STATUS OF RF CONTROL SYSTEM FOR ISAC II SUPERCONDUCTING CAVITIES

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Abstract

The rf control system for the ISAC II superconducting cavities is a hybrid analogue/digital system using a self-excited feedback loop. It has undergone more than a year of testing. Improvements have been made to every aspect of the system including phase detection, loop regulation, data acquisition, as well as communication with EPICS. With a loaded Q of 100,000, amplitude regulation bandwidth of 400 Hz and phase regulation bandwidth of 100 Hz have been achieved. Simultaneous operation of 3 cavities under typical ISAC 2 operating conditions has also been demonstrated.

INTRODUCTION

The design of the RF system has been described in several previous papers[1][2]. Based on the experience gained in tests under superconducting conditions, the present system has eliminated some shortcomings in the original design and has incorporated several important improvements. Crosstalk between different feedback paths has been eliminated. This resulted in much improved regulation bandwidth in the phase/frequency loop. A higher dynamic range phase detector is used which enables self-excited operation at both high and low power levels. However, the most important improvements are in the supervisory software, particularly in the area of EPICS communication and multi-thread synchronization.

RF CONTROL SYSTEM

System Model

The transfer function representation of the self-excited system with quadrature control with perfect alignment in static loop phase is given by[3]:

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

where

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

$$G_{a\omega}=-\frac{1}{v_i}\frac{\Omega}{(1+\tau s)}, \qquad G_{t\omega}=\frac{1}{v_i\tau}\equiv\eta, \qquad (2)$$

$\tau=\dfrac{2Q}{\omega_c}$ 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 is used to form the signal flow graph of the complete RF control system in Fig. 1, where F_a, F_ϕ and F_t/s are the amplitude, quadrature and tuner feedback coefficients, respectively. The $1/s$ factor from the tuner feedback coefficient arises due to that fact we have implemented velocity feedback in the tuner control. The sensitivity of frequency to tuner movement is given by

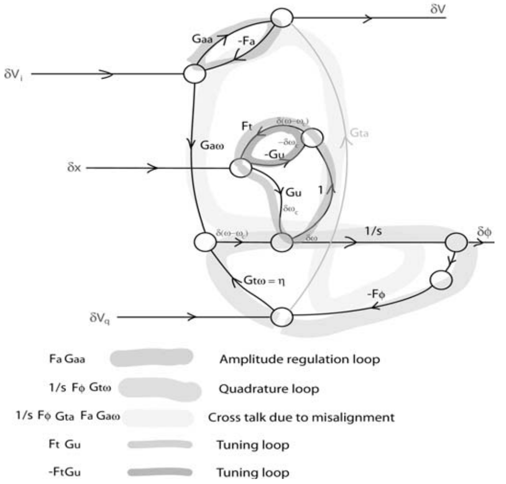

Figure 1: Signal Flow Graph of the Amplitude, Phase and Tuning Loops.

$$G_u=\frac{\partial\omega_c}{\partial x} \qquad (3)$$

and depends only on the geometries of the cavity and the tuning mechanism. From the signal flow graph we get the various open loop gains of the feedback system: Amplitude loop gain is given by:

$$G_a=F_aG_{aa}=\frac{\gamma F_a}{1+s\tau} \qquad (4)$$

and phase loop gain is given by:

$$G_\phi = \frac{F_\phi G_{t\omega}}{s} = \frac{F_\phi \eta}{s} \qquad (5)$$

Furthermore, closed loop gains of the feedback system are:

$$\frac{\delta V}{\delta v_i} = \frac{G_{aa}}{1+F_a G_{aa}} \approx \frac{1}{s\tau + 1 + F_a}, \qquad (6)$$

$$\frac{\delta \phi}{\delta v_q} = \frac{\eta(s+F_t G_u)}{s^2 + F_\phi \eta (s + F_t G_u)}, \qquad (7)$$

$$\frac{\delta \phi}{\delta x} = \frac{s G_u}{s^2 + F_\phi \eta (s + F_t G_u)}, \qquad (8)$$

$$\frac{\delta v_q}{\delta x} = \frac{s F_\phi G_u}{s^2 + F_\phi \eta (s + F_t G_u)} \qquad (9)$$

From Eq. 6, 7, and 9 we see that if one requires zero steady-state errors for both amplitude and phase errors, then one requires at least a pole at the origin in both F_a and F_ϕ. To minimize rf power, one also requires the steady-state error for quadrature drive be zero. This can be achieved when F_t is a constant. Thus Proportional-Integral-Differential controllers are used in the amplitude and phase loops, and a proportional controller is used in the tuner loop.

System Hardware

Each cavity controller consists of two VXI modules: the rf module, colored pink in Figure 2, and the DSP modules, colored green in Figure 2. A total of four controllers are housed inside a VXI mainframe. Another VXI module generates the different phase references for the 4 controllers. An Agilent FireWire VXI slot 0 controller controls all of these modules. The feedback controller consists of three main regulation loops - the amplitude loop, the quadrature phase/frequency loop, and the tuning loop. As seen in Figure 2, part of the feedback signal is amplitude limited.

This amplitude limited signal is used for both amplitude and phase detection. Synchronous demodulation is used in the amplitude detector because it has good amplitude linearity and large dynamic range. The detected signal is filtered, sampled and digitized at 66 k samples/sec and fed into a Motorola DSP56002 Digital Signal Processor. The DSP is configured as a Proportional-Integral controller, providing amplitude regulation. The limiter output is also compared with an external master frequency source using a phase/frequency discriminator. The difference in phase is filtered by the same DSP running a parallel PID controller task, whose output is used to control the quadrature part of the amplifier output. The same amplitude limited signal is mixed with an amplitude limited signal from the input side of the cavity using an edge-triggered JK flip-flop, and the mixing product is filtered, digitized and processed by a separate DSP to form the velocity signal for the tuning servo motor, which is described in a separate paper in this conference[4].

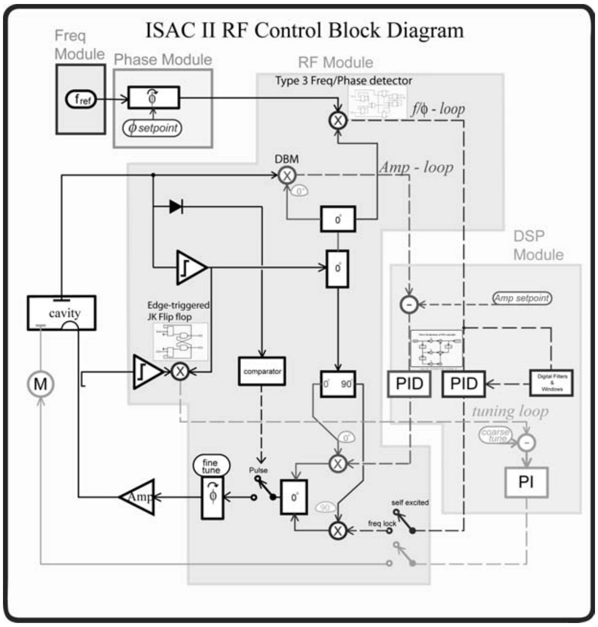

Figure 2: Block Diagram of Superconducting RF cavity control system.

System Software

There are three levels of software in a module controller. The first level controls each individual DSP in each feedback loop. It resides in the program memory of the DSPs and performs open loop output, closed loop regulation, as well as output limiting. It is written in assembler and is loaded into the DSP program memory at power up and executed automatically. It can also be dynamically changed via the VXI interface.

The second level software is the supervisory process for individual cavity control. It sends instructions to the first level software to set feedback loop parameters and power up sequencing. It also performs data acquisitions and most of the cavity controls. These are done via separate threads and access to the DSPs and the ADCs are coordinated with lightweight intra-process thread synchronization, in critical sections. These are 4 such multi-thread processes running per cryomodule, each controlling a single cavity. The software is written in C++ and resides in a rack-mounted PC and communicates with the VXI modules via a FireWire (IEEE 1394) interface. The third level manages VXI modules that are common to all the cavities, other resources, safety interlocks, and communication with the central control system. Communication between the first level of the VXI modules is also done via the same FireWire interface. Data exchange between the second level and the third level is done via a shared memory Dynamic Linking Library. This software also has an embedded EPICS virtual IOC for site-wide communication. Figure 3 shows the deployment diagram of the system software at the second and the third level.

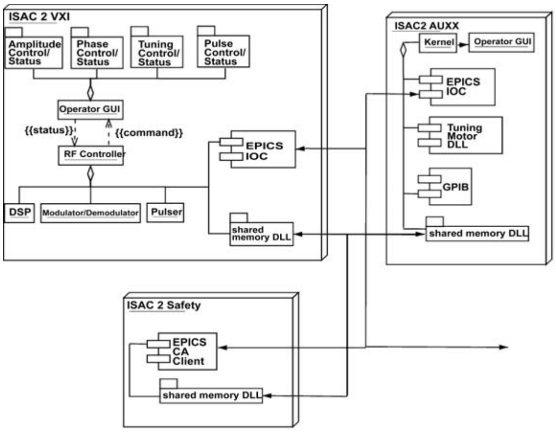

Figure 3: Deployment Diagram of ISAC 2 Control System.

System Performance

Figures 4 and 5 show the achieved open loop gains in the amplitude and phase loops, respectively, under typical operating condition. With PID controllers, the open loop gains of Eq. 4 and 5 can be rewritten as

$$G_a = \gamma K_{ai}\frac{(1+s\tau_a)}{s(1+s\tau)},\quad G_\phi = \eta K_{\phi i}\frac{(1+s\tau_\phi)}{s^2}$$

Since the resonator pole τ and the zero of the amplitude PID controller τ_a are only slightly different in frequency, their effects are almost cancelled. The overall response is similar to that of a simple pole at zero frequency. The unity gain bandwidth for the amplitude loop is 400 Hz, with 90° phase margin and gain margin well in excess of 20dB.

In the phase loop, the system starts with a double pole at very low frequencies. The phase detector and the phase PID controller each contribute a simple pole. The zero of the PID controller τ_ϕ restores the system to that of a single pole response above 100 Hz. The unity gain bandwidth is 120 Hz, with similar gain and phase margin to that of the amplitude loop. The system is thus unconditionally stable in both the amplitude and phase loops, with the accuracy of regulation limited only by the available rf power. The performance of the tuner loop depends primarily on the processor speed and the servo motor controller speed. With a 350 MHz Intel Pentium processor, an update rate of 200 Hz is achieved with four controllers running simultaneously.

CONCLUSION

The rf control system has been tested in every aspect of the system and has performed satisfactory, including phase detection, loop regulation, data acquisition as well as communication with EPICS. With a loaded Q of 100,000, amplitude regulation bandwidth of 400 Hz, phase regulation bandwidth of 100 Hz has been achieved. Simultaneously operation of 3 cavities under typical ISAC 2 operating conditions has also been demonstrated.

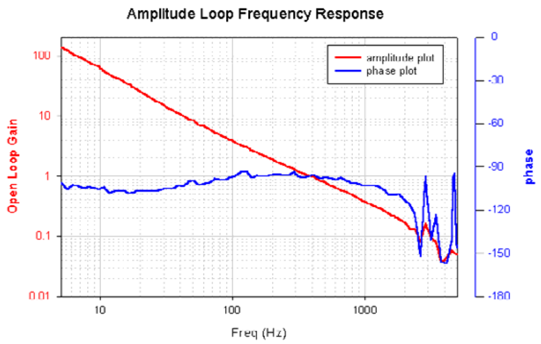

Figure 4: Amplitude Loop Bode Plot.

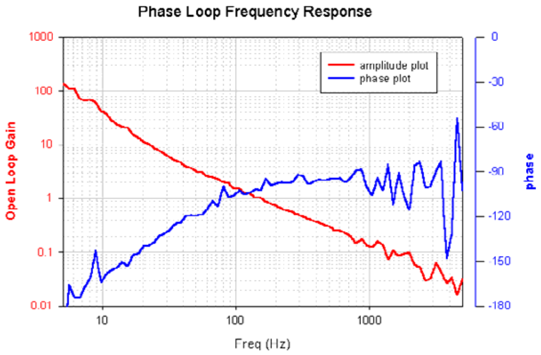

Figure 5: Phase Loop Bode Plot.

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