Ramp Tuning of the APS Booster Synchrotron Magnet Power Supplies*

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Abstract

The acceleration cycle of the Advanced Photon Source (APS) booster synchrotron is completed within 250 ms and is repeated at 2 Hz. The currents in the quadrupole and sextupole magnets must track the dipole current to within tight tolerances if the beam is to remain stable during acceleration. In order to meet the performance specifications, a monitoring system, on-line with the main control system, is used to measure machine performance and adapt power supply reference waveforms from cycle to cycle. The system optimizes the tracking between the power supplies, thus minimizing transient effects and taking care of any slow drifts. Tuning algorithms are described and their performance evaluated. Practical considerations are also discussed.

I. INTRODUCTION

1.1 Description of the Booster

The APS booster synchrotron (booster) raises the energy of a 400-MeV positron or electron beam up to 7 GeV in approximately 230 msec. It is designed to do this at a 2 Hz rate.

The booster employs a classical FODO lattice structure of 292 ramping magnets. Of these magnets there are 68 dipoles, 80 quadrupoles, 64 sextupoles, and 80 correctors. The dipoles are all connected in series and are powered by two 12-phase power supplies operating in a master/slave configuration. The quadrupoles and sextupoles are each separated into two families of equal numbers with each family powered by a separate 12-phase power supply. The correctors are powered with separate bipolar DC/DC convertors.

1.2 Ramp Cycle

With the exception of the correctors, a typical magnet current ramp cycle is shown in Figure 1. At the beginning of the cycle a small DC current is demanded. At an appropriate time, the current begins to ramp up linearly. Injection occurs on the fly 10 - 15 ms after the start of the ramp. The current, and thus energy, continues upward linearly. Extraction occurs approximately 230 ms after injection and is also done on the fly. After extraction, all supplies are ramped back down to zero current.

1.3 Performance/Tracking Tolerances

Tracking tolerances with respect to the dipole must be specified and maintained when beam is present, otherwise the beam transverse tunes will strike destructive resonances. Although one could choose to use a complicated dipole current ramp and force the other power supplies to track this, we choose instead to use a simple linear ramp for the dipoles, quadrupoles, and sextupoles. Due to their importance to the operation of the machine, we will limit our discussion to only the dipoles and quadrupoles.

The nominal horizontal and vertical transverse tunes of the booster are $Q_h = 11.75$ and $Q_v = 9.80$, respectively. A simple, though somewhat restrictive, performance goal is to maintain the tunes to within $\Delta Q = \pm 0.025$. Neglecting variations in the magnetic properties of the magnets, we then require the ratio of magnet currents to remain very close to constant throughout the energy ramp, with maximum deviations dictated from the above tune tolerances.

The allowable current errors are written simply in terms of the fractional quadrupole strength

$$\frac{\Delta K}{K} = \left(\frac{\Delta I_{quad}}{I_{quad}} - \frac{\Delta I_{dipole}}{I_{dipole}} \right) .$$

The tunes vary roughly like $\Delta Q \approx 25\Delta K$. This is true in both horizontal and vertical planes. (The off-diagonal term of the "tune" matrix contributes about a factor of six less than the diagonal term and is neglected in this approximation.) A tracking error of either the dipole or quads will then cause a tune error. The effect is additive. In order to maintain our performance goal we thus require

$$\frac{\Delta I_{q,d}}{I_{q,d}} \le \frac{1}{50K} \Delta Q_{total} \approx 0.029 \Delta Q_{total} \approx \pm 0.14\% \ .$$

Achieving and then maintaining these tolerances is particularly challenging at injection energies where the current is small and the power supplies are still suffering from turn-on transients. The methods we use to do this are the subject of this paper.

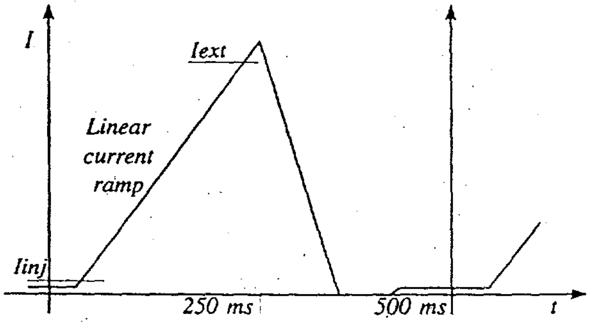

Figure 1: A typical current ramp cycle in the booster.

II. POWER SUPPLY CONFIGURATION AND MONITORING

2.1 Present Configuration

A block diagram of our present power supply control configuration is shown in Figure 2. A more thorough description

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of its operation and performance can be found in [1]. Only a brief description will be given here.

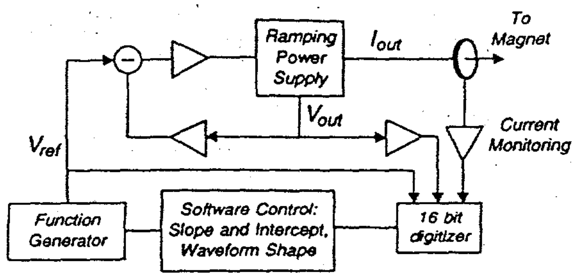

Figure 2: The present power supply control configuration.

Early on in the commissioning of the booster we operated the ramping supply regulators in current-control mode. The bandwidth of this system proved inadequate to achieve the desired fractional current tolerances. Fortunately, cycle-to-cycle repeatability of the supplies was good. We have since switched to operating the supplies in voltage-controlled mode. Taking the *L/R* time constant out of the loop of the load effectively increased our regulator bandwidth; however, we are still not able to achieve the stated tolerances with hardware feedback alone. Current feedback and the artificial extension of the bandwidth required to achieve and maintain the tolerances is done via software which monitors the output currents shot-to-shot and make fractional changes to the arbitrary function generator (AFG) voltage reference waveforms.

2.2 *Monitoring*

Success in our tuning methods relies heavily on our capability to accurately measure what the power supplies are doing. Our primary diagnostic technique is direct measurement of their output currents which are monitored in each case with a high stability current transductor. This signal is digitized by a 16-bit Analogic digitizer. The digitized waveforms are made available shot-to-shot to the control system for further processing. We also continually digitize and monitor the AFG voltage reference and power supply output voltage.

III. CURRENT RAMP TUNING AND CONTROL

There are two distinct ways in which we achieve the current ramps we desire: dead-reckoned tailoring (ramp tuning) of the input voltage reference signal and shot-to-shot control of the gross ramp parameters. A linear current ramp within the specified tolerance is first tuned using the methods described below. In this way the input reference effectively becomes the convolution of the desired output voltage with the inverse response function of the supply (no assumption about the linearity of the response is made). After achieving this, the slope and zero current time intercept are maintained, during actual operation, by a separate control program.

3.1 *Initial Corrections*

Tuning of the ramp tables proceeds in stages. As explained in [1], a nonlinearity is observed in the step response of the power supply. This limits automatic tuning to small corrections about a waveform which already provides reasonable performance. However, even without the nonlinearity, the transient response is still quite complicated and is not fully compensated by the regulator. We first set about developing reference ramp tables which get the supplies to within $\Delta I/I = 1\%$ of the desired linear ramp. Only then do we apply software correction algorithms. Tuning of the ramps starts with a simple application of $V = L di/dt + Ri$ to a linear current ramp. This is the initial voltage reference signal from which we work.

The ramp linearity is first improved by direct hand tuning of the voltage reference waveforms. Visual inspection of the measured $\Delta I/I$ is used to gauge progress. The hand-corrected waveform is then smoothed to eliminate any discontinuities. Smoothed and unsmoothed voltage reference waveforms for the defocusing quadrupole are shown in Figure 3. Only the first 100 ms of the 250-ms ramp cycle are shown. Beam injection occurs at 25 ms. It can be seen from the figure that the reference waveform is still being used to tune out the turn-on transients of the supply at the time beam is injected.

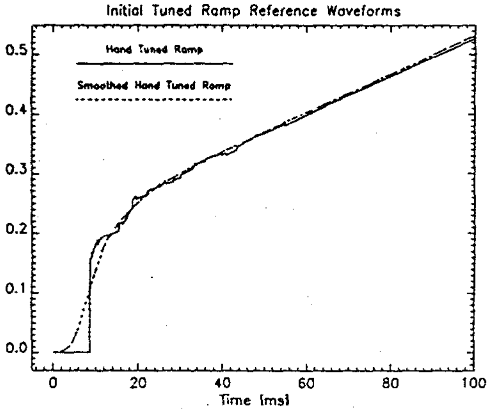

Figure 3: Example of an initial hand-tuned and smoothed voltage reference waveforms.

By tuning in this manner, we are able to routinely achieve a $\Delta I/I \leq 0.5\%$ (Figure 4a). Improvement past this level using hand tuning alone becomes more difficult and time consuming.

3.2 *Fine Tuning*

Further refinement of the current ramp waveform is done through software feedback. At present, a C-shell script makes calls to a suite of **sdds** (self-describing data set) processing tools [2]. A tool we have created is the **sddsPID** program. Given an input error signal, it returns an output correction signal which is determined by the gains and time constants of proportional, integral, and derivative (PID) terms of the defined software feedback loop. This effectively recreates the PID response normally attributed to a conventional analog regulator. The difference is that we are applying successive feed-forward corrections rather than doing real-time compensation.

The error signal for our loop is the point-by-point difference between the measured current waveform and a linear fit to that waveform. This error signal is first smoothed to get rid of high frequency noise. The **sddsPID** program is then run on the error signal and the output subtracted from the latest voltage reference waveform. This new updated waveform is loaded into the respective AFG. The program **Bcontrol** (see below) is then called upon to maintain the ramp slope and zero current time intercept. The process is repeated until the corrected $\Delta I/I$ is at or below the resolution of the present AFGs.

The results of the software feedback process is shown below in Figures 4a and 4b. In Figure 4a the $\Delta I/I$ signal was the best we were able to obtain by hand tuning and smoothing. Note that there is some 60-Hz ripple in the signal; this is real and believed to be on the voltage reference. Figure 4b is the result of successive iterations of the software current control feedback script. The $\Delta I/I$ signal has been corrected to below ± 0.1% during the ~ 230 ms the beam is in the machine (the arrow points to the injection time). The 60-Hz ripple is also no longer visible.

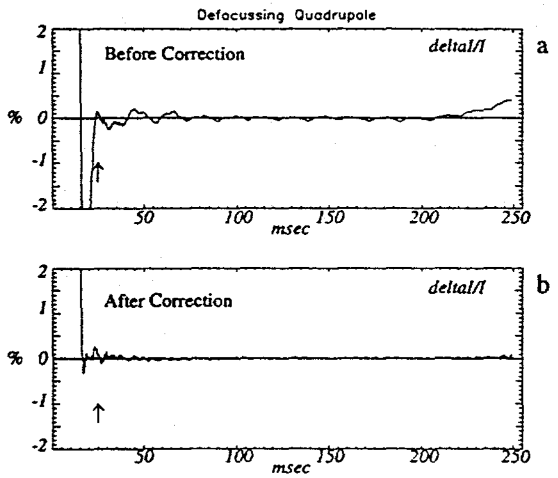

Figure 4: Fractional current errors before and after software feedback correction.

3.3 Maintaining the Slope and Intercept

Once tuned, the current ramp tends to stay within tolerance for long periods of time (days or longer); however, this is only true if the linear fit coefficients are maintained. Of primary importance is the output amplitude of the AFG. By varying this amplitude slightly we can keep the current slope at the desired value independent of slow variations of the line voltage. We must also insure that the quads and dipole all have the same zero current time intercept otherwise the beam transverse tunes will slew with time. **Bcontrol** actively does this control function for us. It monitors the current ramps on a shot-to-shot basis, does a linear fit to the measured current, and adjusts the AFG amplitude and trigger time to maintain the slope and zero current time intercept at the desired values. The values required are first deduced from theory and from magnet measurements. They are then modified as a result of measurement of the beam transverse tunes during ramping.

IV. FURTHER ENHANCEMENTS

4.1 Adaptive Feedback

The method described above still suffers from the fact that the hand-tuned ramps must be very close to optimal before we feel comfortable closing the final control loop. We have also found that occasional adjustments are needed to the control algorithms in order for them to work successfully. We are actively investigating the use of adaptive signal processing to continually determine the inverse response function of the power supply to achieve the desired output waveform. Figure 5 shows the scheme for deriving the inverse voltage response. The two model blocks shown in the figure are digital filters. The weighting factors for the model under refinement are generated using a minimization routine such as the least-mean squares (LMS) [3] or simplex algorithms.

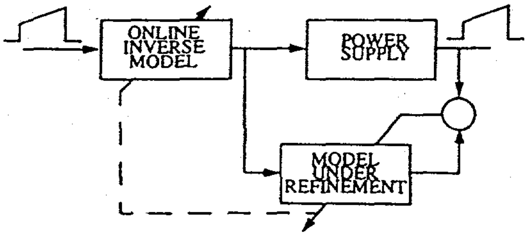

Figure 5: Adaptive Inverse Model Control Scheme.

The adaptive approach has the potential to be more robust than other approaches since it continually updates its model of the inverse response function to whatever subtle changes might occur within the system over time. An accurate forward model of the system has already been created using the LMS algorithm and a finite impulse response filter (FIR).

4.2 Beam-Based Tuning

Of course the beam is the final judge of the quality of the ramp tuning. The ultimate tuning aid would be to use the measured transverse tunes as a function of time during the ramp cycle. To date we have only used the tunes at injection to adjust the ramp reference waveforms.

Since tunes signals are available only when beam is present, tuning with beam can only be supplemental and cannot act as a replacement for the techniques described in this paper. It pays great dividends to be able to confidently tune up the ramps with no beam present using measurements of the supply input and output parameters.

V. SUMMARY

The methods described have proven successful; we routinely and consistently ramp a 400 MeV beam up to 7 GeV in just under 230 msec. Further refinements are being made which will allow full automation of the initial tuning and maintenance of the ramping waveforms.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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