CONTROL OF HEAVILY-BEAM-LOADED SNS-RING CAVITIES

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Abstract

In each of four rf stations that make up the rf buncher system in the SNS accumulator ring, cavity voltage and phase are control led through a negative-feedback system employing digital electronics. With peak beam currents as high as 75 Amperes near the end of each 1.1 ms machine cycle, the rf cavities in the SNS ring are strongly driven by the beam. To provide adequate regulation of cavity fields in the presence of high SNS beam currents, basic feedback loop parameters are pushed to levels where stability becomes a major concern. This note presents a LabVIEW simulation of the ring rf system that demonstrates how Smith compensation can be used to mitigate the destabilizing effect of dead-time delay in the feedback loop and assure adequate regulation of cavity fields. A digital implementation of Smith compensation is outlined that could be incorporated into the LLRF system being provided by BNL.

BACKGROUND

In any feedback system, unstable conditions exist whenever signal-delays in the feedback loop become long enough to produce positive-feedback for loop gains exceeding unity. Mechanisms for compensating delays are usually essential for the attainment of required regulation levels together with acceptable stability margins.

There are two general types of delay in any feedback system. The first type of delay is associated with dead time from signal propagation delays and timing delays. In the SNS system, a major source of propagation delay arises from the round-trip signal-transit-time between signal sources in the rf control room and receiver amplifiers in the ring tunnel. The second type of delay results from energy build-up in energy-storage elements in the feedback path. This second type of delay is associated with poles in the system response. While the delay mechanisms differ, the two types of delay are indistinguishable in the processed signal. However, the delay types differ markedly in their responses to various compensation methods.

Anticipating the effect of delay by adding a predictive signal into the feedback path can mitigate degradation in stability caused by dead-time delays. This compensation technique forms the basis for the Smith compensator [1] that will be described in this report. Other compensation devices, such as the lead-lag network used in PID controllers, are effective in compensating delays resulting from energy-storage elements, but they must be de-tuned to compensate dead-time delays, compromising performance of PID controllers. The simulations presented in this report show that the Smith compensator makes a substantial improvement in stability for the SNS ring buncher system by essentially moving dead-time delays outside of the feedback loops. Additional details are contained in a separate report [2].

SMITH-COMPENSATED FEEDBACK

Figure 1 is a block diagram of the feedback control system that has been simulated in the present study. The diagram contains the basic elements of the Smith compensator. In principle, the compensator forms a signal path in parallel with the actual cavity and delay lines of the SNS ring-rf system. The parallel path contains the cavity analogue and a delay-line analogue that together produce a signal response as close as possible to that of the actual cavity and the actual system delays.

At the differencing ports to the right of the middle *I&Q* demodulator in figure 1, the delayed signal from the cavity analogue is subtracted from the delayed signal from the actual cavity. For a precisely constructed analogue, the resulting difference signal equals the beam-induced signal, or the beam "disturbance," which drives the actual cavity but not its analogue. If the analogue construction is imprecise, the difference signal is only an estimate of the beam disturbance.

At the *I&Q* summing junctions in figure 1, the cavity-analogue output is added to the estimated beam disturbance from the previous differencing ports, producing a predicted cavity signal plus the estimated beam disturbance. This composite signal is then compared to the reference *I&Q* input to form a short, fast feedback loop that does not contain the delay, yet regulates the system based upon an estimated beam disturbance. In effect, the delay has been moved outside of the feedback loop. The demodulators convert rf signals from the delayed cavity, the delayed cavity analogue and the undelayed cavity analogue into digitized envelope signals representing the in-phase, *I*, and quadrature, *Q*, components of the rf signals. The rf signals are sampled at a rate of four times the applied frequency. Samples are de-multiplexed into even and odd samples and retained between consecutive samples (sample and hold feature). Odd samples are multiplied by $cos(2\pi ft)$ and even samples are multiplied by $sin(2\pi ft)$ to

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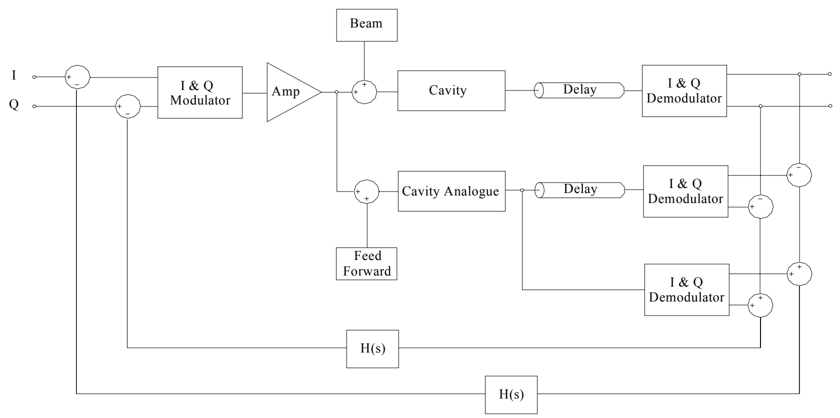

Figure 1. Ring RF Feedback System Utilizing Smith Corporation

produce the desired I and Q values. Because the sampling rate is four times the applied frequency, f, the sine and cosine multiplications are accomplished in the digital domain by simply changing the sign of alternate samples.

The buncher cavity is treated as a parallel RLC circuit. The inductor in the model comprises a ferrite-loaded coaxial transmission line having a time-varying permeability, μ, in order to simulate dynamic tuning of the cavity. The presence of a time-varying inductive element transforms the circuit equations from linear-time invariant forms to non-linear forms given by,

$$C\lambda\mu\frac{d^2 i}{dt^2}+\left(2C\lambda\frac{d\mu}{dt}+G\lambda\mu\right)\frac{di}{dt}+\left(C\lambda\frac{d^2\mu}{dt^2}+G\lambda\frac{d\mu}{dt}+1\right)i=i_d \qquad (1)$$

$$V_g=\lambda\left(\mu\frac{di}{dt}+i\frac{d\mu}{dt}\right), \qquad (2)$$

$$\lambda=\frac{l\cdot\ln\left(\frac{b}{a}\right)}{2\pi} \qquad (3)$$

where C is the capacitance across the buncher gap, i is the current in the inductive element of the buncher cavity, G is the shunt conductance across the gap, l is the length of the coaxial line representing the inductive element, b is its outside diameter, and a is its inside diameter. The quantity, i_d, is the drive current consisting of a linear superposition of currents from the rf power amplifier and the SNS beam.

The power amplifier is treated as a non-linear tetrode in which the output current depends upon both the grid excitation and the anode voltage of the tetrode in accordance with data supplied by the tube manufacturer. The SNS beam is treated as a rigid body of charge, having a longitudinal beam current profile calculated by M. Blaskewitz [3].

The simulation model described above was implemented using LabVIEW. While LabVIEW is most commonly known for applications in instrument control and data acquisition, LabVIEW also includes software tools for control-loop simulations.

SIMULATION RESULTS

Open Loop Response

Without dynamic tuning, but with full beam current, the gap voltage rises to about 60-70 kV at the end of the cycle, implying an effective shunt impedance of approximately 1,000 Ohms per gap, determined largely by the output impedance of the power amplifier.

When dynamic tuning that is linear with respect to time is included, the gap voltage rises rapidly at first, and then falls off slowly as the resonant frequency of the gap separates from the ring revolution frequency. The frequency separation for SNS parameters is large enough that gap voltage is out of phase with the beam by about 87 degrees at the end of the beam cycle. In effect, with dynamic tuning, the beam excites a gap voltage that nearly sustains beam bunching without an active drive signal. Therefore, only a small amount of power is required in the active drive. From another viewpoint, dynamic tuning maintains the gap voltage and anode current at or near their unloaded values, thereby minimizing drive-power requirements.

Closed-Loop Response

When dead-time delays are added to the feedback path, cavity regulation and system stability become inadequate without some form of compensation. Figure 2 shows the system response when a Smith compensator and a single pole filter are added to the basic feedback system. In this case, the cavity analogue is identical to the actual cavity.

A delay of 750 ns has been applied to both the actual feedback path, and the analogue path to test the effectiveness of the compensator. This much delay equals about 80% of the rf period and goes well beyond the threshold for instability in a typical uncompensated network having comparable loop gain. In spite of the presence of this relatively large delay, it is clear from figure 2 that stability is maintained when the Smith compensator is added to the network.

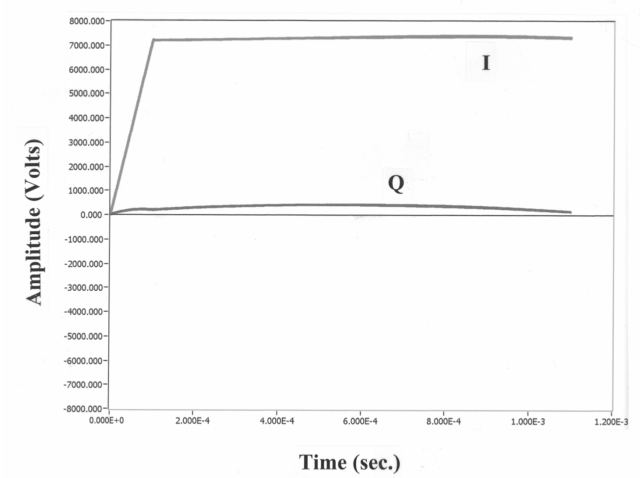

Figure 2. In-phase, I, and quadrature, Q, components of gap voltage with Smith compensation at full beam current.

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For a perfectly constructed analogue, the response with 750 ns of delay is identical to the response of an uncompensated network that has no delay. This behaviour is expected, since the Smith compensator places the delay completely outside the feedback loop in this situation.

In a practical feedback system there will be errors in the cavity and delay analogues. For the SNS, the largest analogue error will occur in the characterization of dynamic tuning in the fast-feedback leg of the Smith compensator. Figure 3 shows the effect of this type of error on gap voltage regulation and stability for the ring buncher system. Stability is maintained when errors in the time dependence of the dynamic tuning is within the range, -5% to +25%. In addition, gap voltage variations are less than 4.5% as long as dynamic tuning errors are less than +/- 5%.

Conclusions

The simulations presented in this report demonstrate that a Smith compensator can stabilize the SNS ring-rf feedback-control system in spite of long delays in signal transmission around the feedback loop. The simulations also demonstrate that an effective Smith compensator can be implemented using only a modest level of care in the construction of the necessary compensator elements.

While the simulations have been carried out using high-frequency compensator elements, similar results should be obtained using equivalent low-frequency base band elements [4]. These base band elements can be readily implemented using reasonably simple algorithms in a digital signal processor. Since the control system being provided by BNL is already digitally based and highly flexible, addition of a Smith compensator with base band analogue elements appears practical.

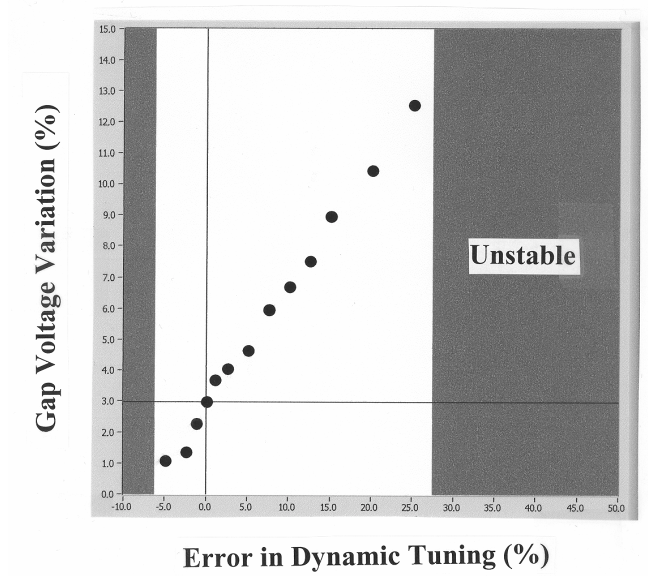

Figure 3. Buncher-cavity gap-voltage variation over SNS beam cycle due to errors in time dependence of the dynamic tuning analogue of the Smith compensator.

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