RF SYSTEM MODELING FOR THE CEBAF ENERGY UPGRADE*

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Abstract

An RF system model, based on MATLAB/SIMULINK, has been developed for analyzing the basic characteristics of the low level RF (LLRF) control system being designed for the CEBAF 12 GeV Energy Upgrade. In our model, a typical passband cavity representation is simplified to in-phase and quadrature (I&Q) components. Lorentz Force and microphonic detuning are incorporated as a new quadrature carrier frequency (frequency modulation). Beam is also represented as in-phase and quadrature components and superpositioned with the cavity field vector. Signals pass through two low pass filters, where the cutoff frequency is equal to half of the cavity bandwidth, then they are demodulated using the same detuning frequency. Because only baseband I&Q signals are calculated, the simulation process is very fast when compared to other controller-cavity models. During the design process we successfully analyzed gain requirements vs. field stability for different superconducting cavity microphonic backgrounds and Lorentz Force coefficients. Moreover, we were able to evaluate different types of a LLRF system's control algorithm: GDR (Generator Driven Resonator) and SEL (Self Excited Loop) [1] as well as klystron power requirements for different cavities and beam loads.

INTRODUCTION

12 GeV Energy Upgrade

The 12 GeV Upgrade is a major accelerator project pointed toward doubling the present maximum energy of 6 GeV. This will be done by adding ten (five per linac) new cryomodules each providing 100 MV of field. 10 new RF stations equipped with 13 kW klystrons will supply RF power. Since every cryomodule contains eight superconducting cavities a total number of 80 new RF systems have to be installed [2].

LLRF system requirements

The stability of the amplitude and phase of the cavity field, a critical figure of merit for nuclear physics experiments has an important contribution to the energy spread in the beam of the linear accelerator,. Table 1 shows maximum allowable cavity field errors to preserve FWHM (Full Width at Half Maximum) beam energy spread of 10^{-4} [3].

Table 1: Cavity field stability requirements

	correlated	**uncorrelated**
Amplitude RMS error	2.2×10^{-5}	4.5×10^{-4}
Phase RMS error	0.25°	0.5°

Such a demanding stability, along with the projected microphonics background of 4 Hz rms thus 6σ=24Hz, create a challenge for the RF field control system. An additional constraint placed on the LLRF system is the Lorentz detuning of the cavity at turn-on. For the CEBAF 12 GeV upgrade cavity detuning caused by the Lorentz force can be 20 times larger than cavity bandwidth.

RF SYSTEM MODEL MODELING

Cavity Baseband Model

A baseband model of the cavity simulates what happens to the RF signal (quadrature representation and at baseband) as it passes through the model. As you can see in Figure 1, the instantaneous value of the detuning frequency, f is converted into angular velocity, ω, and then integrated. The result of integration, an angle φ, is used in the rotation matrix to revolve both quadrature components before they pass through low pass filters. The fixed cutoff frequency is equal to the half of the cavity's bandwidth. After filtering another rotation matrix, driven by the same angle, counterbalances the revolving quadrature components.

Cavity microphonics are modeled as an external signal source which combines with the detuning frequency, f. This source consists of a number of Simulink blocks generating random signals with Gaussian or uniform distribution. These signals pass through different types of filters (LPF, BPF) to achieve the desired power spectral density similar to the expected microphonics background.

Lorentz Force detuning is represented as a state-space model derived from the following equation

$$\Delta f_{total} = \sum_{m=1}^{M} \left(-\frac{\Delta \ddot{f}_m}{\omega_m^2} - \frac{\Delta \dot{f}_m}{\omega_m Q_{mech}} - K E_{acc}^2 \right)$$

where ω_m is an angular frequency of the given mechanical mode m with a quality factor, Q_m. The sum of resonance frequency shifts, Δf_{total}, contributes to the detuning frequency, f.

Beam loading, as well, is represented by quadrature components. For given beam current, $\vec{\iota_b}$, cavity shunt impedance, R_a and angle ψ between beam vector and cavity gradient, the beam induced voltage, $\vec{V_i} \propto \overrightarrow{(\iota_b} \times R_a) \times e^{\psi i}$, is superpositioned with the cavity field vector.

This is a behavioral model which may disregard some of the superconducting cavity features (e.g. fundamental passband modes) for greater simulation speed. For example, simulation of the CEBAF Upgrade cavity's $\frac{6}{7}\pi$ mode would require two additional Butterworth 1.2 MHz passband filters and reduction of the sampling time from the present $5\text{x}10^{-5}$ s down to 10^{-7} s. For simulation time this is a factor of 20.

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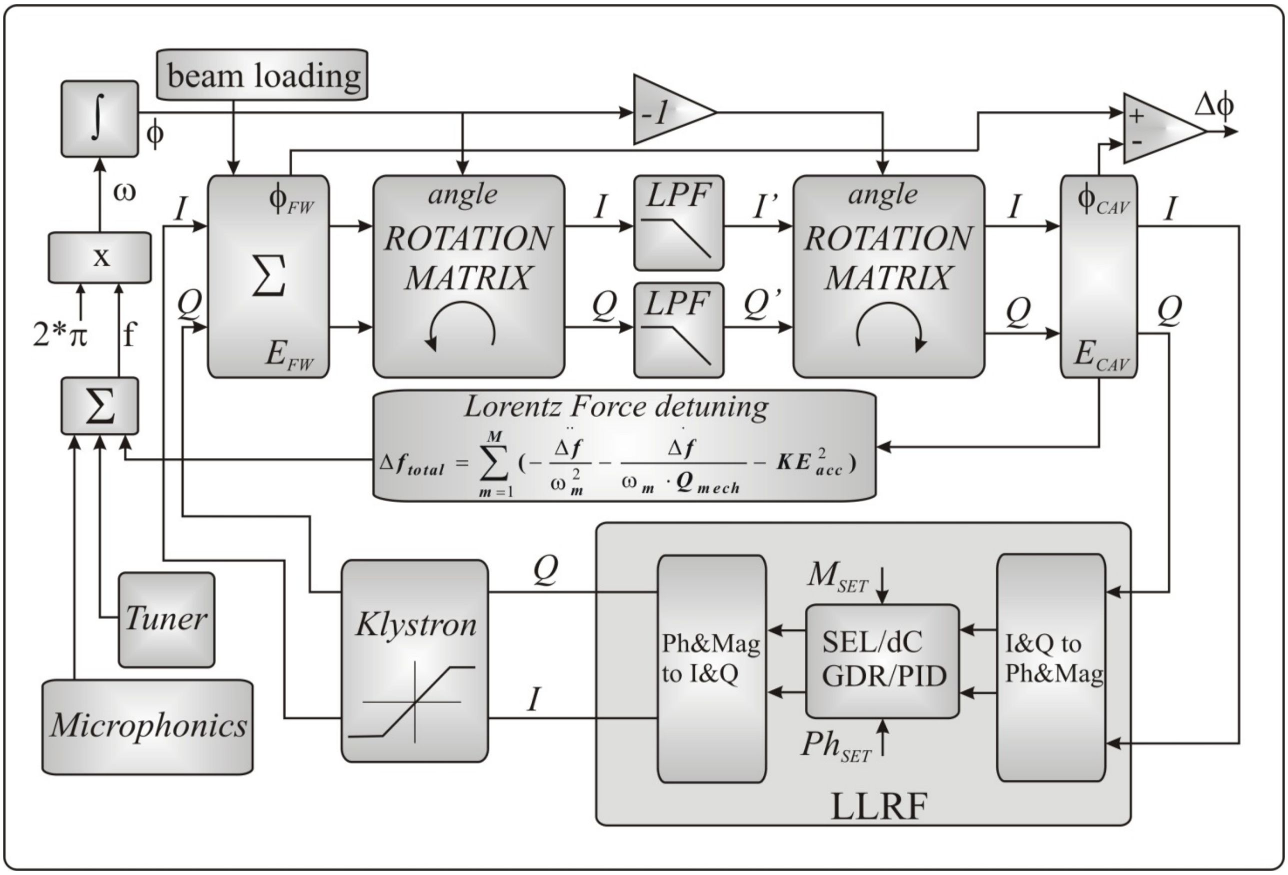

Figure 1: Diagram of the RF System model

THE CONTROLLER ARCHITECTURE

The model was used to simulate the following control schemes: I&Q, Magnitude & Phase (this implementation is shown in Figure 1) and SEL. I&Q as well as Magnitude & Phase consist of two feedback loops usually equipped with PID (**P**roportional–**I**ntegral–**D**erivative) regulators. The behavior of these two systems is, however, quite different when used to control a detuned resonator and requires different gains for the same accuracy. Third scheme: SEL, proposed originally in analog form by J. Delayen [4], has been used to control superconducting cavities in several accelerators. Figure 2 shows the SEL scheme of regulation. When switch S1 is in the upper position and switch S2 in the bottom position, the system is in the SEL mode. Cavity amplitude Am is equal to Am0 and the cavity phase Ph is rolling with the frequency, proportional to tangent of the detuning angle φ. For operational mode (beam on), the phase loop has to be closed (S2 up) to employ a "detuning compensator" then the system is running at constant frequency. Indeed, while the "detuning compensator" is engaged, the system is "GDR" like. As long as we consider cavity detuning to be the only cavity field perturbation, no additional amplitude control is necessary. Therefore switch S1 can remain in the upper position. By switching S1 to the bottom position, we apply additional feedback for cavity amplitude. We also exercised the model to analyze a SEL-I&Q (GDR) "hybrid" architecture, where the "detuning compensator" was replaced with typical I&Q feedback loops. It is not shown on the RF system diagram, but the model contains a low pass filter to limit control bandwidth and delay lines to simulate LLRF system latency caused mostly by digital processing.

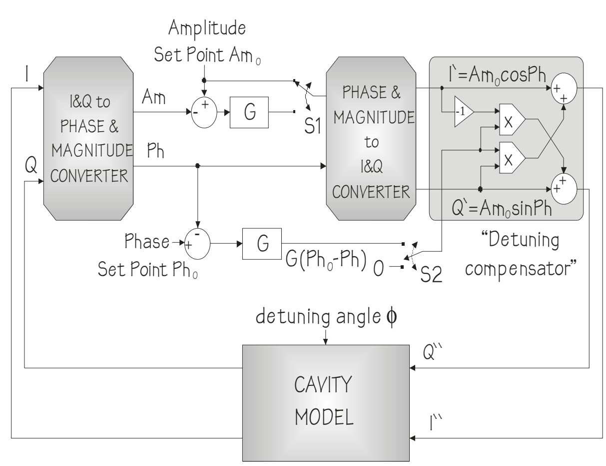

Figure 2: Proposed SEL architecture

SIMULATION RESULTS

Figure 3 shows the cavity gradient and phase plot during a cavity recovery using SEL mode. The Lorentz force detuning coefficient k is equal 2. Gradient rises from 0 to 20 MV/m in less than 30 ms. This time is determined by time constant of the low pass filters. For the real RF system, the SEL mode can be used to determine the loaded Q of a cavity by measuring gradient rise time as well as decay. Once the cavity is close to the chosen gradient, the phase plot starts to expose microphonic disturbances. After the system switches to I&Q mode (gray, vertical line), microphonic detuning is electronically compensated and the phase plot becomes very flat. The gradient line dropped due to finite loop gain. The next objective was to find the minimum loop gain to compensate for 24 Hz detuning with the accuracy required in the Table 1. In our model we apply 24 Hz detuning in the form of the square wave causing 6 MV/m gradient and 45° phase variations if the control loop

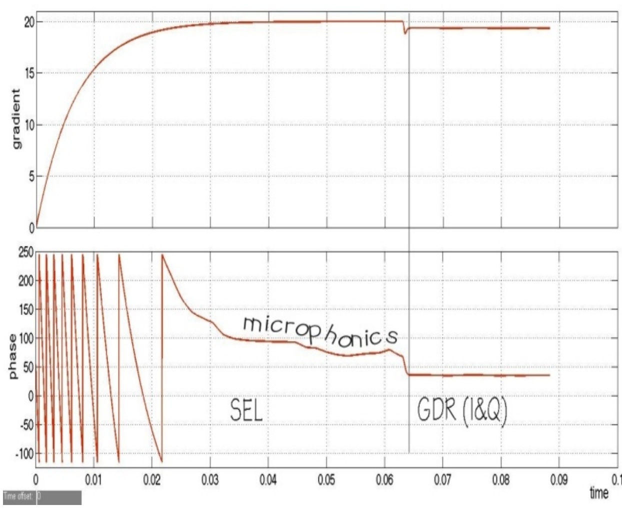

Figure 3: Cavity turn-on process

remains open. We observed that a gain of 32 adequately stabilize cavity gradient (Figure 4) while a gain of 120 is necessary to meet phase stability requirements (Figure 5). A similar simulation was performed for the magnitude and phase control architecture. For the same 24 Hz detuning amplitude, a loop gain of 900 was necessary to meet gradient stability requirements and a phase loop gain of 110 satisfied the phase requirement.

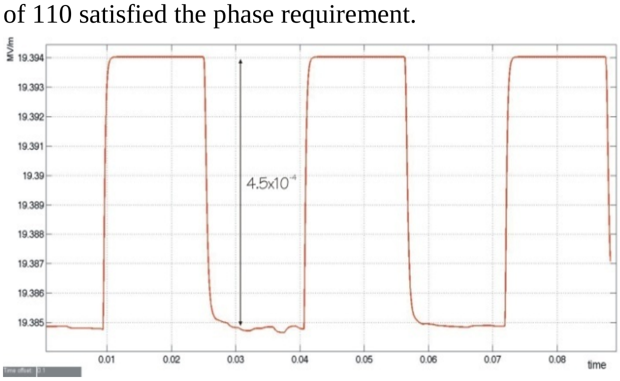

Figure 4: Stabilized cavity gradient for 23 Hz square wave detuning and loop gain of 32.

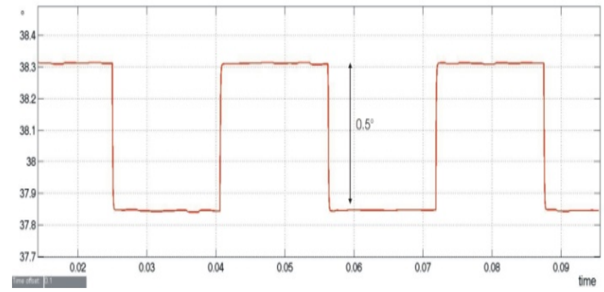

Figure 5: Stabilized cavity phase for 23 Hz square wave detuning and loop gain of 120

This simulation shows that amplitude control under I&Q requires much less gain than under Mag&Phase. From a practical point of view a loop gain of 900 is implausible (for stability reasons) for the required control bandwidth of 100 kHz. Another controller option: "Detuning Compensator + SEL" was also simulated, indicating minimum gain requirements similar to I&Q scheme. For cavity amplitude, Detuning Compensator acts as a predictor, and based on the measured detuning angle, counterbalances the cavity amplitude drop. Phase error is proportional to the tangent of the detuning angle and inversely proportional to the loop gain, so consequently 45° detuning requires gain of 110.

CONCLUSION

A Matlab-Simulink model of the RF control system has been developed and tested for various controller architectures. It has helped us to predict and understand the performance of the simultaneously developed 12 GeV digital LLRF system before the FPGA firmware was created. In addition, the characterization and stability analysis model can be used to determine the klystron power requirement for cavities with different Qs and beam loads.

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