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AN RF SIMULATOR FOR CONTROL SYSTEM DEVELOPMENT

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Abstract

Simulation tools are critical to the prototype and validation of control algorithms prior-to and during commissioning of LLRF systems. Moreover, for industrial systems, diagnostics that are available on test systems and in laboratory accelerators are not always available in the field. RadiaSoft has been developing an RF simulator suite that allows for rapid prototyping of control algorithms in a fully integrated epics environment. As part of this process, we have performed extensive testing and bench-marking using a novel C-band test cavity with a range of diagnostics. This poster provides an overview of the simulator, the physical models which make it up, and results for an example system with two cavities and other typical hardware elements.

INTRODUCTION

Most particle accelerator facilities feature some number of RF cavities and associated low-level (LLRF) control systems, whether as primary mechanisms for acceleration or for use in other subsystems (e.g., injection modules). However, utilizing these devices for secondary purposes such as controls development can be costly in both time and resources, and can impede normal experimental operations.

To that end, RadiaSoft has designed, tested, and deployed a robust RF simulator for developing LLRF control algorithms, input-output control (IOC) software, and user interfaces (UI). The simulator is integrated with the EPICS framework for experimental controls, and can be run through a number of modalities, including basic command line interfaces, Python scripts or Jupyter notebooks, and direct EPICS connections. It describes RF signal propagation using a standard scattering matrix approach and cavity dynamics using an effective circuit model derived in previous work for application to superconducting cavities.

Using our simulator, we have successfully tested several practical LLRF feedback control methods (including PID loops and filters), modeled systems of interest for research applications, and even studied the use of machine learning as a means for noise reduction in industrial RF systems. The simulator itself has been key to the success of these and other ongoing efforts, and will described in greater detail below.

RF SYSTEM MODELING

Cavity Model

Development of our RF simulator began with a simple effective RLC circuit model which accounts for a number of system characteristics, including: coupling and quality factors, frequency, drive amplitude and phase, pulse duration, and cavity detuning. The associated model dynamics are based on equations previously derived in [1] and [2], and an additive white Gaussian noise (AWGN) model for simulated measurements. Simulation is carried out by solving a differential equation for the voltage transmitted by a cavity, which is a function of both the current transmitted voltage and effective applied current supplied to the cavity:

$$\frac{d\mathbf{V}_t}{dt} = \begin{bmatrix} -\omega_{1/2} & -\Delta\omega \\ \Delta\omega & -\omega_{1/2} \end{bmatrix} \mathbf{V}_t + \frac{\omega_{1/2} R_L}{m} \mathbf{I}_f \qquad (1)$$

where

$$\mathbf{V}_t = \begin{bmatrix} \mathrm{Re}\,(V_t) \\ \mathrm{Im}\,(V_t) \end{bmatrix}, \qquad \mathbf{I}_f = \begin{bmatrix} \mathrm{Re}\,(I_f) \\ \mathrm{Im}\,(I_f) \end{bmatrix} \qquad (2)$$

are the transmitted voltage and forward current, respectively. The half-bandwidth $\omega_{1/2}$, coupling factor m, and loaded cavity resistance R_L are all parameters of the cavity itself, and their relationship with the effective circuit model parameters can be found in [1] and [2]. The voltage reflected by the cavity can be similarly computed [2] given a system reference impedance Z_0 using the equation:

$$\mathbf{V}_t = \begin{bmatrix} \mathrm{Re}\,(V_t) \\ \mathrm{Im}\,(V_t) \end{bmatrix} = \frac{1}{m}\,\mathbf{V}_t - \frac{Z_0}{2}\,\mathbf{I}_f \qquad (3)$$

RF Signal Chain

With an RF cavity model implemented, we then extended the generator-to-cavity system used in [1] and [2] to include a number of additional hardware elements commonly employed in RF systems. In order to properly simulate the much more complicated propagation dynamics that can result from the addition of such elements, we chose to describe incoming (**a**) and outgoing (**b**) RF waves at the ports of each element as power waves using a standard scattering matrix approach [3] such that:

$$\mathbf{b} = S\,\mathbf{a} \qquad (4)$$

where the dimension of **a**, **b**, and S are determined by the number of ports on an element, and the elements of S (the scattering matrix, are determined by the internal function of the element. For example, the scattering matrix for an ideal two-port RF transmission line (e.g., a coaxial cable or an RF waveguide) of length l is simply:

$$S_{Line} = \begin{bmatrix} 0 & e^{-(\alpha+i\beta)\,l} \\ e^{-(\alpha+i\beta)\,l} & 0 \end{bmatrix} \qquad (5)$$

where α and β are the typical attenuation and propagation constants of the waveguide. The scattering matrix for some elements, such as the four-port "magic tee" signal splitter, can be derived geometrically:

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$$S_{Tee} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix} \tag{6}$$

By instigating an RF signal from a source control element, the signal is cascaded along the RF signal chain (with order in the chain being determined by the connections between elements, see below) by iteratively multiplying incoming signals by the appropriate scattering matrices.

SOFTWARE DESIGN

In order to implement the models described above, we created a software package written in the Python language which describes RF elements, the LLRF control system, and simulator itself as a series of interacting objects. In order to better approximate real applications and improve utility for testing, the entire simulator has been fitted with an EPICS controls interface which exposes configuration settings for the RF elements as well as the LLRF controls. Initial configuration setting for all aspects of the simulator (included additive measurement noise) are provided by users in the form of human-readable YAML-formatted files.

RF Elements

Hardware elements are the most foundational aspect of our simulator as they provide the actual descriptions of RF signal propagation. In addition to RF cavities, we have implemented object descriptions for amplifiers, three-port circulators, signal isolators, transmission lines, terminal loads, both three- and four-port ("magic tee") splitters, and phase shifters. We are working to continuously improve the realism of the simulated dynamics for each element, for example the implementation of rise times for signal amplifiers, and to seek additional elements of practical interest.

LLRF Controls

The LLRF controls system used to drive the RF signal chain and conduct feedback processes on the system in response to simulated measurements constitutes an entirely distinct portion of the simulator. With configurable control parameters, dynamic readback queues, and control processes implemented in the form of user-defined Python scripts, we have attempted to make the integration of new and potentially experimental controls methods as seamless and as closely reflective of a real system as possible.

EPICS Interface

Leveraging the P4P module for Python [4], we were able to fit our simulator with an interface for the Process Variable Access (PVA) protocol of the EPICS framework in order to mimic the most typical interfaces for LLRF controls. This interface exposes all configurable parameters and readout data for the simulator over an EPICS network, much the same as is done for a real RF system.

DISCUSSION

We have successfully adopted, augmented, and integrated existing methods of modeling RF systems to produce a high-fidelity simulator for the express purpose of conducting control system development and other useful studies (e.g. noise removal). We have deployed this simulator to provide accurate predictions for existing and proposed RF systems (see Figs. 1 and 2), which have been used to conduct tests for LLRF control mechanisms as well as studies of interest in accelerator applications such as noise removal in RF signals. We plan to develop this simulator further to improve the realism of it internal dynamics, and to use it for a broader range of industrial and medical purposes.

ACKNOWLEDGMENTS

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REFERENCES

[1] T. Czarski, K. T. Pozniak, R. S. Romaniuk, and S. Simrock, "Tesla cavity modeling and digital implementation in fpga technology for control system development", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 556, no. 2, pp. 565–576, 2006. doi:https://doi.org/10.1016/j.nima.2005.10.122

[2] P. Echevarria, E. Aldekoa, J. Jugo, A. Neumann, A. Ushakov, and J. Knobloch, "Superconducting radio-frequency virtual cavity for control algorithms debugging", *Rev. Sci. Instrum.*, vol. 89, no. 8, p. 084 706, 2018. doi:10.1063/1.5041079

[3] F. Caspers, "Rf engineering basic concepts: S-parameters", 2012. doi:10.48550/arXiv.1201.2346

[4] EPICS, PVAccess for Python (P4P). https://epics-base.github.io/p4p/

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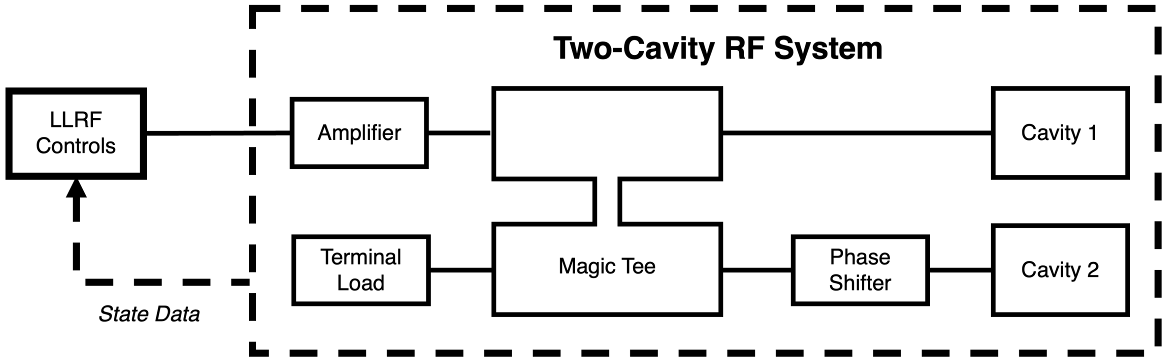

Figure 1: Schematic of a two-cavity RF system featuring an amplifier, terminal load, and phase shifter elements.

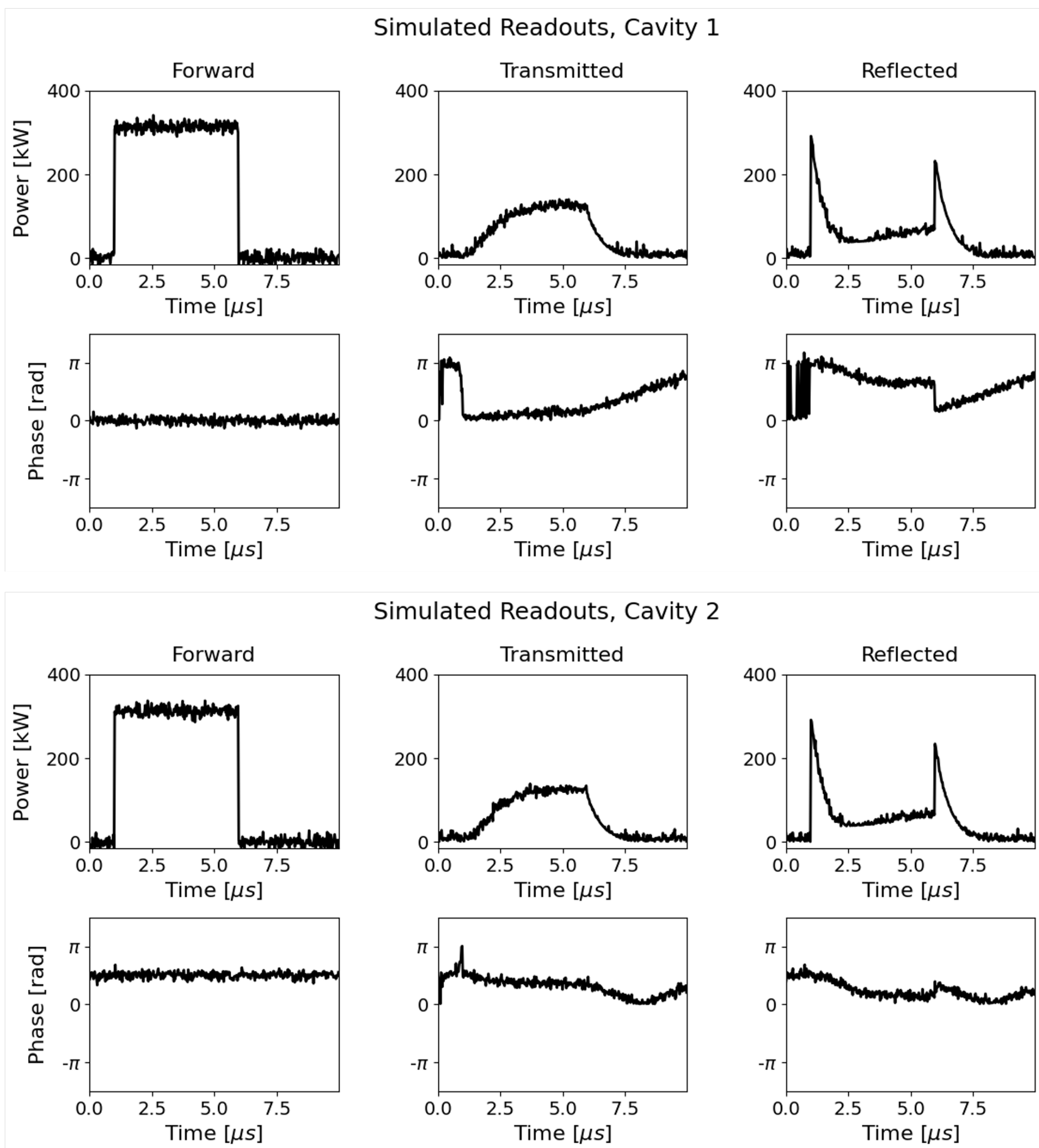

Figure 2: Readouts for a simulation of the two-cavity system pictured in figure 1, including forward, transmitted, and reflected RF signals for each cavity as well as their phases.