DIGITAL RF CONTROL FOR SPALLATION NEUTRON SOURCE ACCUMULATOR RING *

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Abstract

The proposed upgrade plan for the rf control of the Spallation Neutron Source (SNS) accumulator ring requires that the new digital field control module (FCM) have the capability of adaptive feed forward (AFF) compensation for the heavy beam loading in the cavities. The feed forward compensation capability should support both the conventional software driven AFF algorithm and a new beam current driven AFF algorithm. A user-friendly Epics GUI for all the FCM functionalities is also a part of the requirement. The first prototype for test has been built. It is a narrowband system based on the conventional I/Q sampling scheme. Both the hardware and software are currently under test in the lab, and the field test in a near future has been planned.

INTRODUCTION

The Spallation Neutron Source (SNS) accumulator ring has a circumference of 248 m and revolution frequency of 1.058 MHz. The injected beam energy is 1 GeV. The beam current ramps up to maximum 50 A at the end of the full 1060 turn stacking [1], [2], [6]. There are three fundamental and one 2nd harmonic cavity powered by four tetrode RF power amplifiers. Based on the original design specifications and operation experience, some specific requirement for the rf control has been updated and defined [3], [5], and they are listed in Table 1.

Table 1: Requirements for Ring RF Control

Parameter/Functionality	Specification
Control scheme	AFF + feedback combined
Control bandwidth	100 kHz
Field Regulation	(fundamental only)
Phase	+/-2.5 deg
Amplitude	+/- 5%
Bean loading handling	50 A
Gap signal dynamic range	40 dB min.
RF vector input	Gap_V, Grid_V, Beam_I
RF vector output	LLRF Drive
Conventional AFF	supported
Beam current AFF	supported
Cavity dynamic tuning	supported
Tetrode Grid boost	supported
Grid-Gap phase monitor	yes
Regulation error monitor	yes
RF protection response	less than 1 µs

ANALYSIS AND CONTROL SCHEME

SNS ring rf control is a problem of conventional normal-temperature cavity rf control, with an exceptionally heavy, but ramped beam loading. The application is subject to a set of specific conditions. These conditions influence the choices of control schemes, and ultimately determine the achievable system performance. The specific constraints include the loop delay-control gain, cavity beam loading and detune, as well as the rf power limit and the non-linearity in the system.

Choice of Basic Controller

The delay of the ring rf feedback loop was estimated to be just under 2 µs [7], while the latency of the SNS digital rf control hardware is 6 cycles of the 40 MHz clock, which renders a total loop delay of ~ 2 µs. Given a cavity bandwidth $\omega_{1/2}$ of ~ 10 kHz (for a maximum Q of 48), the usable proportional control gain K_p is limited to the estimate of

$$K_p \le \frac{1}{4\tau \cdot \omega_{1/2}} \approx 2 \qquad (1)$$

This means that with the proportional control alone, the steady-state control error $e_{ss}=1/(1+K_p)$ would be as large as 33% even before the linearly ramped heavy beam loading starts. Furthermore, the proportional control alone is a zero-order system, and is incapable of tracking a linearly ramped disturbance (i.e., the ramped beam loading). To be able to handle the heavy ramped beam loading, the system order needs to be at least one. The common P-I control configuration is a type 1 system. With a series P-I control and a perfectly tuned cavity, the steady-state control error to a ramped input is given by

$$e_{ss} = \lim_{s \to 0} \frac{1}{sG(s)H(s)} = \frac{1}{K_p \cdot K_i} \qquad (2)$$

For meeting the requirement [3] of a 5% tracking error, the integral gain needs to be about 10, which is very high. Nevertheless, the P-I controller seems to be a reasonable choice for the basic control.

Beam Loading Compensations

With the basic P-I control just meeting the requirement on the field control error under an ideal condition, some preliminary simulations show that field regulation

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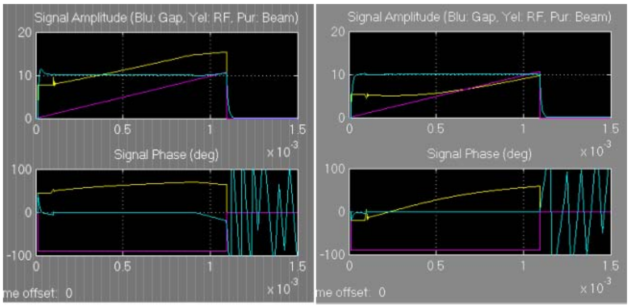

Figure 1: Simulation for the effect of the heavy beam loading (4.5) on the cavity field control for the case of the cavity detuned by -ω1/2 (left), and by $+\omega_{1/2}/2$ (right).

performance can be easily jeopardized by the changes in the system, such as the beam loading induced cavity detuning effect. This problem can be remedied by some compensation techniques. The simplest one is to pre-detune the cavity in the opposite direction by some amount. A simulation result in Figure 1 (left) shows that with a cavity detune of merely $-\omega_{1/2}$, the P-I controller based field regulation starts loosing the control when the 90 degrees off-phase beam loading rises to near its peak. A smaller cavity pre-detuned by $+\omega_{1/2}/2$ can bring the control back to stability (Figure 1, right). Effectiveness of this method has been tested. A little more sophisticated cavity tuning method using a 180 Hz AC bias current has proved its value in the operation [2], and will continue to be supported in the new system.

It has also been concluded in a simulation study [4] that the feed forward controls should be included in the overall control scheme. The AFF controls put out additional rf power to cancel the effect of beam current, reducing the burden on the feedback control. Among the considered AFF algorithms, two have been implemented for testing. One is software driven ("Soft AFF"). It uses a pre-defined linear ramp shaped rf envelope. The AFF software adaptively adjusts the level, phase and starting time to match with the beam loading. The other is beam current driven ("Beam AFF"). The Beam AFF copies the

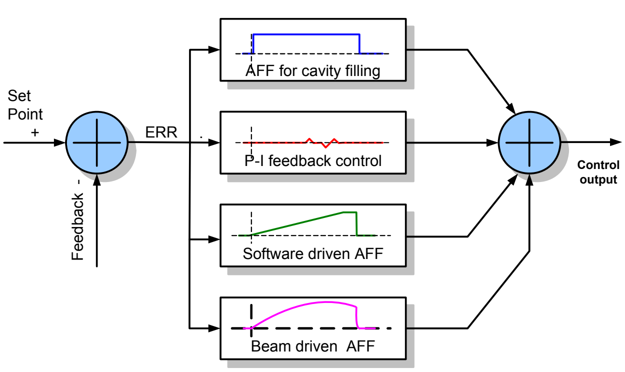

Figure 2: The combined feedback and feed forward control scheme for the ring rf offers a better capability in handling the heavy beam loading and the flexibility for the study of various control methods.

rf envelope of the beam current signal (from a wall current monitor), applies a proper scaling (or weighing) and phase rotation, and adds the weighed beam signal into the rf drive output. This beam AFF technique had been briefly tested in the operation with a beam current up to 500 turns. The result was promising. Based on the SNS Linac rf control experience, the ring system also includes a third AFF for the cavity filling ("Filling AFF") to minimize the turn-on transient of the feedback control. The block diagram in figure 2 illustrates this composite control scheme of one feedback control and multiple feed forward controls.

HARDWARE IMPLEMENTATION

For reducing the development time and hardware inventory, the digital ring rf control is implemented on the proven digital hardware of the SNS Linac Field Control Module (FCM), with the only customization in the rf analogue I/O adapter boards for working at lower ring rf frequency of 1, 2 MHz. The all rf control functionalities, including the real-time digital signal processing (DSP) and controls are implemented on a single Xilinx FPGA chip XC2V1500. The HDL design and software of the Linac system has also been largely reused on the first prototype. The justification for reusing the HDL and software designs is to be able to have an operating test system and install it in the field for study sooner. A small penalty for such a strategy is that the first prototype ring system will basically operate in the same way as the Linac system, i.e., its DSP is based on the conventional quadrature sampling ("I/Q sampling") throughout. Therefore, the first prototype is a narrowband system, operating on one frequency only, either the fundamental or the 2nd harmonic. Such a single frequency operation mode may not be the optimal for the ring rf as the waveform of the beam signal is not truly sinusoidal. Some of the considerations in customizing the hardware for the ring application include;

Sampling Clock Frequency

Although the ring rf frequency is only 1 or 2 MHz, the analogue-to-digital converter (ADC) clock rate used is still 40 MHz as in the Linac system in order to keep the data latency low. The 40 MHz clock signal is coherently generated from the 32 MHz ring clock, and phase-synchronized with the beam using Cycle-Rest trigger from the ring timing system. The 40 MHz clock is distributed to the four LLRF systems through cables.

Intermediate Frequency

To process the I/Q algorithms efficiently at the rate of 40 MS/s, the 1, and 2 MHz RF need to frequency up-converted to a higher 10 MHz intermediate frequency (IF). After the DSP in FPGA, a 40 MS/s output I/Q signal data is sent to the high-speed digital-to-analogue converter (DAC) to produce an 10 MHz IF output, which is then down-converted to 1, 2 MHz RF again to drive the rf PA. It is planned that in the final system for commissioning, the DSP algorithms will be able to directly process all ring rf signals without the frequency up/down conversions.

Signal I/O and Channel Hook-up

The SNS digital hardware is basically a universal DSP board of KIS ("keep it simple") style. It has a larger FPGA chip for specific application development, four high-speed ADC input channels, and one high-speed DAC output channel. The circuit board is in VXI format, and packaged in a single-wide module. For the ring rf control application, the vector signal input and output channels are hooked up to the ring rf signals as shown in Figure 3.

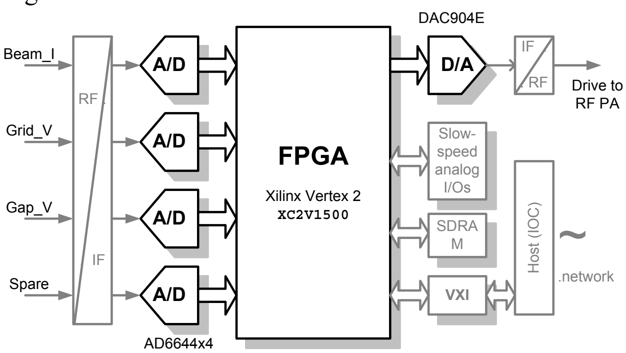

Figure 3: Signal channel hook-up of the digital hardware for the ring rf control application.

DEVELOPMENT STATUS

The customization on the hardware and software for the ring application has been completed. The first prototype system has been built and is currently under test in the lab as shown in Figure 4 and 5. The functions of feedback and feed forward controls are working properly with a test cavity and simulated beam loading. A field test in a near future has been planned.

DISCUSSION

The proven digital hardware of the SNS Linac FCM has provided a good platform on which the rapid prototyping of a ring rf control system can proceed smoothly. A narrowband prototype system has been built first. The hope is to use it for study, and to gain the necessary knowledge and experience which will lay the foundation for developing the proper rf control techniques for SNS accumulator ring.

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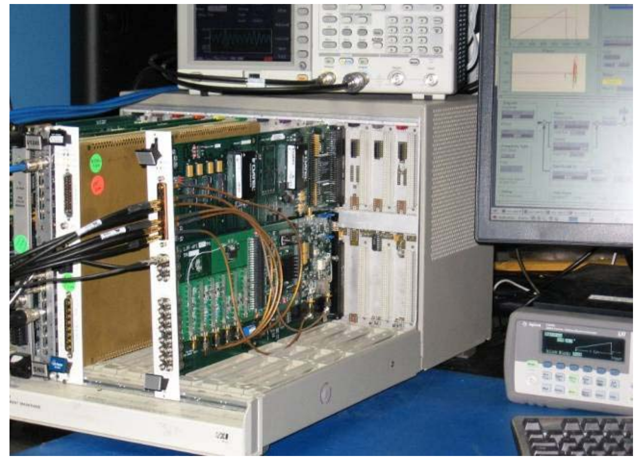

Figure 4: The first prototype of SNS digital ring rf control under bench test.

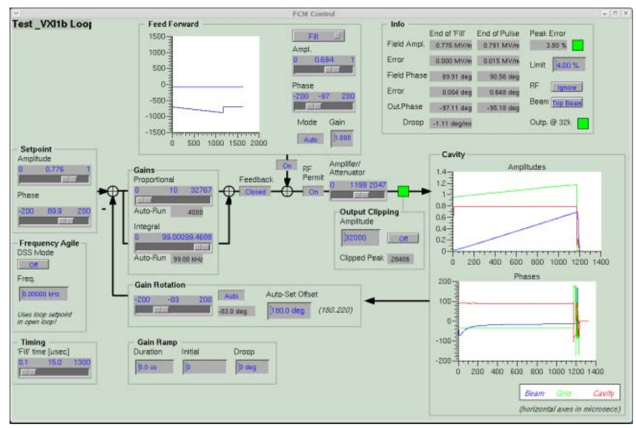

Figure 5: The new ring rf control is supported by a full set of user-friendly control GUI, which is an essential part of the system.

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