FERMILAB-CONF-21-831-AD
12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB337

RESONANCE CONTROL SYSTEM FOR THE PIP-II IT HWR CRYOMODULE*

P. Varghese†, B. Chase, S. Raman, H. Maniar, D. Nicklaus, P. Hanlet
Fermi National Accelerator Laboratory (FNAL), Batavia, IL, USA
L. Doolittle, C. Serrano, S. Paigua
Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA, USA

Abstract

The HWR (half-wave-resonator) cryomodule is the first one in the superconducting section of the PIP-II LINAC project at Fermilab. PIP-II IT is a test facility for the project where the injector, warm front-end and the first two superconducting cryomodules are being tested. The HWR cryomodule comprises of 8 cavities operating at a frequency of 162.5 MHz and accelerating beam up to 10 MeV. Resonance control of the cavities is performed with a pneumatically operated slow tuner which compresses the cavity at the beam ports. Helium gas pressure in a bellows mounted to an end wall of the cavity is controlled by two solenoid valves, one on the pressure side and one on the vacuum side. The resonant frequency of the cavity can be controlled in one of two modes. A pressure feedback control loop can hold the cavity tuner pressure at a fixed value for the desired resonant frequency. Alternately, the feedback loop can regulate the cavity tuner pressure to bring the RF detuning error to zero. The resonance controller is integrated into the LLRF control system for the cryomodule. The control system design and performance of the resonance control system are described in this paper.

INTRODUCTION

The HWR cryomodule is the first one in the superconducting section of the PIP-II LINAC project at Fermilab. PIP-II IT is a test facility for the project where the injector, warm front-end and the first two superconducting cryomodules are being tested. The HWR cryomodule comprises of 8 cavities operating at a frequency of 162.5 MHz and accelerating beam upto 10 MeV. Resonance control of the cavities is performed with a pneumatically operated slow tuner which compresses the cavity at the beam ports. Helium gas pressure in a bellows mounted to an end wall of the cavity is controlled by two solenoid valves, one on the pressure side and one on the vacuum side. There is a pressure transducer that provides an electrical voltage as an indicator for tuner pressure for monitoring and feedback purposes. A simplified schematic of the tuner system is shown in Fig. 1. The resonant frequency of the cavity can be controlled with a pressure feedback control loop that holds the cavity tuner pressure at a fixed value for the desired resonant frequency

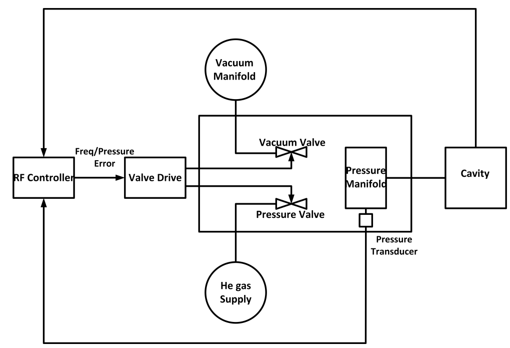

Figure 1: HWR Pneumatic Cavity Tuner System.

- this is referred to as the ’Pressure Mode’ operation. Alternately, the feedback loop can regulate the cavity tuner pressure to bring the RF detuning error to zero which is referred to as the ’RF Mode’. In the latter case, the tuner can compensate for slow drifts in resonant frequency. In the GDR (generator driven) mode of operation, all cavities are run at the same reference frequency. The RF Mode is neccessary for the GDR mode. A state machine based system controller can provide an automatic transition between the modes of operation according to the machine state. The tuner implementation is done with a signal conditioning module and the same LLRF SOCFPGA controller used for cavity field control.

TUNER CONTROL IMPLEMENTATION

The slow tuner control implementation is integrated into the LLRF controller as shown in Fig. 2 [1]. Each controller drives two cavities and their tuners. Each tuner has two actuators for the Pressure and Vacuum valves which are driven by two DAC channels through a signal conditioning unit. Each tuner also has a pressure transducer signal that is digitized using a DC coupled ADC channel whose output represents the pressure in the cavity manifold which is the primary physical parameter that is controlled. The cavity resonant frequency being directly dependent on the pressure allows us to use the cavity detuning from the reference frequency also as an error signal to drive the feedback control. Cavity detuning is computed in the FPGA from the cavity probe and forward power signals [2, 3].

TUNER CONTROLLER DESIGN

Operational experience with the pneumatic tuner system in the ATLAS accelerator at Argonne National Laboratory

* Work supported by Fermi Research Alliance LLC. Under DE-AC02-07CH11359 with U.S. DOE.
† varghese@fnal.gov

12th Int. Particle Acc. Conf. IPAC2021, Campinas, SP, Brazil JACoW Publishing
ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB337

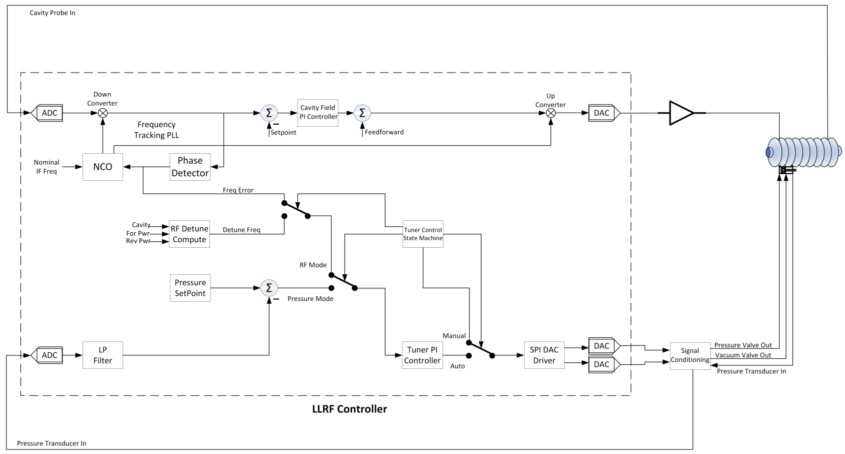

Figure 2: HWR Tuner Control System.

(ANL) has been documented [4]. The pneumatic pressure control system can be modeled as a single pole system with the time constant RC where R is the fluid resistance of the valve and C is the fluid capacitance of the pressure chamber [5]. This time constant for the pressure loop was determined to be about 12-15 seconds by a step input measurement shown in Fig. 3. This represents the delay in helium flow from the point of the valve actuator voltage change. A transport delay τ of a 100 ms for the valve delay is also included in the model as described in reference 4. In the analog hardware based pressure control loop, a LP filter with a corner frequency of 1.5 Hz was used after the pressure transducer. These components along with PI controller represent the tuner control system model used for designing and evaluating the new FPGA based tuner control system. The model is shown in Fig. 4.

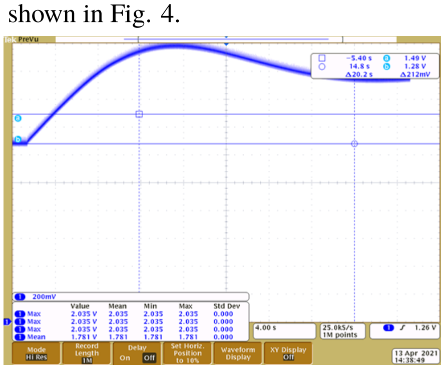

Figure 3: Measured Step Response.

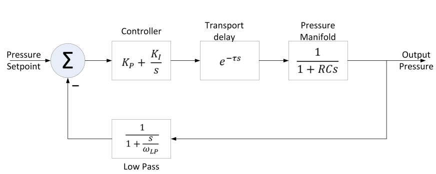

Figure 4: Tuner Control System Model.

The closed loop transfer of the control system excluding the transport delay can be written as

$$T(s) = \frac{\omega_c \omega_{LP}(sK_P + K_I)}{s^3 + s^2(\omega_c + \omega_{LP}) + s(K_P + 1)\omega_c \omega_{LP} + K_I \omega_c \omega_{LP}}. \quad (1)$$

The closed loop frequency response simulation of the system in Fig. 5 shows the closed loop bandwidth to be about 0.074 Hz.

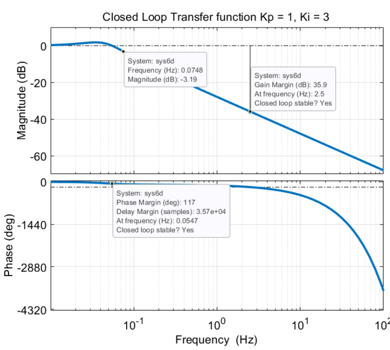

Figure 5: Closed Loop Frequency Response for $K_I = 3, K_P = 1$.

The step response simulation is shown in Fig. 6, which compares well with the measured response in Fig. 3.

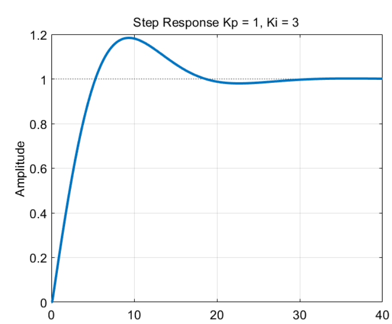

Figure 6: Step Response for $K_I = 3, K_P = 1$.

The detuning block can also provide a quench detection feature by monitoring the reflected power in addition to cavity transmitted and forward power waveforms used for detuning computation. A manual input to the pressure and vacuum valves provides an additional feature for testing and characterizing the tuner system. Both the Pressure loop and the RF loop share the same PI controller. RF measurements have shown that all 8 cavities have a tuning range of an average of ≈ 180 kHz over a pressure range of ≈ 60 psi giving

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB337

a 3kHz/psi tuning sensitivity. The pressure loop sensitivity is determined by the ADC converter which is 14-bit with a dynamic range of 8192 bits for a 100 psi pressure variation. A gain of 4 bits is applied to make the error signal 18 bits like the output of the detuning computation block and the frequency error from the tracking PLL. A decimating CIC filter introduces an attenuation of 11000/16384. The gain of the pressure loop is 880 bits/psi. The corresponding numbers for the RF Loop and the RF detune loop are 8192 and 10000 bits/psi respectively. Thus the loop gain in the RF loops is about 9-10 times that of the pressure loop.

TUNER PERFORMANCE

Cavity 1 and 2 had a resonant frequency tuning range outside the RF reference frequency of 162.5 MHz and cavity 3 became inoperable due to a coupler bias system failure and were therefore excluded from the RF testing. Once the cavity tuner pressure is set to a value that brings its resonant frequency close to the machine frequency of 162.5 MHz, RF is applied to the cavity and the field reaches a magnitude sufficient to allow the tracking PLL to lock to the cavity. The frequency error from the PLL is a direct measurement of the frequency offset from the reference frequency. The system is placed into the RF mode with this error as the input to the tuner feedback loop. The same PI controller is used to drive the tuner feedback loop in all of its three possible configurations. Thus the switch to the RF loop is accompanied by increased gains as indicated in the previous section. The frequency offset is quickly eliminated and the frequency oscillates around 0 Hz with fluctuations of +/- 10 Hz. The RF level can now be increased to the desired level. In order to go into the GDR mode, the frequency error should be sourced from the detune computation block while running the cavity field control with feedback. The switch to the detune block in GDR mode is necessitated by the fact that in GDR mode the tracking PLL is tracking the reference source - hence the frequency error is zero. Cavities 4, 5, 6, 7 and 8 were run in GDR mode at their operating gradient in this manner.

The histogram of the frequency error for cavity 8 is shown in Fig. 7. The microphonics amplitude spectrum for cavity 4 is shown in Fig. 8.

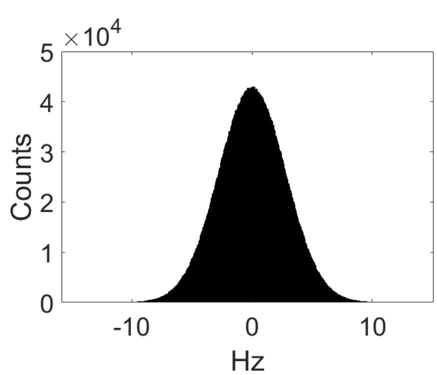

Figure 7: Caviy 8 Frequency Error - Histogram.

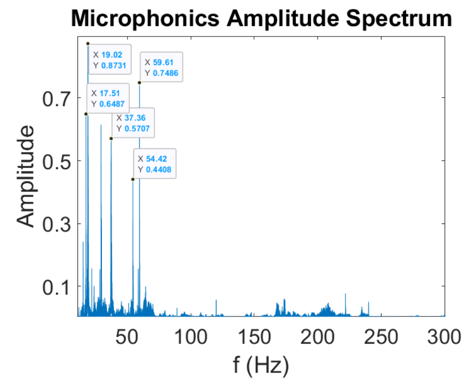

Figure 8: Caviy 4 Microphonics Amplitude Spectrum.

The detuning fluctuations are seen to be within a +/- 10 Hz range which is well within the specifications for PIP-II. The microphonics spectrum shown for cavity 4 shows the major disturbances to be within the sub 60 hz frequency range. Since this is a pneumatic tuner system dependent on the helium flow to the cavity manifolds, it is susceptible to any fluctuations in the helium flow and pressure regulation systems. Cavity 4 was seen to have periodic excursions in cavity detuning and a corresponding rise in forward and reflected power levels with a 3 to 4 minute repetition interval. This is likely due to the slow variations in the helium pressure regulation systems.

The amplitude and phase feedback regulation for cavities 4- 8 are shown in Table 1. The PIP-II specifications for the field regulation are 0.065 % rms for amplitude and 0.065 degrees rms for phase [6]. All the cavities are well within the specifications.

Table 1: Amplitude and Phase Regulation

Cavity	Amplitude (% rms)	Phase (°rms)
4	0.0115	0.0228
5	0.0106	0.0065
6	0.0101	0.0056
7	0.0081	0.0055
8	0.0103	0.0062

CONCLUSION

A resonance control system for the HWR cryomodule was implemented and integrated into the LLRF system controller. The new system replaces the analog hardware based tuner control used with the HWR cryomodule at ATLAS. The new tuner control system performed well keeping the cavity detuning under the +/- 20 Hz specification for the PIP-II project. The tuner control system allowed the cavities to be run in the GDR mode with feedback at the full operational gradient for each cavity. The amplitude and phase regulation for the cavity field was measured at 0.01% rms and 0.02 degrees respectively which exceeds the specifications for the PIP-II project.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB337

REFERENCES

[1] P. Varghese, B. Chase, and D.Sharma, “Fixed point implementation of an RF Controller in FPGA”, Fermilab LLRF Note, private communication, Nov. 2017

[2] L. Doolittle, “LCLS-II LLRF Quench and Detune Revisited”, LBNL Note, private communication, Oct. 2016.

[3] L. Doolittle *et al.*, “Detune Calculation with Digaree”, LBNL Note, private communication, Dec. 2016.

[4] G. P. Zinkmann, S. Sharamentov, and B. Clifft, “An Improved Pneumatic Frequency Control for Superconducting Cavities”, in *Proc. PAC’05*, Knoxville, USA, Jun. 2005, paper WPAT082, pp. 4090–4092.

[5] K. Ogata, *Modern Control Engineering*. New Jersey, USA: Prentice Hall, 2002.

[6] J.Steimel *et al.*, “PIP-II Linac RF Systems Physics Requirement Document (PRD)”, paper ED0010220, Dec. 2019, unpublished.