RF CONTROL SYSTEM FOR ISAC II SUPERCONDUCTING CAVITIES

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Abstract

The RF Control system for the superconducting cavities of the ISAC II project is a hybrid analogue/digital system. Each system consists of a self-excited feedback loop with phase-locked loops for phase and frequency stabilization. Amplitude and phase regulation, as well as tuning control, are performed using digital signal processors. Special pulsing circuitry is incorporated into the system for fast punching through multipactoring. This paper describes the RF control system, the characteristics of the feedback loops, and the experience gained in operating this system.

INTRODUCTION

The design of the RF system is based on a self-excited oscillating loop, where the self-excited frequency is determined solely by the loop phase. The system oscillates at a frequency that results in a loop phase that is an integer multiple of 360°. This frequency is locked to an external reference by regulating the phase shift within the self-excited loop. The system is operated at a coupling strength of approximately 100 to have a manageable bandwidth. The phase difference between the input and output of the cavity is used to drive a mechanical tuner to minimize the drive power required.

RF CONTROL SYSTEM

A block diagram of the RF control system is presented in Fig. 1. The system consists of two main parts: The first is the RF Module, where the RF signal is processed and converted into baseband. The second is the DSP Module, where the baseband signal is converted into digital form and processed by a <u>D</u>igital <u>S</u>ignal <u>P</u>rocessor, then reconverted back into analogue form for modulation of the RF module. Up to 4 pairs of modules can be housed in a C-size VXI mainframe, which is controlled by a PC via an IEEE 1394 interface.

System Hardware

The RF control system hardware consists of a rack mounted PC, a VXI slot zero control module, the RF Module, and the DSP Module housed in a VXI mainframe. These function together to provide three main regulation loops: the amplitude loop, the quadrature phase/frequency loop, and the tuning loop. The primary amplitude detector is a synchronous demodulator, in which an internal PLL supplies an amplitude-stabilized reference to be multiplied with the RF input. The product is filtered, sampled and digitized at 40 k samples/sec and processed by a Motorola DSP56002 DSP. A lower than normal sampling rate is used because of the long time constant of the cavity when it is superconducting. The DSP is configured as a <u>P</u>roportional-<u>I</u>ntegral controller, providing amplitude regulation. The internal PLL output is also compared with an external master frequency source using a square wave phase/frequency detector from Analog Devices (AD9901). A different channel of the same DSP processes this phase error. The output of this channel is used to control the quadrature part of the amplifier output, providing phase regulation. Another phase detector measures the phase lag of the cavity. An edge-triggered JK flip-flop, which is constructed out of 8 ECL NAND gates, is used for this purpose. The phase shift is processed by a separate DSP to drive the mechanical tuner and keep the cavity in tune with the external master frequency. The complete tuning system is described in another paper[1].

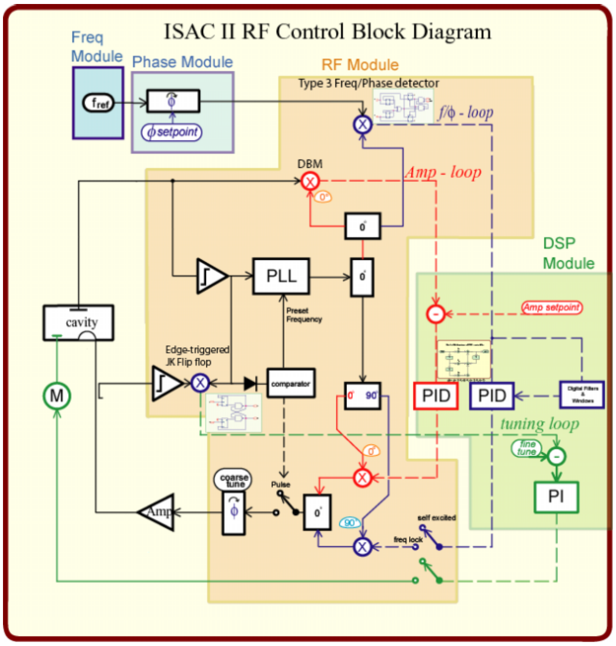

Figure 1. Block Diagram of RF Control

During pulsing on power-up, the phase detector in the internal PLL is disconnected from the VCO. The VCO is then driven directly by a voltage source so that the output frequency matches the resonant frequency of the cavity. This frequency is pulsed by hardware with a pulse width of 256 μs and a period of 35 ms. The coupling loop is moved inward to lower the loaded Q in order to decrease the rise time of the voltage. A Schottky diode detector provides fast cavity voltage detection. When the cavity voltage rises above the multipactoring threshold, the diode detector enables the PLL and switches the system into CW mode automatically, as illustrated in Fig. 2.

A rack-mounted PC provides supervisory control and data acquisition. Communication between the PC and the VXI mainframe is done via a FireWire (IEEE 1394) interface. A National Instruments GPIB interface card enables the PC to act as a controller for other GPIB-enabled instrumentation, including a frequency counter, a RF power meter and a digital oscilloscope.

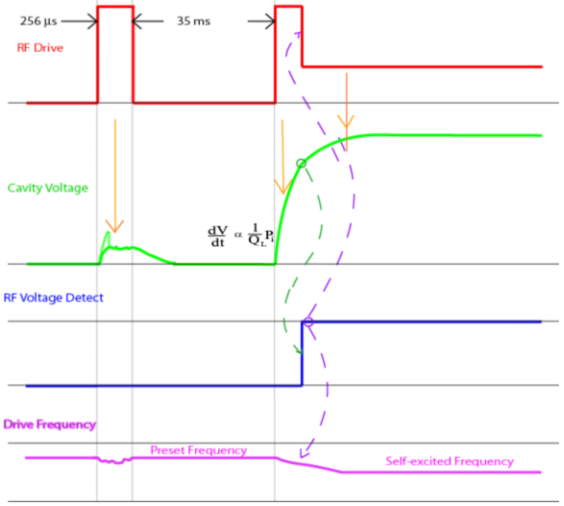

Figure 2. Power-up sequence

System Software

There are three main functions of the system software:

- Control of the superconducting cavity.
- Data acquisition and calculation.
- Communication with the central control system.

The control system can be sub-divided into supervisory tasks and online feedback control. Supervisory tasks, which require low signal bandwidth but relatively complex decision logic, are performed with the rackmount PC. The supervisory PC performs the tasks of setting feedback loop parameters, local status display, and communication with the EPICS-based master control system. These high level controls are written using 32 bit C++ with Windows API's.

The low-level feedback control requires higher signal bandwidth and is performed with DSPs and FPLAs. The DSPs perform digital filtering, open and closed loop regulation, output limiting, low-level decision making as well as exchanges of status information with the supervisory PC. For speed and compactness this software is hand coded in assembler. This code is stored in flash EEPROM, and can be changed remotely. Other logic functions that require still faster response are performed with FPLA's. These include power-up sequencing and fault-detection.

Communication between the PC and the central control system is done via an EPICs IOC server running in the same PC.

SYSTEM MODEL

Using a similar method as in [2], but ignoring beam loading and assuming perfect alignment in static loop phase, we get a transfer function representation of the system:

$$\begin{bmatrix} \delta V \\ \delta \Omega \end{bmatrix} = \begin{bmatrix} G_{aa} & G_{ta} \\ G_{a\omega} & G_{t\omega} \end{bmatrix} \begin{bmatrix} \delta v_i \\ \delta v_q \end{bmatrix} \qquad (1)$$

where

$$G_{aa} = \frac{\gamma}{1+\tau s}, \qquad G_{ta} = 0,$$

$$G_{a\omega} = -\frac{1}{v_i}\frac{\Omega}{(1+\tau s)}, \qquad G_{t\omega} = \frac{1}{v_i \tau} \equiv \eta,$$

$\tau = \dfrac{2Q}{\omega_c}$ is the time constant of the cavity,

$\Omega = \omega - \omega_c$ is the detuning of the cavity,

with γ is the voltage transformation ratio, ω_c the natural resonance frequency of the cavity and Q the loaded cavity quality factor. Eq. 1 states that while the cavity voltage is a simple lag response to the input voltage, the cavity frequency varies instantaneously to the input phase.

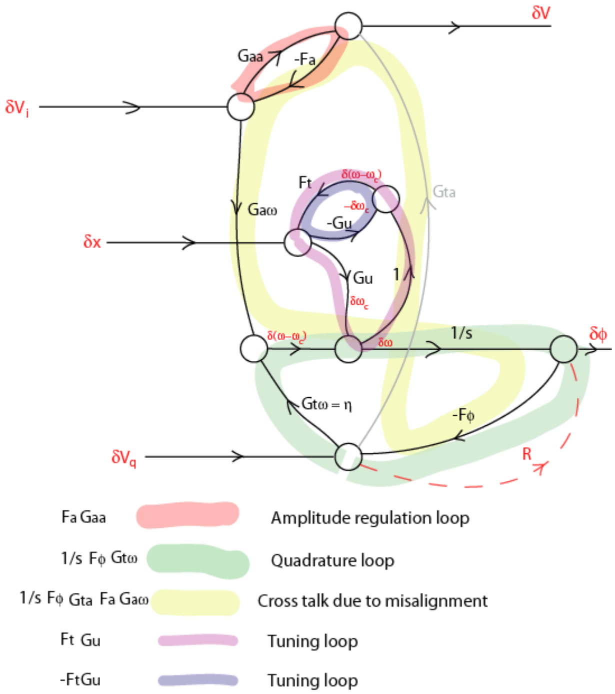

Figure 3. Signal Flow Graph of the Amplitude, Phase and Tuning Loops

Eq. 1 is used to form the signal flow graph of the complete RF control system in Fig. 3, where F_a, F_ϕ and F_t are the amplitude, quadrature and tuner feedback coefficients, respectively. Also the sensitivity of frequency to tuner movement is given by

$$G_u = \frac{\partial \omega_c}{\partial x}$$

and depends only on the geometries of the cavity and the tuning mechanism. From the figure, since the phase-to-amplitude cross coupling term G_{ta}, drawn in lighter color, is zero, the amplitude loop is independent from the phase and tuning loops.

From the signal flow graph we get the various closed loop gains of the feedback system:

$$\frac{\delta V}{\delta v_i} = \frac{G_{aa}}{1+F_a G_{aa}} \approx \frac{1}{s\tau + 1 + F_a}, \tag{2}$$

$$\frac{\delta \phi}{\delta v_q} = \frac{\eta(1+F_t G_u)}{s + F_\phi \eta (1+F_t G_u)}, \tag{3}$$

$$\frac{\delta \phi}{\delta x} = \frac{G_u}{s + F_\phi \eta (1+F_t G_u)}, \tag{4}$$

$$\frac{\delta v_q}{\delta x} = \frac{F_\phi G_u}{s + F_\phi \eta (1+F_t G_u)}. \tag{5}$$

From Eq. 2, 3 and 4 we see that if one requires zero steady-state errors for both amplitude and phase in response to step inputs, then one requires at least a pole at the origin, i.e. an integration, in both F_a and F_ϕ. To minimize RF power, one also requires the steady-state error for quadrature drive be zero. Given that F_ϕ has one integration, Eq. 5 then requires F_t to have also one integration. Thus PID controllers are used in the amplitude, phase and tuner loops.

SYSTEM PERFORMANCE

Fig. 4 shows the Bode plot of the amplitude loop. The feedback parameters are adjusted such that the dominant pole due to the cavity response is almost cancelled by the zero from the proportional gain. The result agrees with that predicted by theory.

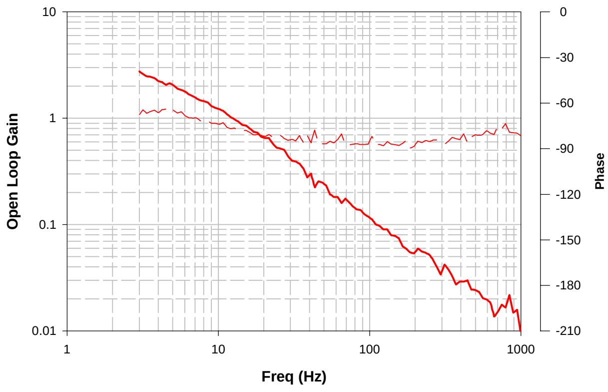

Figure 4. Open Loop Frequency Response for Amplitude Loop

Fig. 5 shows the Bode plot for the quadrature phase loop without tuner feedback. At low frequencies the result is in agreement with theory, but at higher frequencies it shows the behavior of a non-minimum phase system. System stability is seriously degraded with a zero on the right hand side of the complex plane at 100 Hz. A crystal ladder network with a Q of 10^5 was used in trying to locate the source of this zero, which was not predicted by theory. Referring back to Fig. 3, if we include the leakage path R, then the phase open loop response is

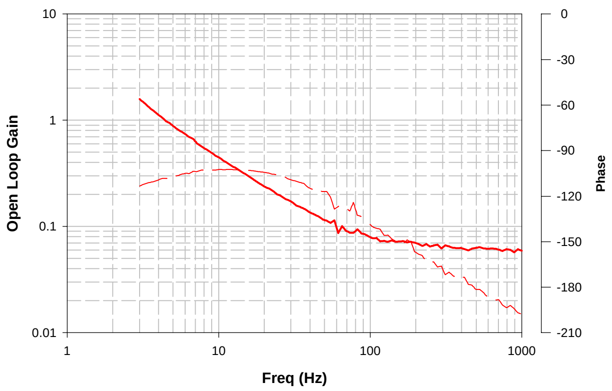

Figure 5. Open Loop Frequency Response for Phase Loop showing Non-minimum phase characteristics

$$\left(\frac{1}{s}\eta + R\right)F_\phi. \tag{6}$$

The residue R is found empirically to have the form

$$R = -Av_i e^{ik}, \tag{8}$$

where $A \geq 0$ and $k \approx 0$ are variables that depends on the layout of the RF Module and cabling, resulting in a zero on the right hand side of the complex plane at

$$s = \frac{1}{\tau A}. \tag{7}$$

To prevent instability in operation due to this zero, we have to operate the phase feedback loop at a lower feedback gain and resulted in a reduced bandwidth.

CONCLUSION

The prototype RF control system for the superconducting cavity has been operated in many cold tests. It has been found to be able to provide amplitude, phase and tuning regulation to within the specifications. The power-up circuit has provided reliable way to punch through multipactoring, even when the cavity is not well conditioned. A parasitic leakage path in the phase feedback loop has caused a reduced operational bandwidth and is being investigated.

REFERENCES

[1] T. Ries et al , “A Mechanical Tuner for the ISAC-II Quarter Wave Superconducting Cavities”, This proceeding.

[2] J.R. Delayen, "Phase and Amplitude Stabilization of Beam-Loaded Superconducting Resonators", Proc. Linac 92, p. 371.