplitude, ±5° phase regulation of the accelerating field. These specifications are to be met during beam loading as high as 90% and during non-uniform charge distribution around the synchrotron. Other factors affecting control include:

	PETRA II	HERA '52'
bunch spacing (at transfer)	96.82 ns	96.08 ns
frequency	51.64 → 52.04 MHz	52.03 → 52.05 MHz
frequency sweep time	> 60 s	> 60 s
harmonic number	400	1100
loaded Q	≈4000	≈7500
rf amplitude dynamic range	12 dB	21 dB
average beam current	170 mA	170 mA
real part of revolution sideband impedance	< 4 kΩ	< 4 kΩ

Physical constraints and potential radiation damage require the control electronics to be located in a shielded area near the resonant cavities. The shortest possible cable length between control electronics and cavity is 6 m.

The acceleration cycle is sufficiently slow that the beam current can be considered to be in quadrature to the accelerating field. Consequently, beam loading is a reactive load on the final amplifier. Reactive cavity power is dissipated as real power in the final amplifier. The challenge is to compensate the large quadrature beam current and simultaneously adjust the final amplifier load impedance to avoid unreasonable power dissipation.

Both controllers are based on schemes proposed by Pedersen [1] and Boussard [2]. The overall rf systems are described by Funk in [3] and [4]. A rf feedback servo loop (fast loop), a feedback resonance controller, and rf feedforward compensation are combined to achieve the performance goals without placing unreasonable demands on the rf drive chain.

An overall block diagram of these three controllers is given in Fig. 1. The fast feedback loop and the feedforward input are used to correct for transient beam-induced disturbances, keeping the cavity field matched in amplitude and phase to that specified by an rf reference signal. Resonance control tunes the cavity such that the time-average load presented to the final rf amplifier is resistive.

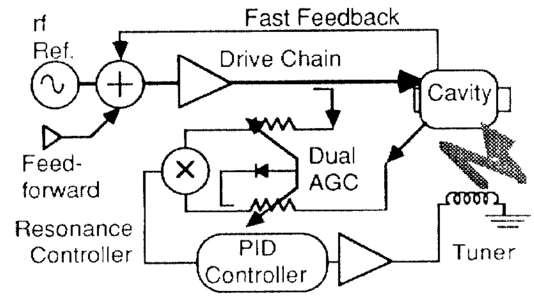

Fig. 1. Fast Loop, Feedforward and Resonance Controller.

Resonance Control

Resonance control manages power dissipation and average beam loading. The controller keeps the average drive current in phase with the cavity voltage; thus, compensating quadrature drive current (called for by the fast loop and feedforward) forces a detuning from resonance such that the total of the drive and beam currents produces the desired gap voltage, as shown in Fig. 2. When $\psi = \mathrm{Tan}^{-1}(Y)$, $\mathbf{I}_g$ will be in phase with $\mathbf{V}$ [5].

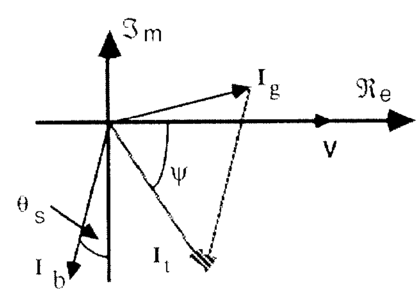

Fig. 2. Phasor Diagram in 52 MHz Frame of Reference.

Legend

I_g	final amplifier plate current	I_b	beam current
I_t	total of $\mathbf{I}_g$ and $\mathbf{I}_b$	$\mathbf{V}$	cavity gap voltage
θ_s	synchronous phase angle	ψ	detuning angle
Y	$\lvert \mathbf{I}_b \rvert \div \lvert \mathbf{I}_g \rvert$ = beam loading factor		
τ	fast loop transit time	ω_0	resonant frequency
Z_r	cavity impedance with respect to reference current		
Z_b	cavity impedance with respect to beam current		

Tuning is accomplished by varying a solenoid magnetic biasing current surrounding a perpendicular biased ferrite loaded resonator. This resonator is coupled to the main cavity; hence, altering its frequency alters the overall resonance. The solenoid time constant is on the order of 200 ms; consequently, it is impractical to use resonance control to compensate for transients on the time scale of the revolution period. Tuning to compensate the time-average beam loading minimizes peak and average power requirements.

A dual-channel automatic gain control (AGC) decouples resonance control from changes in voltage setpoint for $\mathbf{V}$. When used in conjunction with the fast loop, it also modifies the mixer input signals such that the mixer output is proportional to frequency error rather than phase error. AGC bandwidth in excess of 2 kHz was required to prevent undesired interaction between the AGC and resonance control as a whole.

A simple proportional-integral-differential (PID) controller processes the frequency error, producing a control voltage for the solenoid power supply.

Fast Loop Design Options

Fast control must be used to correct for deviations from average beam loading. The objective of fast control is to add to the generator current a current equal but opposite in sign to the disrupting current. Four methods of fast control were considered:

1) separate phase and amplitude feedback control loops,
2) direct proportional feedback,
3) feedforward, and
4) combined direct proportional feedback, and feedforward.

Separate Phase and Amplitude Feedback Loops

Two feedback loops could be used to control the amplitude and phase, as shown in Fig. 3. One loop senses the amplitude error and modulates the drive amplitude. The other loop senses the phase error and modulates the drive phase.

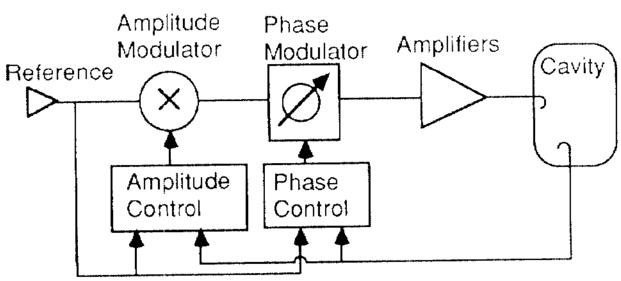

Fig. 3. Separate Amplitude and Phase Loops.

This option is inappropriate because of the cross-coupling between the phase and amplitude loops. This cross-coupling increases with beam loading (and the corresponding detuning). At full beam loading, the phase and amplitude error measurements have essentially switched meaning. The loops could be decoupled; however, this requires some method of determining the detuning angle.

Direct Feedback:

Cross-coupling of phase and amplitude is avoided by measuring the error directly at the operating frequency (i.e., 52 MHz). The resulting control loop is a single-loop servo system, as shown in Fig. 4:

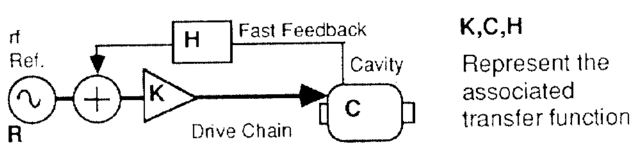

Fig. 4. Basic Components of Direct Feedback.

Using Laplace transforms, where s is the Laplace variable, the closed-loop transfer function for the reference is:

$$Z_r(s) = \frac{V(s)}{R(s)} = \left(\frac{1}{K(s)C(s)} + H(s) \right)^{-1}$$

The closed-loop transfer function as seen by the beam is:

$$Z_b(s) = \frac{V(s)}{I_b(s)} = \left(\frac{1}{C(s)} + K(s)H(s) \right)^{-1}$$

For stability reasons, loop transit time, τ, is selected so that $e^{-s\tau} = (-1 + j0)$ for $s = j\omega_o$. Over the frequency band of interest, $(\mathbf{K}(s)\mathbf{C}(s))^{-1} \ll \mathbf{H}(s)$; therefore, $\mathbf{Z}_r(s)$ is dominated by $\mathbf{H}(s)$. Thus, nonlinearities in $\mathbf{K}(s)$ can be suppressed.

Disturbances caused by $\mathbf{I}_b$ are reduced by roughly a factor of $\mathbf{K}(s)\mathbf{C}(s)\mathbf{H}(s)$, the open-loop gain. A first-order approximation of the required open-loop gain can be calculated from the specified $\pm 5°$ phase error. With an average beam current of 9 times the nominal drive current, the effect of $\mathbf{I}_b$ must be reduced by $9 \div \mathrm{Tan}(5°)$ times, giving an open-loop gain of 100.

While feedback reduces the magnitude of the disturbance generated by the beam, it alters the phase relationship between the current and voltage in a way that makes the real part of the system impedance greater than without feedback (over certain frequency bands). In order to reduce $\mathrm{Re}\{\mathbf{Z}_b(j2\pi f)\}$ to 4 kΩ, given a cavity shunt impedance of 750 kΩ, a reduction of 188 times is required. If this reduction is to be achieved by the first revolution sideband (47 kHz from ω_0 for HERA), an open-loop gain of ≥200 is required.

A simple (but not complete) stability criterion is that the phase of the open-loop gain must never be 180° whenever the magnitude of the open-loop gain is ≥ 1. Factors contributing to phase rotation are:

- the cavity bandwidth (180° rotation),
- amplifier and coupling network bandwidths, and
- the electrical length of the loop.

Both the PETRA and HERA designs call for part of the amplifier chain to be located in a shielded area, separated from the cavity; hence, the effect of loop length is a major factor.

Loop Delay with Feedback Methods

The impact of loop transit time upon stability applies equally to both direct and separate amplitude and phase feedback. The separated feedback loops process a demodulated (frequency shifted and rectified) sample of the cavity voltage. For narrow-band systems, the amplitude and phase characteristics of the frequency shifted signal are the same as those of the rf signal. Consequently, component bandwidth and transit time present the same limitations to both feedback approaches.

Feedforward

In feedforward, a compensating current, equal but opposite to the 52 MHz component of the beam current, is added to the drive current. In contrast to feedback, with feedforward it is possible to anticipate these disturbances and compensate their leading edges. Feedforward has the disadvantage that only known disturbances can be compensated, and this compensation will only be as good as the prediction of the disturbance.

Additional instrumentation and circuitry are required to implement feedforward control. A beam sensor is required to measure the amplitude and timing of the beam. Physical and time-delay constraints may prohibit positioning the beam sensor ahead of the cavity. Consequently, a one-turn-delay is usually employed, making it impossible to compensate for beam the first time it enters the ring.

The expected feedforward compensation signal accuracy is 90%. While this accuracy may be sufficient to compensate cavity fields during the passage of a single beam pulse, the error will accumulate over multiple revolutions, eventually exceeding tolerances.

Combined Feedforward and Feedback:

By using both feedforward and feedback the advantages of each method can be achieved. Feedforward can be used to compensate for most of the beam disturbance. Feedback can correct for inaccuracies of feedforward. The amount of open-loop gain required is reduced because the size of disturbance that feedback must handle is reduced, and the system impedance to the revolution sidebands is reduced. If the feedback is able to account for 80% of the beam, then the restrictions on system impedance are relaxed by 5 times for the feedback. A minimum open-loop gain of 50 has been specified in order to meet the 4 kΩ sideband impedance specification.

Simulations

Two simulations were used to aid in controller design. Both were written in Fortran for use with the FORSIM simulation program [6].

Fast Loop

Simulation was used so that factors could be considered such as: final amplifier nonlinearity, component limiting, and loop transit time. Time resolution on the order of 1 ns was used so that individual beam bunches and rf cycles could be examined. Such a fine time scale prohibited simulation cases of more than about 10 μs. These cases were sufficient to show the delayed response of feedback. It was also used to show that requirements should be satisfied (with a factor of two margin) when 80% feedforward is combined with proportional feedback having an open-loop gain of 50. It was found that simple time advance of the feedforward signal adequately overcame the bandlimited response of the rf drive chain.

Resonance Loop

PETRA resonance control was designed without the aid of simulation. While performance is adequate, it is poorer than expected. For the HERA design, a simulation was written to model resonance controller components and characteristics, including: AGC, phase detector, PID controller, solenoid power supply, frequency-versus-current characteristic, and the steady-state fast loop response. Nonlinear and saturation characteristics were modelled for each component. Use of this simulation enabled a factor of four improvement in response time for HERA relative to PETRA.

Implementation

Fast loop stability was challenged by drive loop and tuner resonances close to the operating frequency. The difference between the operating frequency and these resonances, coupled with the loop transit time, places these responses at rather unpredictable phase angles. A typical Bode plot of the HERA cavity fast loop is shown in Fig. 5. The feature labelled "1" is the primary response at 52 MHz, 36 dB gain. Tuner resonance is labelled "2"; "3" marks the drive loop resonance. A 47 MHz response labelled "4" is a weak cavity mode produced by an internal supporting post. Drive loop response is only 6 dB below the primary response; therefore, cable lengths were adjusted to stabilize both these resonances.

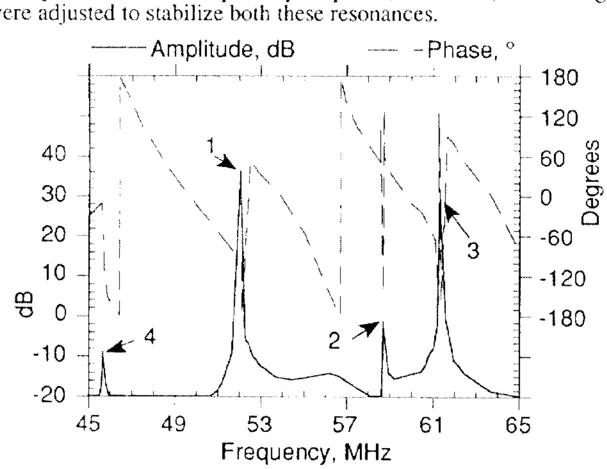

Fig. 5. HERA Fast Loop Bode Plot.

A feature of both feedback loops is that the loops may be closed gradually. Start-up proceeds by partially closing the fast loop with the tuning solenoid current set to mid-range. The resonance control gain is smoothly ramped over a few seconds and once tuning error drops below a threshold, fast loop gain is stepped to maximum.

Performance

The controllers described here have been successfully implemented for both the PETRA and HERA systems. Predicted performance has been verified by simulating beam loading by frequency modulating the rf reference. This modulates cavity impedance such that the magnitude and phase of the load presented to the final amplifier is equivalent to that expected during beam loading.

Measurements of open-loop gain (for the fast loop) revealed a dependency on cavity voltage, believed to be the result of multipactor. Specifications were met by increasing the gain for a minimum of 50. Under these conditions the maximum gain was >75, yet no adverse effects were observed.

Resonance acquisition was problematic with the PETRA systems. Careful adjustment is required of initial solenoid current setting and controller gain ramp-rate. Once resonance is found, the prescribed acceleration cycle is tracked. The HERA controller has no such shortcomings. It reliably acquires resonance within 4 s.

Both systems are installed at DESY, Hamburg, awaiting completion of the synchrotrons.

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