SIMULATION ANALYSIS OF ANALOG IQ BASED LLRF CONTROL OF RF CAVITY

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Abstract

This paper presents the simulation work and results in Matlab Simulink for the analogue Inphase-Quadrature (IQ) based Low Level Radio Frequency (LLRF) control of RF cavity voltage. The RF cavity chosen here is the Radio Frequency Quadrupole (RFQ) cavity in our RIB project. All the subsystems in the IQ based RF control were modelled using the Simulink blocks/components. The envelope simulation was carried out using the IQ model of RF cavity. The PI controller was properly tuned to achieve good control performance in time. The simulation graphs showing the time evolution of the RF cavity voltage with a step change of the input reference signal is presented. The simulation graphs showing the control response time needed to correct a disturbance is presented. The simulation results showing Nichols plots of the control loop and the gain and phase margin values obtained from them are presented, which are good enough for stability considerations.

INTRODUCTION

An ISOL type RIB facility is presently being developed at VECC. At present the RIB facility comprises of a RFQ (3.4m), three rebunchers and three Linacs. A schematic of the RIB facility is shown in Figure 1. The RFQ, first rebuncher, and first two Linacs operate at 37.8 MHz, while the third Linac and the other two rebunchers were designed to operate in the second harmonic at 75.8 MHz. For proper beam acceleration it is essential to regulate the RF cavity voltage at proper amplitude and phase. At present the RF cavity voltage are controlled in the conventional amplitude and phase loop control method and it is planned to upgrade the LLRF control to analog/digital IQ method.

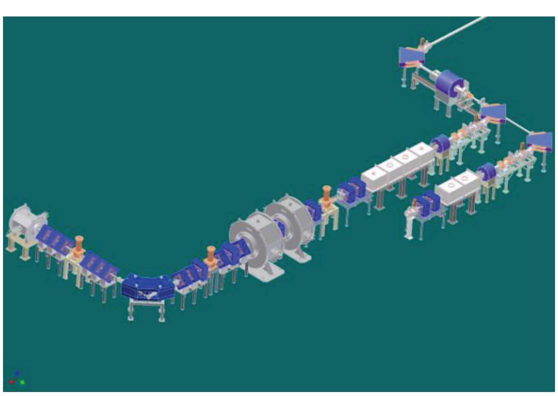

Figure 1: Schematic of RIB Facilityat VECC.

In this paper the IQ based LLRF control simulation work is presented for the RFQ cavity. The advantage of RFQ is its high beam transmission efficiency for low velocity, high current beams, and the fact that a single structure is used for bunching, focusing, and acceleration of ions. Some of the important RFQ parameters are presented in Table 1.

Table 1: RFQ Parameters

Parameter	Value
Frequency	37.83 MHz
Q_o (measured)	5393
R_{sh} (measured)	42 KΩ
Input energy	1.68 keV/u
Output energy	95.7 keV/u

IQ METHOD OF LLRF CONTROL

The IQ LLRF control method is based on the principle that we can control the amplitude (A) and phase (φ) of a RF voltage i.e., $V = A \sin(\omega t + \varphi) = (A \cos \varphi) \sin \omega t + (A \sin\varphi) \cos\omega t = I \sin \omega t + Q \cos\omega t$ by controlling the Inphase ($I = A \sin \varphi$) and Quadrature ($Q = A \cos \varphi$) components of the RF signal fed to the high power amplifier. The RF cavities are operated at a particular frequency. The advantage of this method is that I and Q components can be controlled in two paths using two set points for I and Q components. The In-Phase (I) and Quadrature (Q) signals could be obtained by passing the RF signal through a IQ demodulator device. The schematic of the analog IQ LLRF control system is shown in Figure 2.

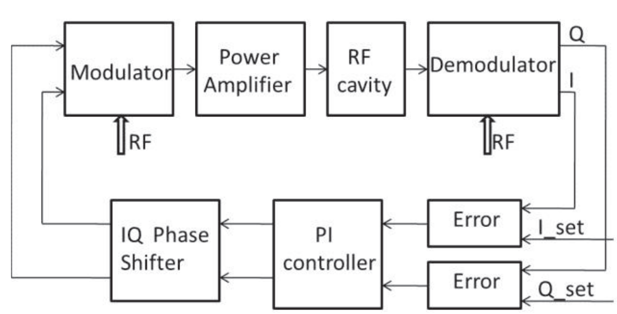

Figure 2: Schematic of analog IQ LLRF control.

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The components in analog IQ based LLRF control comprises of RF power amplifier, RF cavity, couplers (input and pick-up), IQ demodulator, IQ phase shifter, PI controllers, IQ modulator etc. In IQ method the controller processes the input I and Q components in two parallel paths and gives the appropriate output I and Q components so as to get the desired output.

Although the actual analog IQ LLRF control have the IQ demodulator (IQ modulator) devices for the down-conversion (upconversion) of the RF signal to lowpass (baseband) and vice-versa. However in order to reduce the simulation time greatly we have modeled the RF cavity in IQ baseband description and performed the simulation.

The RF cavity was modeled in IQ baseband in terms of the inphase (=V_r) and quadrature (= V_r) components of cavity voltage (=V) using the standard differential equation description namely,

$$\frac{dV_i}{dt} + \omega_{1/2} V_i - \Delta\,\omega\, V_r = \omega_{1/2} R_L\, I_i$$

$$\frac{dV_r}{dt} + \omega_{1/2} V_r + \Delta\,\omega\, V_i = \omega_{1/2} R_L\, I_r$$

where$\omega_{1/2} = \omega_o/2Q_L$is the half bandwidth of the RF cavity and $\Delta\,\omega = \omega_o - \omega$ represents detuning and I is the driving current.

The beam loading effects are neglected (ignored) in the simulation since the typical beam current is quite small for our RF cavities. The cavity is operated at resonance in usual 50 Ω system. The parameters of the PI controller are adjusted for the getting the desired response. The desired cavity voltage and phase is set by two I and Q parameters namely I_set and Q_set.

SIMULATION RESULTS

In this paper the simulation of the RFQ cavity voltage is presented for a test voltage of 12.4 kV and for synchronous phase of -30˚ (defined from peak of RF voltage) i.e., to say for RF phase of 60°. The simulation results for the time evolution of the RF cavity voltage and phase are shown in Fig. 3 and Fig. 4 respectively which accurately matches with the desired output voltage and phase.

The required RF power from the simulation was calculated to about 1.87 kW which closely matches with the measured power of 1.8 kW required for above voltage as was measured in a beam test [1]. In order to measure the response time of the control system a perturbation of about 15% of cavity voltage was introduced in simulation at time = 150 μs. We observe from Figure 3 that the controller was able to correct the disturbance in about 10 us. The control system stability analysis was carried out by obtaining the Nichlos plot as shown in Figure 5.

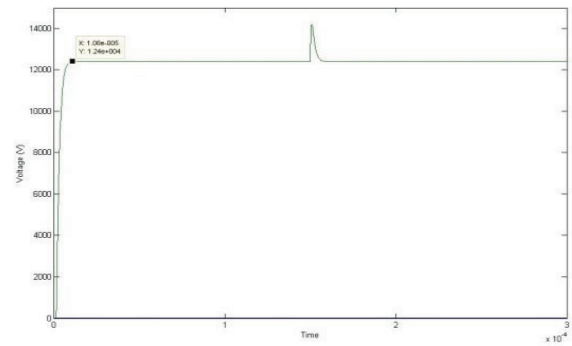

Figure 3: RF cavity voltage amplitude versus time.

The graphs show that the cavity voltage hasfast rise time (~10 us) and settles at the desired voltage.

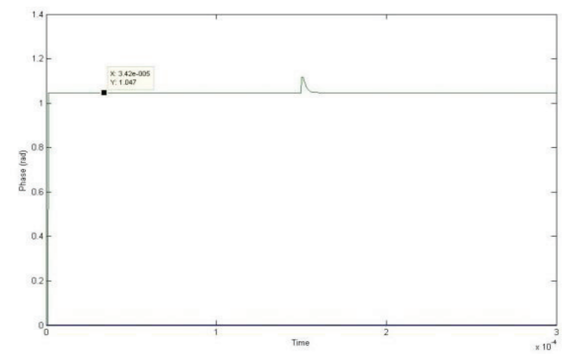

Figure 4: RF cavity voltage phase versus time.

The plot shows that the locus curve is away from the critical point and also the gain margin and the phase margin are almost 13 dB and 70˚ respectively which indicates adequately stable system.

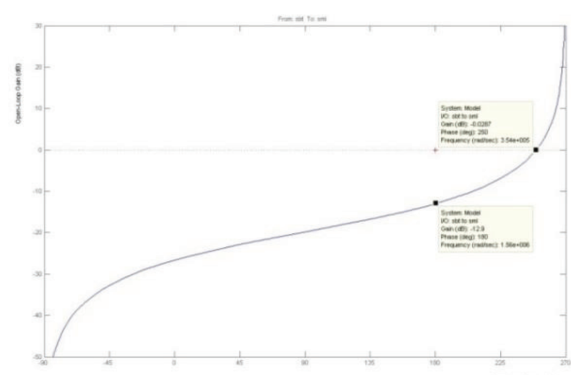
Figure 5:Nichols plot of the control system.

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[1] S. Dechowdhury et al., "Design and development of a radio frequency quadrupolelinac postaccelerator for the Variable Energy Cyclotron Center rare ion beam project", Review of Scientific Instruments, 81, 023301 _(2010).

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