RF CONTROL SYSTEM FOR ISAC II SUPERCONDUCTING CAVITY TEST STAND

K. Fong, M. Laverty, S. Fang, TRIUMF, Vancouver

Abstract

The first phase of the ISAC II project consists of the acceleration of radioactive ions by 20 superconducting DTL's with a total effective voltage of up to 20 MV. Each of these quarter-wave cavities will be powered at a frequency of 106.08 MHz to a maximum field gradient of 6 MV/m. A test area was built to clean and test each cavity before installation. With unloaded cavity Q's of $\sim 10^9$, the RF control system of these superconducting cavities is based on self-excited feedback loop, with the self-excited frequency stabilized by an internal analogue Phase-Locked Loop, capable of operating in both CW and pulse mode. A digital phase/frequency detector and a quadrature combiner are used to provide phase locking to an external frequency reference. The demodulated amplitude, phase and frequency are feedback regulated with digital signal processors. This paper describes the RF control system and the experience in operating this system with a prototype cavity.

1 INTRODUCTION

The control system used for the superconducting cavity test stand retains some elements, in particular the digital circuitry, with systems employed for the normal conducting cavities of the ISAC accelerator. The latter system has been documented in earlier papers [1], [2]. However, due to the very high Q of the superconducting cavities the frequency/phase control and the pulsing circuitry require different approaches. A Voltage-Controlled Oscillator, which is part of a Phase-Locked Loop, is used to provide an initial frequency for pulsing. The pulsing frequency and duty cycle are adjustable. A fast RF detector senses RF voltage in the cavity and, when it exceeds the multipactoring threshold, the system switches to CW in self-excited mode. The frequency is then determined by the resonant frequency of the cavity. Once amplitude stability is achieved, the control system is used to achieve frequency and phase coherence between the cavities by locking to an external frequency source. The details of this design and some initial test results with a prototype cavity are outlined in the sections following.

2 RF CONTROL SYSTEM

A block diagram of the RF control system is presented in Figure 1. The basic design is similar to the ISAC I design, except for one important difference: instead of operating in driven mode, the system now operates in self-excited mode, where the self-excited frequency is determined solely by the loop phase. This frequency is locked to an external reference by regulating the phase shift within the self-excited loop. The system consists of two main parts: The first is RF Module, where the RF signal are processed and converted into baseband. The second is DSP Module, where the baseband signal is converted into digital form and processed by a pair of Digital Signal Processors, then re-converted back into analogue form for modulation by the RF module. These are housed in a VXI mainframe. Other diagnostic instruments not shown in the figure include forward and reverse power meters, a frequency counter and oscilloscopes. These instruments are used to measure the accelerating field and Q of the cavity.

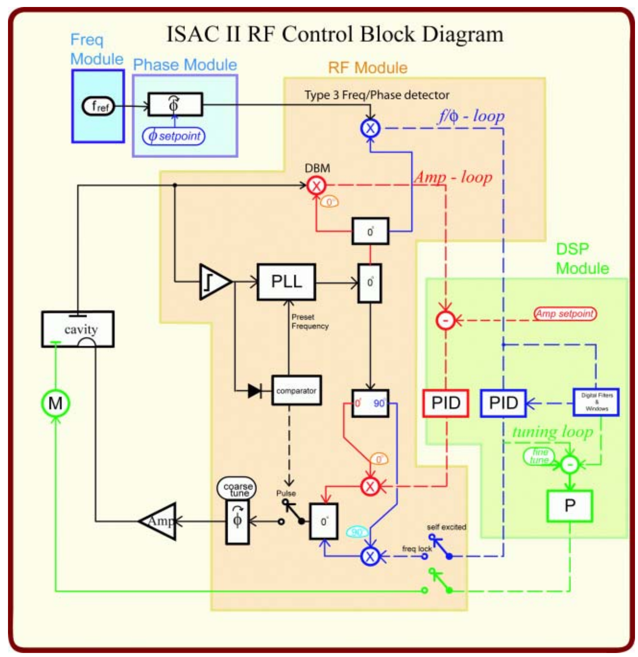

Figure 1 - Block Diagram of ISAC 2 RF Control System

2.1 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. As seen in Figure 1, 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 Proportional-Integral controller, providing amplitude regulation. The internal PLL output is also compared with an external master frequency source using a phase/frequency detector. 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. Because of this quadrature component, the self-excited frequency changes to a new value such that the phase shift due to the cavity exactly cancels the phase shift introduced by the quadrature circuit. The PI controller plus the integration provided by the phase detector enables zero phase and frequency error. The presence of a quadrature correction is also an indication that the reference frequency is different from the resonant frequency of the cavity. Thus the quadrature correction is also processed by a separate DSP to drive the tuner until the quadrature correction becomes zero again.

During pulsing, a secondary amplitude detector employing schottky diodes provides fast voltage detection, when the pulse-on time is shorter than the locked-in time of the PLL. The phase detector in the PLL is disabled and the VCO is driven by an adjustable voltage source. When the cavity voltage rises above the multipactoring threshold the secondary amplitude detector enables the PLL and switches the system into CW automatically as indicated in Figure 2.

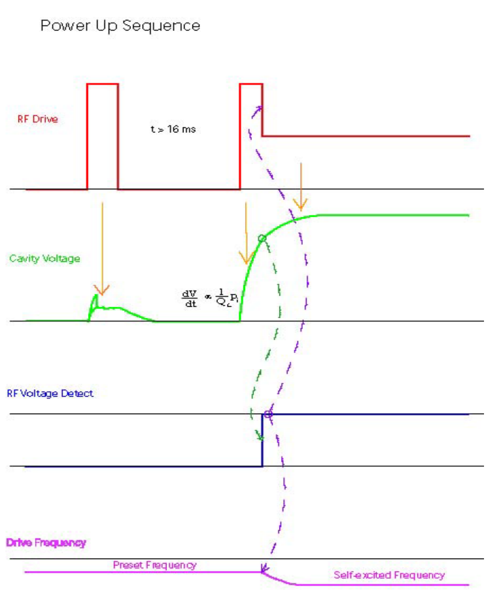

Figure 2 – Timing diagram of pulse-to-CW sequence.

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 Instrument GPIB interface card enable the PC to act as Controller for other GPIB-enabled instrumentation. Communication between the PC and the central control system is done via 100BaseT Ethernet.

2.2 System Software

There are two main functions of the system software:

- Control of the superconducting cavity.
- Data acquisition and calculation.

The control system can be sub-divided into supervisory task and online feedback control.

Supervisory tasks, which require low signal bandwidth but relatively complex decision logic, are performed with the desktop PC. . The supervisory PC performs the tasks of setting feedback loop parameters, local status display and communication with the EPICS-based master control system. This and other Inter-task communication is performed using TCP/IP and UDP/IP packets. These high level controls are written using 32 bit C++ with Windows API's. In an effort to encapsulate and reuse the software as much as possible, most modules are compartmentalized into Component Object Modules. Figure 3 shows the deployment diagram of the system software using UML.

The same PC is also used for data acquisition, and communicates with instruments such as a frequency synthesizer, a frequency counter, and power meters via VISTA and GPIB driver.

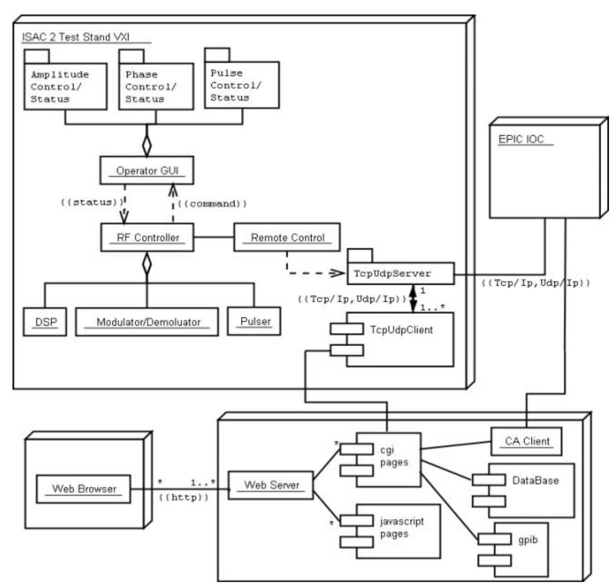

Figure 3 - Deployment Diagram of ISAC 2 Control System

For data acquisition, an Apache httpd server communicates with the control processor and GPIB instruments using Common-Gateway Interface. The same or another computer running a http browser can access the server and request data from the control processor and any other connected instruments. This enables data acquisition requests to be initiated in any computer. Data can be manipulated on-line, stored and retrieved using a relational database as indicated in Figure 3.

For controlling the cavity, the low-level feedback control firmware for the DSP's performs 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.

3 TEST RESULTS

The cavity was first tested on April 14, 2002. Subsequent tests were performed at about one month intervals. In between these tests the cavity and the RF control system were modified, based on the knowledge gained in these tests. It was discovered that, due to the design of the coupling loop, it was not possible to condition the cavity while the cavity was not superconducting. Because of this, overcoming multipactoring was very difficult, until an automatic voltage detection circuit was built to pulse through multipactoring.

3.1 Multipactoring

Before self-excited oscillation can start, the cavity has to be conditioned until the cavity voltage goes above multipactoring level. Getting the cavity voltage above the multipactoring threshold turned out to be quite difficult with the dimensions of the coupling loop that we used. The coupling is moved all the way inward to reduce the loaded Q of the cavity. Once multipactoring is initiated, the cavity requires a minimum of 16 ms with RF power removed to recover. (Figure 2) Once the cavity does punch through multipactoring, indicated by the RF level rising above multipactoring threshold as detected by the secondary voltage detector, the RF drive is switched into CW and the system goes into self-excited oscillation. Then the coupling loop can be retracted and the loop phase adjusted in order to reduce the reflected power.

3.2 Amplitude and Phase Regulation

After the CW RF is achieved, the amplitude-regulating loop can be closed. Closing the amplitude loop is an easy procedure. The amplitude regulation demonstrated by the prototype system is better than 0.25 %. As the last step, the self-excited frequency is locked to the external frequency reference by enabling the quadrature loop. We have been able to phase lock the cavity even at when it is critically coupled. However, this required very careful phase and frequency matching between the external source and the cavity. In normal practice, the cavity is slightly over-coupled to increase the bandwidth of the cavity for easier phase locking.

3.3 Helium Conditioning

In order to reduce electron loading at high electric field due to field emission, helium conditioning was performed on the cavity. Evaporated helium from the cryostat was fed into the vacuum space through a calibrated leak to a pressure of 10^{-5} torr. Figure 4 shows the Q_u vs. E_a curve for the May test and the July test. Included in the figure are also results when the cavity was first tested in INFN Legnaro. In the May test, the second curve was measured after conditioning the cavity at CW for 1 hour at 200W. Before Helium conditioning, field emission began at 4 MV/m. After 1 hour of conditioning, the onset of field emission was increased to 5 MV/m. High pressure water rinsing was performed before the July test. As result even before Helium conditioning the onset of field emission was increase to 8.5 MV/m. After Helium conditioning the threshold for field emission was above the threshold for quenching. In all of these tests the starting Q_u was at 4×10^8, instead of what was first obtained in Legnaro (1×10^9). We suspect that this is because our cryostat does not have a magnetic shield protecting the solid niobium cavity. Work is in progress to install a magnetic shield before the next measurement.

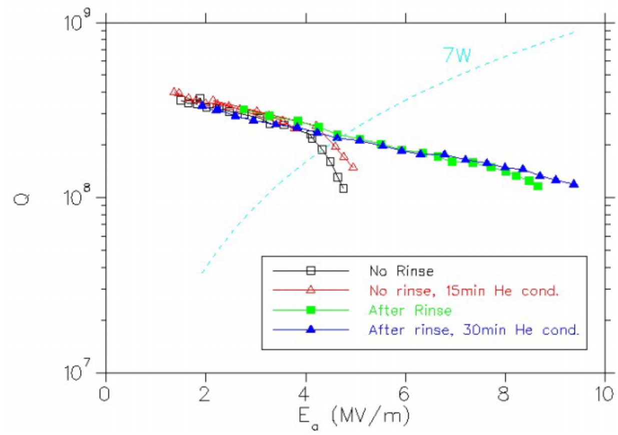

Figure 4 – Q_u vs E_a Measurement Results

4 CONCLUSION

This self-excited mode control system has been tested with the ISAC 2 prototype cavity and has been able to regulate the cavity both in the self-excited mode as well as the frequency-locked mode. A pulsing circuit enables the RF to punch through multipactoring in a relatively short time. Helium conditioning was performed on the cavity which increased the onset of field emission from 4 MV/m to 9.5 MV/m.

5 REFERENCES

[1] K. Fong, M. Laverty, S. Fang, "RF Control Systems for the TRIUMF ISAC RF Structures," Proceedings of the 2001 Particle Accelerator Conference, Chicago, June 2001, pp. 948-50.

[2] M. Laverty, K. Fong, S. Fang, "Design and Testing of the ISAC RFQ Control System", Proceedings of the1999 Particle Accelerator Conference, New York, March 1999, pp. 890-2.

[3] K. Fong. M. Laverty, S. Fang, "RF Control System for ISAC II Superconducting Cavities". Proceedings of the 2002 European Particle Accelerator Conference, Paris, June 2002, to be published.