DIGITAL CONTROL OF CAVITY FIELDS IN THE SPALLATION NEUTRON SOURCE SUPERCONDUCTING LINAC*

Hengjie Ma, Mark Champion, Mark Crofford, Kay-Uwe Kasemir, Maurice Piller
Oak Ridge National Laboratory, Oak Ridge , TN37831, U.S.A
Lawrence Doolittle, Alex Ratti, LBNL, Berkeley, California, U.S.A.
Alexander Brandt, DESY, Hamburg, Germany

Abstract

Control of the pulsed RF cavity fields in the Spallation Neutron Source (SNS) superconducting Linac uses both the real-time feedback regulation and the pulse-to-pulse adaptive feed-forward compensation. This control combination is required to deal with the typical issues associated with superconducting cavities, such as the Lorentz force detuning, mechanical resonance modes, and cavity filling. The all-digital implementation of this system provides the capabilities and flexibility necessary for achieving the required performance, and to accommodate the needs of various control schemes. The low-latency design of the digital hardware has successfully produced a wide control bandwidth, and the developed adaptive feed forward algorithms have proved to be essential for the controlled cavity filling, the suppression of the cavity mechanical resonances, and the beam loading compensation. As of this time, all 96 LLRF systems throughout the Linac have been commissioned and are in operation.

RF CONTROL SCHEME FOR PULSED SUPER-CONDUCTING CAVITIES

The center component in SNS Linac rf control (LLRF) system is a field control module (FCM). As usual, the super-conducing cavities (SC) used in SNS SCL also have large time constants, and dynamically deform when subject to pressure changes. Those characteristics add additional problems to the rf control, and therefore require a combined use of the feedback control, adaptive feed forward controls (AFF), as well as other measures in the FCM. Figure 1 gives a symbolic representation of this control scheme, and the scheme is described in the following;

Low-latency Feedback Control

The rf control uses a SISO real-time P-I Control [1] for field regulation. It is the primary control for the cavity rf. As the primary control, it needs to provide a major part of the required control precision, and have a fast response. A low latency of the digital hardware is therefore necessary as it permits using higher loop gain and thus renters a wide control bandwidth.

Adaptive Feed Forward Controls

The FCM currently uses two adaptive feed forward controls (AFF). The first AFF control (designated as AFF 1 in Figure 1) is used for the cavity filling. The purpose is to establish the cavity field in a controlled manner, and let the feedback control operate in a more linear small-signal region. The AFF waveform for the cavity filling is pre-defined, and the rf phase and the waveform magnitude are adaptively adjusted from pulse to pulse using an algorithm similar to that of a simple integral control.

The second AFF control (designated as AFF 2) is used to compensate the beam loading and suppress the 2 kHz mechanical resonance found on many SNS medium-beta cavities [2]. The algorithm is a straightforward pulse-to-pulse P-I control. Another AFF algorithm (AFF 3) using an anti-causal backward-smoothing [3] has also been developed, and is currently under test.

FCM Operation Automation

There are totally 96 LLRF systems for the 96 cavities in SNS Linac. To be able to operate such a large number of systems, the automated operations of each and all FCMs are a necessary part of the control scheme.

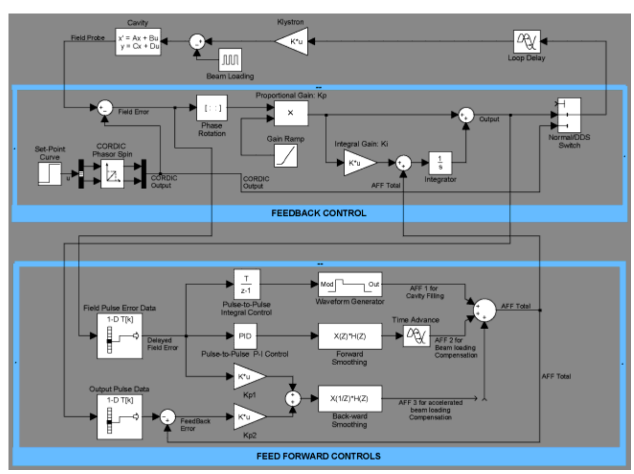

Figure 1: The combined feedback and feed forward control scheme is used in the field control module in SNS Linac.

*SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy.

FCM HARDWARE IMPLEMNTATION

The logic for all FCM control functionalities is implemented in a single high-density FPGA chip XC2V1500. The complexity of the logic design, as well as the scale and power of the Lianc machine require that the risk of introducing errors in the design be minimized. Again, an automated process as shown in Figure 3 is therefore used in the digital hardware development [4]. Two important aspects in this process are the co-simulation that checks both the logic functions and the control behavior in each code rebuild. The machine code generation produces some of the components that either have a huge number of net connections or repetitive instantiations of the basic building blocks.

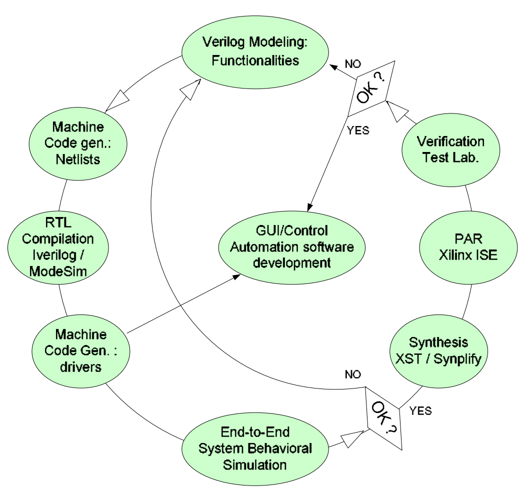

Figure 2: The automated development and co-simulation process for the FCM.

PERFORMANCE AND COMMISSIONING RESULTS

The development of the FCM hardware and software is completed. All 96 rf control systems have been commissioned throughout the Linac, and now are in operation. The performance characterizations of the commissioned systems are described in the following.

Closed-loop Control Bandwidth

As previously mentioned, the low-latency design of the FCM hardware allows the use of higher loop gain for faster control response. The result of a step response test on a medium-beta SC cavity as shown in Figure 4 indicates that the FCM feedback allows a maximum loop gain around 80, which produces a closed-loop control bandwidth greater than 50 kHz.

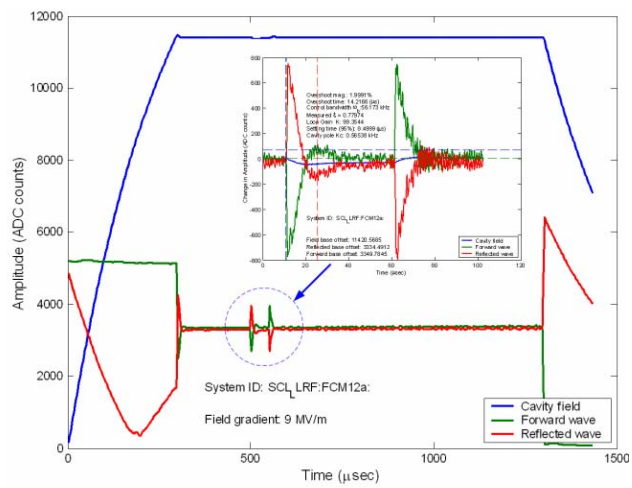

Figure 3: The FCM step response measured on the medium-beta cavity SCL-12a indicates that the feedback has a closed-loop control bandwidth greater than 50 *kHz.*

Adaptive Feed Forward Controls

The commissioned basic AFF control using a straightforward delayed pulse-to-pulse P-I control algorithm proved to be effective and stable over a long period of machine operation. For the beam loading compensation, the speed of learning ranges from 10 to 20 iterations, depending on the setting of the correction gains. The same AFF algorithm is also very effective in suppressing the 2 kHz mechanical resonance found on most of the medium-beta cavities.

Control Precision and Robustness

The measurements made on the FCMs in operation indicate that the FCM have achieved the specified field control precision of 1% and 1 deg or better [5]. Figure 5 shows the a typical performance of FCM on a medium-beta cavity running at a field gradient close to its designed value, and with a presence of 200 us, 20 mA beam.

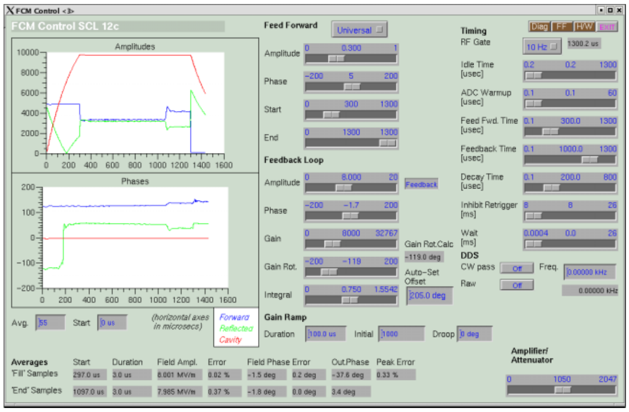

Figure 4: The typical FCM performance in the field control precision on SNS SC cavities.

In the operation, the commissioned FCMs have also demonstrated a good control stability and robustness. The FCM can operate over a wide dynamic range. Figure 6 shows a case when it was decided that the high-beta cavity SCL-18b which normally runs at 15 MV/m had to run at only 2 MV/m in closed-loop control. At such a low cavity rf level, the relative beam current became very big – a factor 16. At the arrival of each 20 mA beam pulse, the FCM correctly raised the rf drive power 1600% almost instantaneously in order to effectively compensate the huge beam loading, while still managed to stay in a stable control.

Figure 5: This beam loading response of the FCM on a high-beta cavity demonstrates the very wide control dynamic range that the FCM has.

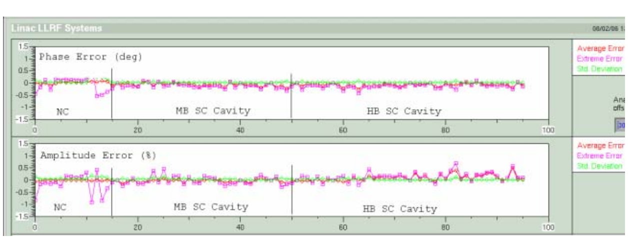

Figure 6: Linac-wise system performance of rf control measured in a recent beam run. The beam current is 20 mA, and the beam pulse length is 200 us.

Linac System-wise Performance

Shown in Figure 6 is a snapshot of the rf control performance across the entire Linac in a recent beam run. It shows the field control errors on each of all the 96 cavities. The SCL section begins from the cavity index 15 on the x-axis. This snapshot shows that at any point along the SCL, the rf field error is under +/-1% in the amplitude, and error in the phase is actually under +/-0.5 degree. Again, the required control performance is met.

CONCLUSION

The project of the rf control system for the SNS super-conducting Linac is a success. All installed rf control systems have demonstrated the required performance, and have successfully supported the Lianc commissioning, and operation. The robustness and reliability of the systems have been satisfactory.

ACKNOWLEDGEMENT

The SNS Linac rf control system development is collaborative effort among Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory and Los Alamos National Laboratory.

REFERENCES

[1] Kuo, B., “Automated Control Systems,” Prentice Hall, 1987.
[2] Ma, H., “Low-level RF Control of spallation neutron source: System and characterization,” Phys. Rev. ST Accel. Beam. Vo. 9, Issue 3, March 10, 2006.
[3] Brandt, A., DESY Tech Report.
[4] Doolittle, L. , “llc-suite,” http://recycle.lbl.gov/llc-suite/ .
[5 Champion, M., “Low-level RF Control System Requirements for RFQ, LINAC and HEBT,” SNS 104010300-SR0002-R00, October, 2002.