RF CONTROL MODELLING ISSUES FOR FUTURE SUPERCONDUCTING ACCELERATORS

A.S. Hofler, J.R. Delayen, TJNAF, Newport News, Virginia, USA
V. Ayvazyan, A. Brandt, S.N. Simrock, DESY, Hamburg, Germany
T. Czarski, WUT, Warsaw, Poland; T. Matsumoto, KEK, Ibaraki, Japan

Abstract

The development of superconducting accelerators has reached a high level of maturity following the successes of ATLAS at Argonne, CEBAF at Jefferson Lab, the TESLA Test Facility at DESY and many other operational accelerators. As a result many new accelerators under development (e.g. SNS) or proposed (e.g. RIA) will utilize this technology. Covering all aspects from cw to pulsed rf and/or beam, non-relativistic to relativistic particles, medium and high gradients, light to heavy beam loading, linacs, rings, and ERLs, the demands on the rf control system can be quite different for the various accelerators. For the rf control designer it is therefore essential to understand these issues and be able to predict rf system performance based on realistic rf control models. This paper will describe the features that should be included in such models and present an approach which will drive the development of a generic rf system model.

INTRODUCTION

Nowadays the designer of an rf control system for superconducting accelerators can make use of powerful digital processing hardware including digital signal processors (DSPs) and field programmable gate arrays (FPGAs) allowing processing times reaching from a few hundred nanoseconds for basic field control algorithms to several microseconds or more for complex algorithms. In cases where lowest possible latency is critical (to achieve higher feedback gain and immediate feedback response) the designer may want to choose an analog feedback solution, possibly a hybrid system with fast analog feedback and digital control of operating parameters, built-in diagnostics, and exception handling. In all cases it is desirable to develop a model for the rf control system to be able to predict the expected performance while assuming realistic noise source and performance limitation of the llrf subsystems. The model will allow for comparisons between different controls concept and aid the designer in the synthesis of the optimal controller design [1,2].

RF CONTROL REQUIREMENTS

The rf control requirements for amplitude and phase stability are usually derived from the desired beam parameters. The beam parameters include emittance, energy spread, bunch length and arrival time of the bunch which is critical for seeded XFEL applications. Since the bunch-to-bunch energy spread ranges from around 1% to better than 0.01%, the typical categories for field control are of the order:

Table 1: Typical requirements for field stability rf control

Category	1^a	2^b	3^c
σ_A/A	1e-2	1e-3	1e-4
σ_φ [deg.]	1	0.1	0.01

a. SNS, RIA main linac
b. CEBAF, TESLA, XFEL main linac
c. XFEL critical sections (bunch compressor)

The requirements in Table 1 are considered uncorrelated errors for category 1 and 2 (the correlated error budget is certainly tighter) and correlated errors for class 3 (only few cavities before bunch compressor). The requirements for the phase stability become also more severe for off-crest operation. In the case of the control of the vector-sum of several cavities driven by one klystron, the requirement for the phase calibration of the vector-sum components may become critical depending on the magnitude of microphonics.

Besides field stabilization the RF control system must provide diagnostics for the calibration of gradient and beam phase, measurement of the loop phase, cavity detuning, and control of the cavity frequency tuners. Exception handling capability must be implemented to avoid unnecessary beam loss. Features such as automated fault recovery will help to maximize accelerator up-time. A thorough understanding of the RF system will allow for operation close to the performance envelope while maximizing accelerator availability. Often the RF control must be fully functional over a wide range of operating parameters such as gradients and beam current. For efficiency reasons the RF system should provide sufficient control close to klystron saturation. The cavities are limited in their maximum operable gradients by quench, field emission or coupler sparks. Maximum operable gradient can be achieved with proper exception handling.

SOURCES OF PERTUBATIONS

An essential feature of the rf model will be the appropriate accounting for noise. Evaluating control schemes requires a clear understanding of sources of pertubations and its implementation.

A first classification distinguishes between a modulation of parameters of the model and noise that is added at certain points of the model. The resonance frequency of superconducting cavities is a parameter that undergoes modulations due to mechanical and electromagnetic

effects (in the case of normal conducting resonators even due to thermal effects).
Therefore, the system response of the cavity model is likely to become non-linear to a non-negligible degree.
Further, in the case of pulsed mode simulation, the model should incorporate the possibility for repetitive noise in addition to statistical noise. Many components of the cavity drive system turn out to have repeating imperfections, such as the high-voltage characteristics of a klystron.

Modulation of the Cavity Resonance Frequency

The center frequency of accelerating structures is exposed to changes mainly due to excitation of low-frequency mechanical resonances (microphonics) and mechanical distortions based on strong electromagnetic fields (Lorentz force detuning). Mechanical distortions are always present and are caused by vacuum, cryogenic devices and ground motion. The typical variation of the resonance frequency is of the order of 5-10 Hz with frequencies ranging from 0.1Hz up to a few hundred Hz, reflecting the convolution of mechanical resonances with the spectral components of the sources of pertubations. The steady state resonance frequency changes due to Lorentz force detuning is at the order of 1Hz/(MV/m)^2. In the case of changing gradients, especially in pulsed mode operation, the mechanical resonances of the cavities will be excited resulting in a time varying detuning even during the flat top portion of an rf pulse.

Cavity Drive Signal

A number of effects affecting the high power drive signal of the cavities need to be considered. The HV-Pulse of microwave amplifiers usually shows modulation in the order of a few percent. Additionally, in pulsed operation, there are fluctuations from pulse to pulse. HV instabilities cause errors on the high power drive signal in amplitude and phase. It can be exposed to a ripple caused by the power supply. Additionally, phase noise from the master oscillator, jitter on the timing signal and mismatch in the power distribution as well as non-linearities in the (high power) amplifiers influence the quality of the field and need to be included adequately.

Beam Loading

Fluctuations in the beam current and the impact of pulsed beam transient can be modelled as well as the effects of wake fields. The beam can excite higher order modes and other passband modes, which may increase the demands on the cavity model to include several modes each with its own coupling to the beam.

Other

It can be necessary to model other effects, such as multipacting and field emission in the cavity, thermal drifts of various components of the control system, the response of the feedback system and recovery of interlock trips.

The designer of the noise model needs to carefully decide the level of detail of each source of noise suggested here. He may come to the conclusion that some sources are negligible compared to others. The required accuracy of each noise source implementation strongly depends on the queries made towards the model.

ACCELERATOR TYPE SPECIFIC ISSUES

The design of the acceleration system (cavity + frequency tuner, fundamental coupler, HOM coupler, rf power source, rf power distribution) is based on

- type of beam (relativistic (electron) or non-relativistic (proton or heavy ion))
- beam current (high or low)
- pulsed or cw operation (rf and/or beam)
- control of individual cavities vs. vector-sum control

which in turn determine cavity type and affects operating parameters such as

- cavity single and multi-cell, beta=1 or beta<1, elliptical, HWR, QWR, spoke, RFQ etc.
- loaded Q high (>1e7) or low (<1e6)
- on-crest or off-crest operation

The rf model must be able to support the accelerator specific requirements for the differents types of accelerators. For non relativistic beam it is desirable to model sections with several cavities including simple longitudinal beam dynamics to study the effects of beam loading variations caused by cavity field fluctuations. For high currents linacs it will be important to include beam based feedforward in the rf control system for beam loading compensation. In the case of lightly beam accelerators such as ERLs where the cavity loaded Q is high it will be important to implement a self-excited loop scheme in the controller and to provide resonance control with VCX or fast ferrite phase shifters.

RF SUBSYSTEMS

The RF system consists of various subsystems which are illustrated in Figure 1.

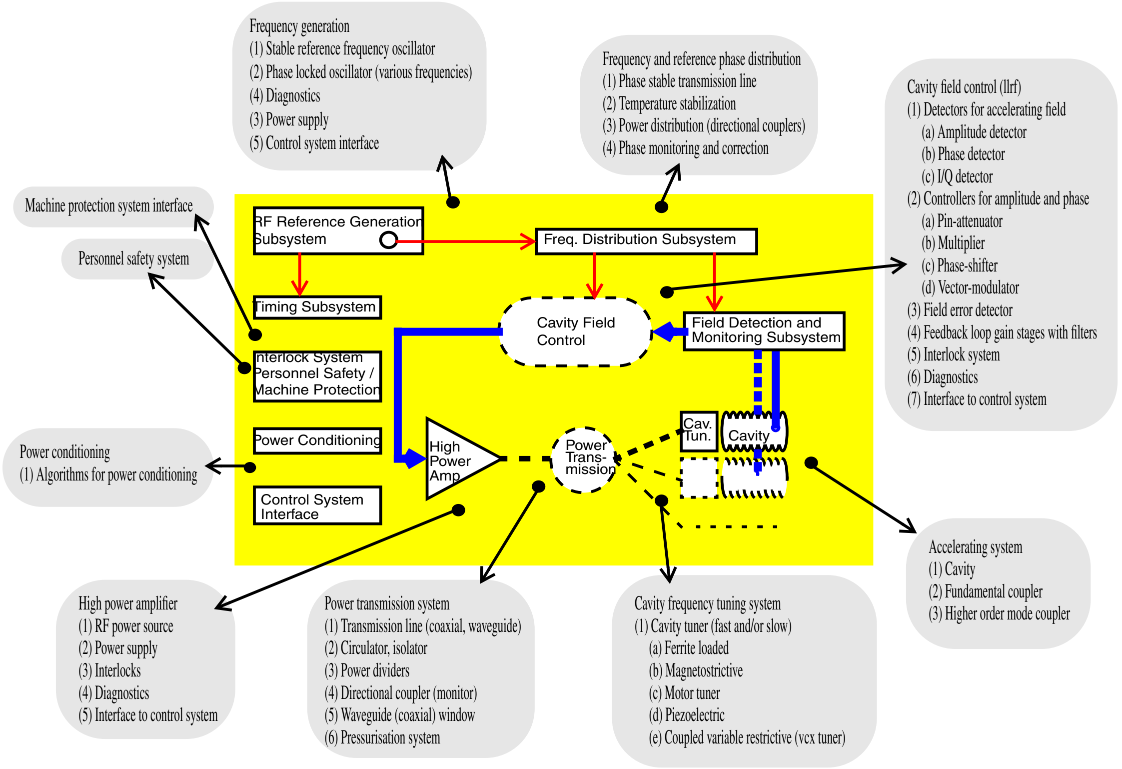

Figure 1: Typical rf system configurations.

RF MODEL IMPLEMENTATION

The design process should be accompanied by a certain set of rules that guarantee the reusability of the model and maximize its output.

- Modularity

On the implementation level, one should follow modern programming guidelines in order to minimize dependencies among program units. This eases the cooperation of different programmers as well as a fast modification of single program parts without affecting the rest. Many programming languages offer the use of libraries (either precompiled or interpreted), such as Matlab or C++.

- Flexibility

The modularity should be continued on the front end side of the model. It is desirable to split the components of the rf model into separate units that can be connected, repeated and exchanged without big effort. Ideally, every type of subsystem of different laboratories has an rf model implementation that can easily be exchanged. Matlab Simulink for example offers blocks of active elements with well-defined in- and output channels that can be replaced very quickly.

- Scalability

The model should be designed in a way, that the number of (repeated) subsystems as well as the degree of precision can be adjusted. Experience has shown that during the operation of the model questions and expectations towards it change. Scalability therefore can mean the freedom to reduce or increase the number of accelerating structures that are controlled by a single feedback loop. It can also mean to trade off the precision of a simulation against its execution time.

- Portability

In a world where many incompatible platforms compete against each other, it is desirable to not depend on a single one of them.

CONCLUSION

For the design of future superconducting accelerators extensive rf control modelling will be required. While the main goal of the model will be to predict the expected amplitude and phase stability of a given design, also other aspects of the rf system will be studied. The model must be flexible enough to accommodate accelerator type specific issues. A generic rf model following a modular architecture should be able to cover wide spread needs.

REFERENCES

[1] T. Schilcher, S.N. Simrock, L. Merminga, D.X. Wang, “A Design and Performance Analysis Tool for Superconducting RF Systems”, PAC’97, Vancouver, Canada, 1997

[2] A. Vardanyan, V. Ayvazyan, S.N. Simrock, “An Analysis Tool for RF Control for Superconducting Cavities”, EPAC’02, Paris, France, 2002