SELF-ADAPTIVE FEED FORWARD SCHEME FOR THE SNS RING RF SYSTEM

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Abstract

The RF beam current in the SNS ring ranges from 0 to 50 amperes during the 1 millisecond accumulation time. The control loops of the RF system are operative throughout this process. Acceptable setpoints will be found during commissioning, but as vacuum tubes age and beam currents rise these setpoints will become less than optimal. A scheme by which the system can optimize itself is presented.

INTRODUCTION

In broad terms, the Spallation Neutron Source consists of a linear accelerator, accumulator ring, and mercury target[1, 2]. The linear accelerator produces a 1 GeV, H^- beam which is charge exchange injected for ≈ 1000 turns. After accumulation the beam is extracted using a fast kicker and sent to the mercury target. The RF maintains a gap for the rise time of the extraction kicker while maintaining an acceptable peak beam current and momentum spread[3]. RF parameters are summarized in Table 1.

parameter	value
circumference	248m
transition gamma	5.25
total h=1 voltage	40 kV
h=1 gap capacitance	3 nF
total h=2 voltage	20 kV
h=2 gap capacitance	0.75 nF
space charge Z/n	i200 Ω
proton kinetic energy	1 GeV
injected bunch length	610 ns
injected energy spread	± 3.8MeV, full with energy spreader
injected energy spread	± 1.5MeV, full without energy spreader
protons at extraction time	1.5×10^{14}
accumulation time	1000 turns
extraction gap	250ns
repetition rate	60 Hz

Table 1: SNS Machine Parameters.

The parameters listed in the table are fiducial values. It is unlikely, for instance, that 1.5×10^{14} protons per bunch will be used during commissioning. The energy spreader cavity has been defered and a less expensive technique, based on modulating the last accelerating cell in the linac, could be substituted. The point here is that one cannot predict exactly what the RF system will be called upon to do at a given point in time.

The ring RF system is based on a mix of digital signal processor (DSP) and field programmable gate array (FPGA) technologies. The FPGAs are used to heterodyne the sampled RF signal to baseband and back. They will be timed by a master clock which will supply a fixed number (64) of samples per turn. Therefore, the FPGA architecture will not need to adapt. All other RF control is done using the DSP. The DSP reads control setpoints from local memory every SNS cycle. Therefore, we can imagine another program, running under the SNS control system, which continually optimizes the DSP setpoints. The algorithms this other program executes are the focus of this note.

RF SYSTEM PARAMETERIZATION

A large number of simulations are required to develop and test the algorithms, so a full model of the SNS is not practical. Also, a robust algorithm should not depend on the details of the simulation model. With this in mind, a relatively simple simulation is done to model an SNS cycle. Suppose that the RF voltage for a given cycle is turned on at $t = 0$. The generator current I_G, gap voltage V_g and beam current I_b are modeled via

$$\begin{aligned} I_G(t) - I_b(t) &= \frac{V_g(t)}{R_\ell} + C_g\frac{dV_g(t)}{dt} \\ &+ \frac{1}{L_g}\int_0^t V_g(t')dt', \end{aligned} \tag{1}$$

where C_g and L_g are the equivalent capacitance and inductance of one gap and R_ℓ is the loaded gap resistance. The power amplifier and ferrite are nonlinear, so the values of L_g and R_ℓ depend on the fields. We neglect the variation in R_ℓ and set

$$L_g = L_g^0(t)\left[1 + \frac{1}{V_f^2}\int_0^t \frac{dt_1}{\tau_f}V_g^2(t_1)e^{(t_1-t)/\tau_f}\right], \tag{2}$$

where $L_g^0(t)$ is the small signal inductance, controlled by the bias current. The parameters V_f and τ_f are positive constants, characterizing the ferrite. The, directly controlled, RF parameters are the small signal cavity inductance $L_g^0(t)$ and the generator current $I_G(t)$. With a one

* Work performed under the auspices of the U.S. Department of Energy. SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. SNS is a partnership of six national laboratories: Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos, and Oak Ridge.

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millisecond cycle time, we take $L_g^0(t)$ to be a straight line. The generator current is of the form

$$I_G(t) = Re\left[\hat{I}_G e^{j\omega_{rf} t}\right], \quad (3)$$

where the complex baseband signal $\hat{I}_G(n)$ is updated every turn, n. It is the sum of three terms,

$$\hat{I}_G = \hat{I}_G^1 + \hat{I}_G^2 + \hat{I}_G^3.$$

Most important is the contribution from the error in the gap voltage,

$$\hat{I}_G^1(n+1) = \hat{I}_G^1(n) + \frac{\hat{U}_g(n) - \hat{V}_g(n)}{\omega_{rf}\tau_g R_\ell} e^{j\psi_z(n)}. \quad (4)$$

In (4), $\hat{V}_g(n)$ is the measured baseband gap voltage, $\hat{U}_g(n)$ is the target voltage, τ_g is a time constant, and ψ_z is a best guess for the cavity detuning angle. The second important term is the feedforward correction $\hat{I}_G^2 = g_{ff}[\hat{I}_b - \bar{I}_b]$, where

$$\bar{I}_b(n) = j\hat{U}_g(n)\left[\frac{1}{L_g(n)\omega_{rf}} - C_g\omega_{rf}\right]$$

is the beam current for which the cavity is tuned. The instantaneous resonant frequency is $\omega_r(n) = 1/\sqrt{L_g(n)C_g}$, and g_{ff} is the feed forward gain. The last term in the generator current is the best guess setpoint $\hat{I}_G^3$, which will be set to zero.

Fully modeling the beam is computationally intensive. We neglect space charge and other forms of impedance, and take a pointlike bunch. To start the simulation in a well defined way we assume an injection timing error, τ_0. The update equations for the beam are

$$\Delta E_{n+1/2} = \Delta E_n + qV\sin(\omega_{rf}\tau_n) \quad (5)$$

$$\tau_{n+1/2} = \tau_n + \frac{T_{rev}\eta}{E_s\beta^2}\Delta E_{n+1/2} \quad (6)$$

$$\tau_{n+1} = f_0\tau_{n+1/2} + (1-f_0)\tau_0 \quad (7)$$

$$\Delta E_{n+1} = f_0\Delta E_{n+1/2} \quad (8)$$

where ΔE_n is the energy error of the bunch on turn n, τ_n is the arrival time error, η is the frequency slip factor, and $f_0 = I_b(n)/I_b(n+1)$ with $I_b(n)$ the total beam current on turn n. The complex amplitude of the beam current is

$$\hat{I}_b(n) = I_b(n)\exp(j\omega_{rf}\tau_n + j3\pi/2)$$

where the factor of $3\pi/2$ makes $\tau_n = 0$ the stable synchronous phase.

In previous work [3] the target voltage, $\hat{U}_g(n)$ was a fixed array, $\hat{V}_T(n)$. To allow for energy damping we set $\hat{U}_g(n) = \hat{V}_T(n)\exp(j\Delta E_n g_E)$ with a constant value for g_E.

OPTIMIZATION ALGORITHM

There are two parts to the optimization algorithm, the penalty function and the iteration scheme. Since SNS is not operational the penalty function was taken to be fairly simple.

$$P = \sum_{n=1}^{N_t}\left\{W_\phi|\hat{I}_b(n)||\tau_n|^2 + W_V|\hat{U}_g(n) - \hat{V}_g(n)|\right\}, \quad (9)$$

where $N_t \approx 1000$ is the number of turns, W_ϕ is the phase error weighting and W_V is the voltage error weighting. The weights were chosen so that approximately equal contributions from each of the errors were obtained at the minimum. Note that the phase error is weighted quadratically while the voltage error is weighted linearly. This was an arbitrary choice reflecting the generality of the scheme. Instead of simple power laws one might take a function with a dead band,

$$G(x) = \begin{cases} C(|x/a|-1)^n & \text{if } |x| > a \\ 0 & \text{otherwise,} \end{cases} \quad (10)$$

where C, n and a are positive constants.

With the penalty function chosen one needs a scheme to minimize it with respect to some control parameters. There are many schemes to minimize functions [4]. To keep things simple and robust we chose a grid search algorithm.

In our implementation the penalty function is viewed as a function of the control parameters $P = P(\alpha)$, where $\alpha = (\alpha_1, \alpha_2, \ldots \alpha_M)$ is the array of the M control parameters. Next one chooses an array of increments $(\Delta\alpha_1, \Delta\alpha_2, \ldots \Delta\alpha_M)$. The increments are large enough to result in a measureable change in P, but small enough so that a single step is unlikely to cause an unacceptable machine configuration (*eg.* losses too high). Next one sets $\alpha_1 = \alpha_1 + \Delta\alpha_1$ and evaluates P. If P decreased step again, if not set $\Delta\alpha_1 = -\Delta\alpha_1$ and step. Stepping continues until a minimum is bracketed. Additional accuracy may be obtained by using parabolic interpolation of the three lowest points, but we have not bothered with this. Next one minimizes with respect to α_2, then α_3, etcetera. We use a very simple scheme on the size of the increments, setting $\Delta\alpha_k = \Delta\alpha_k/2$ after minimizing with respect to parameter k.

IMPLEMENTATION

To implement the algorithm we chose four control parameters ψ_z, τ_g, g_{ff}, and g_E. In principle each of these is an array, but we took constant values throughout the cycle. Figure 1 shows the ideal gap voltage and the beam current throughout a sample SNS cycle. Figures 2 and 3 show the optimization results for a model with linear ferrite properties. The sweep in L_g was chosen so that the cavity was tuned at the beginning and the end of the cycle. The initial conditions were not too bad and the penalty function

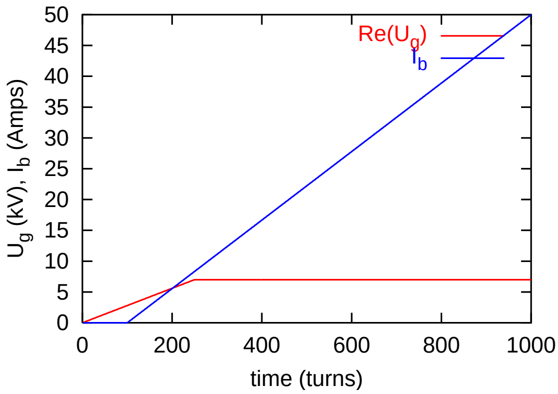

Figure 1: Ideal gap voltage and beam current.

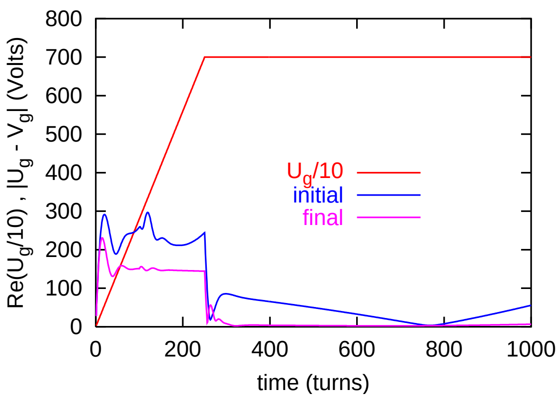

Figure 2: Voltage error before and after optimization.

dropped by about a factor of two between the initial and final states.

Figures 4 and 5 show the optimization results for a model with nonlinear ferrite properties. Again, the penalty function drops only by about a factor of 2.

It is interesting to note that the optimized values of the control parameters were quite different for the two cases. For the first case the optimized control parameters were

$$(\psi_z, g_{ff}, \tau_g, g_E) = (17^\circ, 1.0, 8\ \mu\text{s}, -2\ \text{GeV}^{-1}).$$

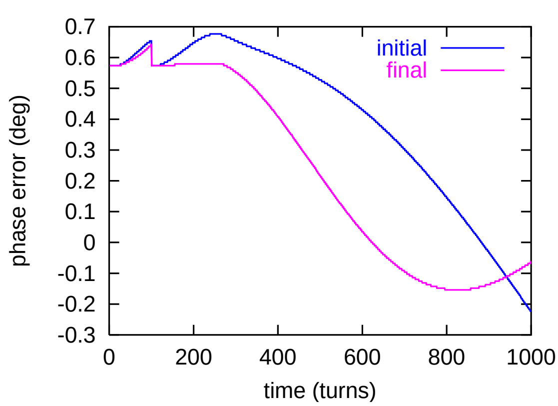

Figure 3: Phase error before and after optimization

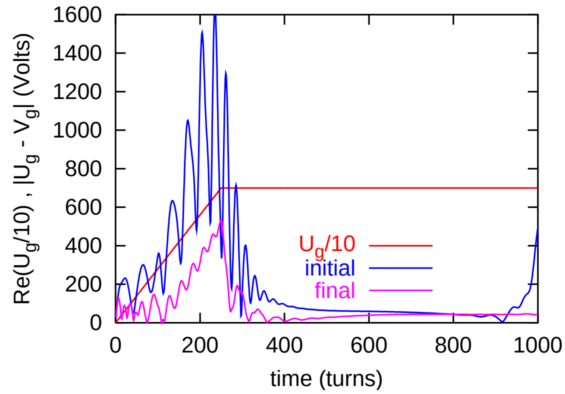

Figure 4: Voltage error before and after optimization.

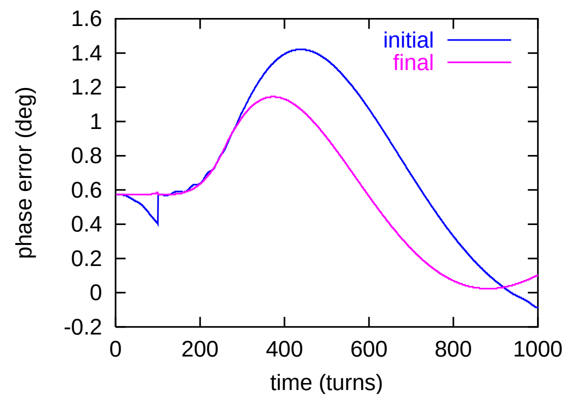

Figure 5: Phase error before and after optimization

For the nonlinear case the optimized vector was

$$(-1^\circ, 1.9, 3\ \mu\text{s}, -50\ \text{GeV}^{-1}).$$

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