MODELLING AND SIMULATION OF INDUS-2 RF FEEDBACK CONTROL SYSTEM

D. Sharma*, P. S. Bagduwal, N. Tiwari, M. Lad, P. R. Hannurkar
RRCAT, Indore-452003, India

Abstract

Indus-2 synchrotron radiation source has four RF stations along with their feedback control systems. For higher beam energy and current operation amplitude and phase feedback control systems of Indus-2 are being upgraded. To understand the behaviour of amplitude and phase control loop under different operating conditions, modelling and simulation of RF feedback control system is done. RF cavity baseband I/Q model has been created due to its close correspondence with actual implementation and better computational efficiency which makes the simulation faster. Correspondence between cavity baseband and RF model is confirmed by comparing their simulation results. Low Level RF (LLRF) feedback control system simulation is done using the same cavity baseband I/Q model. Error signals are intentionally generated and response of the closed loop system is observed. Simulation will help us in optimizing parameters of upgraded LLRF system for higher beam energy and current operation.

INTRODUCTION

Indus-2 is a synchrotron radiation source at Raja Ramanna Centre for Advanced Technology, Indore, India. Presently it is being regularly operated in round the clock mode with stored current of 100 mA at 2.5 GeV. The role of RF system at this facility is to boost the electron energy from 550 MeV to 2.5 GeV and compensate for synchrotron radiation losses. The RF system employs four numbers of elliptical cavities to generate sufficient accelerating RF voltage, each excited by individual RF station. Each station consists of a high power RF amplifier, solid state driver amplifier & LLRF feedback loops to keep the cavity RF field stable [1].

For higher beam current and better performance of LLRF feedback control loop it is being upgraded to digital feedback system. Inphase and Quadrature (I/Q) modulation technique is being implemented with FPGA based digital controller. To understand the behaviour of I/Q based feedback LLRF control system under different operating conditions, modelling and simulation is done. Modelling and simulation also helps in algorithm study, controller design and optimization. Baseband simulation has been performed as it makes the simulation faster due to better computational efficiency and for its close correspondence with the actual implementation. A description of the models and corresponding results has been discussed.

*dheerajsharma@rrcat.gov.in

RF CONTROL SYSTEM MODELLING

RF Cavity Model

Resonant modes of cavity can be described by means of resonant LCR circuits. In equivalent LCR model it is assumed that voltage across the resistor is the cavity gap voltage. A parallel LCR circuit with an input current source is shown in Fig. 1.

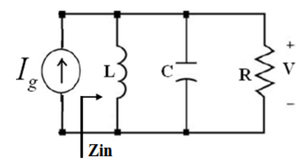

Figure 1: Parallel LCR resonant circuit.

The power source feeding power to RF cavity can be modeled as an LCR circuit driven by a current source I_g through transformer as a coupler [2]. An RF cavity resonator coupled by means of a *1:N* transformer [3] to an input RF power source with internal impedance Z_o is shown in Fig. 2 and the same is simplified in Fig. 3.

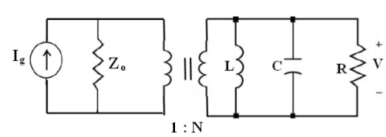

Figure 2: RF cavity coupled to an RF power source.

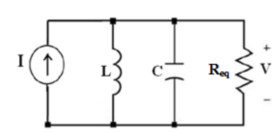

Figure 3: Equivalent circuit of Figure 2.

Where R_{eq} represents the equivalent impedance of the cavity under loaded condition. Cavity gap voltage is given by Eq. (1).

$$I = \frac{1}{L}\int V dt + C\frac{dV}{dt} + \frac{V}{R_{eq}} \quad (1)$$

Eq. (1) can also be rewritten in terms of bandwidth $\Delta\omega$ and resonance frequency ω_o as Eq. (2):

$$\frac{d^2V}{dt^2} + \Delta\omega\frac{dV}{dt} + \omega_0^2 V = \frac{1}{C}\frac{dI}{dt} \quad (2)$$

Laplace transform of Eq. (2) is given by

$$\frac{V(s)}{I(s)} = \frac{s/C}{s^2 + \Delta\omega s + \omega_0^2} \quad (3)$$

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Eq. (3) can be used for finding the transfer function of the normal conducting RF cavity of Indus-2. Different parameters of Indus-2 RF cavity are given in Table 1.

Table 1: Indus-2 RF Cavity Parameters.

Parameter	Symbol	Value
Unloaded Quality Factor	Q	40000
Loaded Quality Factor	Q_L	10000
Resonant Frequency	f_0	505.812 MHz
Shunt Impedance	R	6.6 MΩ

After using the parameters given in Table 1 the transfer function of Indus-2 RF cavity is given by Eq. (4)

$$\frac{V(s)}{I(s)} = \frac{0.5235464\times10^{12}s}{s^2+0.3173008\times10^6 s+0.10067984\times10^{20}} \quad (4)$$

RF Cavity Baseband I/Q Model

As the new control system will be based on I/Q modulation technique Inphase and Quadrature baseband response of the cavity has been modeled. This facilitates the simulation and designing in following ways:

- Controller is to be designed for I and Q signals.
- Only amplitude and phase of RF signal is of concern.
- Simulation gets faster as high frequency carrier information is removed.

Eq. (2) using can be represented in terms of half bandwidth of cavity as Eq. (5):

$$\frac{d^2V}{dt^2}+2\Delta\omega_{1/2}\frac{dV}{dt}+\omega_0^2V=2\Delta\omega_{1/2}R_{eq}\frac{dI}{dt} \quad (5)$$

Further input RF current *I,* and cavity output voltage *V,* in terms of vector notations can be represented as follows:

$$I=\vec{I}e^{j\omega t}=(I_r+jI_i)e^{j\omega t} \quad (6)$$

$$V=\vec{V}e^{j\omega t}=(V_r+jV_i)e^{j\omega t} \quad (7)$$

As the envelope of the cavity voltage *V*, is a slowly varying function of time compared to the time period of the RF oscillations, the following assumptions can be made

$$\frac{d\vec{V}}{dt} << \omega\vec{V} \quad \& \quad \frac{d^2\vec{V}}{dt^2} << \omega\frac{d\vec{V}}{dt}$$

For operation of cavity near its resonance frequency i.e. $\omega \approx \omega_0$ with the above assumptions Eq. (5) can be written as Eq. (8):

$$\frac{d\vec{V}}{dt}+\left(\Delta\omega_{1/2}-j\,d\omega\right)\vec{V}=\Delta\omega_{1/2}R_{eq}\vec{I} \quad (8)$$

Where $d\omega(=\omega_0-\omega)$ is called "detuning parameter".

After separating real and imaginary part one set of coupled differential equations are found which represent the baseband I/Q model of RF cavity as follows:

$$\frac{dV_r}{dt}+\Delta\omega_{1/2}V_r+d\omega\,V_i=\Delta\omega_{1/2}R_{eq}I_r \quad (9)$$

$$\frac{dV_i}{dt}+\Delta\omega_{1/2}V_i-d\omega\,V_r=\Delta\omega_{1/2}R_{eq}I_i \quad (10)$$

As the high frequency information is not present in the baseband I/Q model of the cavity the simulation becomes faster without losing the precision.

For Indus-2 RF cavity the above equations are as follows:

$$\frac{dV_r}{dt}+158.65043\times10^3\,V_r+d\omega\,V_i=26.177321\times10^{10}\,I_r \quad (11)$$

$$\frac{dV_i}{dt}+158.65043\times10^3\,V_i-d\omega\,V_r=26.177321\times10^{10}\,I_i \quad (12)$$

Comparison of Cavity RF Model and Baseband I/Q Model

A model for comparing the response of the cavity RF model and baseband I/Q model at resonant frequency is shown in Fig. 4.

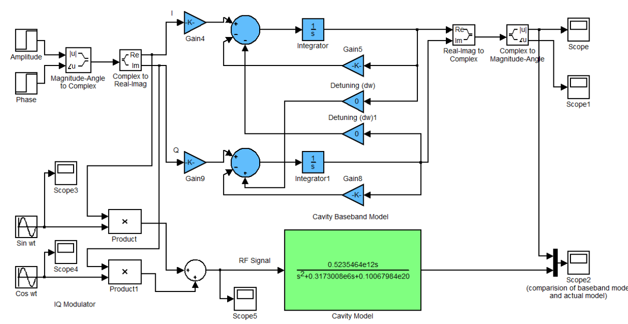

Figure 4: Comparison of cavity baseband and RF model.

In Fig. 4 an RF current source of amplitude 1A, phase 45° (I_r = 0.707A & I_i = 0.707A) and frequency 505.8 MHz is applied as input to the cavity RF model and baseband I/Q model simultaneously. Output response from both the models shown in Fig. 5, clearly indicates the close correspondence between them. The response from baseband model is envelope of the response from RF model.

The cavity peak voltage obtained from the simulation at steady state is 1.648 MV which is very close to the expected value of 1.65MV (R_{eq}*I). The cavity filling time t_{fill} is found to be 6.295 µs.

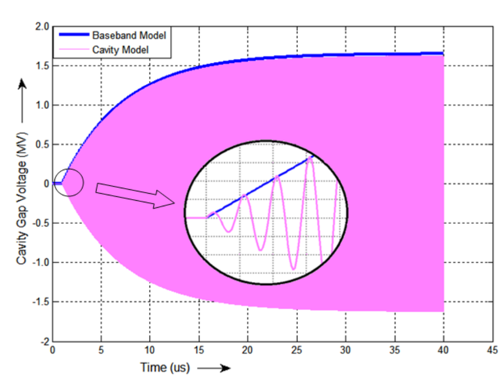

Figure 5: Comparison of simulation waveforms.

Correspondence of cavity RF model and baseband model for amplitude and phase response is also verified by the bode plots as shown in Fig. 6 and Fig. 7.

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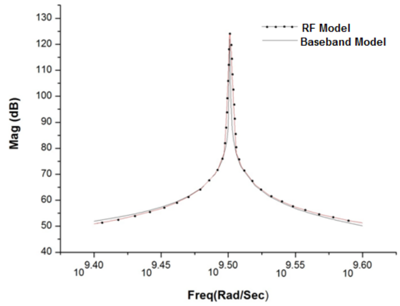

Figure 6: Magnitude plot of RF and baseband model.

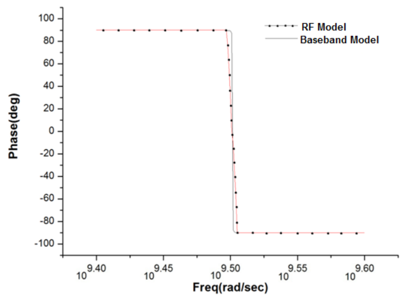

Figure 7: Phase plot of RF and baseband model.

LLRF Feedback System Modelling

Finally the baseband I/Q model of RF cavity is used for complete LLRF feedback control system modelling. From Eq. (9) the baseband transfer function for real part with zero detuning is given by Eq. (13) which is also same for imaginary part.

$$\frac{V_r(s)}{I_r(s)} = \frac{R_{eq}}{(\frac{1}{\Delta\omega_{1/2}})s+1} \tag{13}$$

A PI controller has been designed for in phase response of cavity and same is used for quadrature response due to the symmetry at resonance. Fig. 8 shows a unity feedback system with PI controller for the transfer function of Eq. (13) with 15 dB step error.

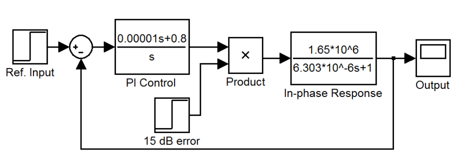

Figure 8: Unity feedback system with PI controller for in-phase response of cavity.

For the applications like Indus-2 RF cavity operation, if we restrict the maximum overshoot up to 5% of the final field amplitude (i.e. 420 kV) then the value of proportional and integral constants can be calculated as k_p = 0.00001 and k_i = 0.8 respectively. Different operating conditions like beam loading, temperature variations etc can easily be modelled by changing the detuning parameter $d\omega$ in the baseband I/Q model of the cavity.

For cavity operation at resonance the LLRF feedback model is shown in Fig. 9. The derived cavity baseband I/Q model has been put as a subsystem block. Setting input amplitude and phase as 400 kV and 45° respectively after reaching steady state a step error (15 dB) has been introduced. The response of LLRF feedback system model shown in Fig. 10 closely matches to the expected behavior with PI controller. The same baseband LLRF model can be used for designing and optimization of the system for various operating conditions.

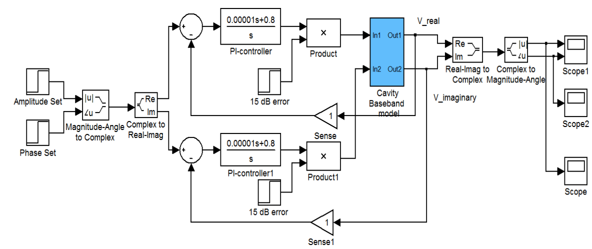

Figure 9: Baseband LLRF feedback control system.

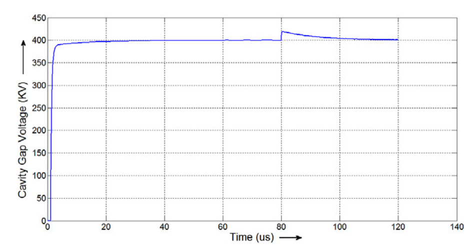

Figure 10: Cavity voltage amplitude (step error at 80 μs).

CONCLUSION

This simulation is a helpful tool to model, design and optimize the closed loop LLRF control system under different operating conditions of RF cavity. Similar model will also help in studying the behaviour of I/Q based digital LLRF system for various controlling algorithms.

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