Performance of the Ramping Power Supplies for the APS Booster Synchrotron*

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Abstract

The Advanced Photon Source (APS) booster ramp cycle is completed within 250ms and repeated at 2Hz. Separate phase-controlled power supplies deliver current to each of the dipole, quadrupole, and sextupole magnet families. Tracking requirements are particularly challenging because of the fast (non-resonant) ramp. In order to meet the requirements, both conventional regulation and cycle-to-cycle adaptation are used. The power supply system and its performance are described.

I. INTRODUCTION

The APS booster uses a simple FODO magnet lattice consisting of 68 dipole, 80 quadrupole, and 64 sextupole magnets. The quadrupole magnets are connected in chains of 40 magnets creating 'focussing' and 'defocussing' families. Similarly for the sextuples with 32 magnets per family.

During routine operation of the booster the betatron tunes should remain constant throughout the energy ramp cycle and from cycle to cycle. Since the tunes are determined by the relative strengths of the quadrupole and dipole magnets, the ratio of currents in the magnet chains must also remain constant. Any deviation from the nominal current profile will result in a deviation from the nominal tunes; how large a deviation is tolerable will determine the magnet power supplies' performance criteria. Whilst in principle the dipole current could follow any path from the injection to extraction levels, we have chosen to use a linear ramp to simplify the tracking control of all the magnets. During a typical ramp cycle, beam is accelerated at a nominal 29MeV/ms. This corresponds to a rise rate of ~4A/ms for the dipole and ~2.5A/ms for the quadrupoles.

II. REQUIREMENTS

The APS booster tune sensitivities are given by [1]:

$$\Delta Q \approx 0.2 \frac{\Delta I_{quad}\,[\mathrm{A}]}{E\,[\mathrm{GeV}]}$$

The target tune error throughout the ramp is 0.02. In order to achieve this, the quadrupole power supplies must track the dipole to within ~0.1%. Power supply ramp tracking errors can occur within a single ramp cycle and from cycle to cycle.

The booster is reasonably tolerant to chromatic effects. Therefore, since control of the sextupole ramps is not nearly so critical as with the quadrupoles, a maximum tracking error of 1% is allowed in the sextupole currents.

Ramp characteristics for all the magnets are determined from a least-squares linear fit to the measured current waveforms. Three factors are identified: the slope of the fit, the zero (current) crossing time of the fit relative to beam injection, and the deviation from the fit as a function of current (ΔI/I).

Table 1 shows the worst case error in each of these three parameters if the entire tolerance were to be taken up by any one of the parameters.

Table 1: Target Worst Case Errors in Quadrupole Ramps

Linear Fit Characteristic	Nominal Value	Worst Case Error
Ramp ΔI/I (%)	0.0	0.1
Ramp Slope (A/ms)	2.5	0.003
Zero Crossing (ms)	12.5	0.018

In practice of course, there will always be errors in each of these parameters, so the actual errors have to be even smaller, although it is worth noting that errors do not necessarily add up in quadature.

III. POWER SUPPLY OVERVIEW

Each of the five power supplies consists of a 12-pulse thyristor-controlled bridge rectifier and an associate ripple filter. The 12 pulses are generated from two pairs of 3-pulse half-bridges connected via interphase transformers. Figure 1 shows a simplified schematic of the quadrupole power supply. The dipole power supply is similar except that two such power circuits are series-connected in a 'master-slave' arrangement. The nominal operating conditions are given in Table 2.

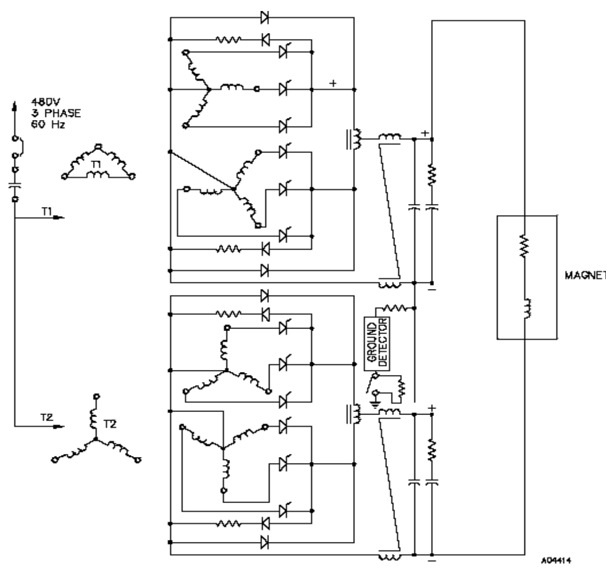

Figure 1: Simplified Schematic of Quadrupole Power Supply

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Table 2: Nominal Magnet Parameters (* focusing magnet)

	Dipole	Quad*	Sext*
Current @ 450MeV (A)	58.0	39.3	~8
Current @ 7GeV (A)	902.5	610.8	~160
Nom. di/dt (A/ms)	3.93	2.50	~0.6
Load Inductance (H)	0.55	0.058	0.012
Load Resistance (Ω)	1.26	0.73	0.8

The original power supply design did not incorporate freewheel devices, however it was discovered that the power supply behaved differently at low currents than at higher currents. This was believed to be a consequence of the magnetization of the interphase transformer as the current increased. Adding freewheeling devices to each half-bridge has helped to reduce the magnitude of these non-linearities.

IV. CONTROL SCHEME

Figure 2 shows the simplified scheme used to regulate the current in each of the five magnet families. Two control loops are shown: a primary voltage loop and a secondary current loop. Presently, only the voltage loop is implemented. Due to the relatively long time constants of the magnets (dipole: 540ms, quadrupole: 79ms) the bandwidth of the current loop is far too low to be used as the primary loop, so the faster voltage loop is supplied with its own reference waveform corresponding to the '*Ldi/dt + iR*' load voltage.

To date, the implementation of the current loop (shown dotted in the figure) has been considered unnecessary since corrections for drift are made using software feedback. However, the current loop will shortly be implemented since it is now believed that it will help to reduce cycle-to-cycle jitter.

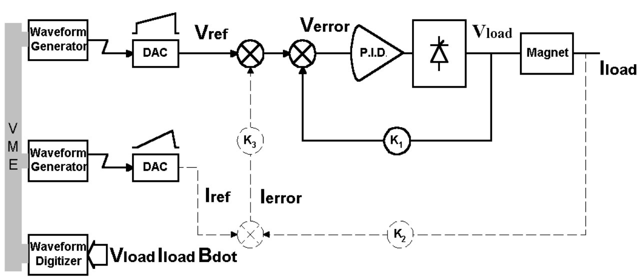

Figure 2: Control Scheme Block Diagram

Reference waveforms will be generated using in-house designed arbitrary function generators (AFG) mounted in a VME controller and accessed via the APS control system. Each waveform record will consist of 8K discrete 16-bit values. The waveform records are sent to the power supply digital-to-analog converter at 17.2kHz, giving a waveform duration of 475ms. By extending the duration of the waveforms past the 250ms required for the ramp cycle, the current decay can also be controlled. A dual waveform buffer allows a new waveform to be loaded in background and then swapped to the foreground between cycles. Updates can therefore be made to the reference waveforms without loss of ramp cycles.

Extensive monitoring of all waveforms (Vref, Iref, Vout, Iout, Bdot) is already done using proprietary 16-bit digitizers which sample the waveforms at 20kHz. The monitored waveforms are downloaded to the control system at the end of each cycle to be used by the software control system and for future analysis.

V. POWER SUPPLY TRANSIENTS

The most challenging part of this system is handling the power supply transients at the start of the current ramp. Since the power supply bandwidth is limited (at best) to 360Hz by the 12-pulse thyristor bridge, it is not possible to meet the performance criteria with a conventional regulator alone. The response of the quadrupole power supply voltage loop to various step inputs is shown in Figure 3.

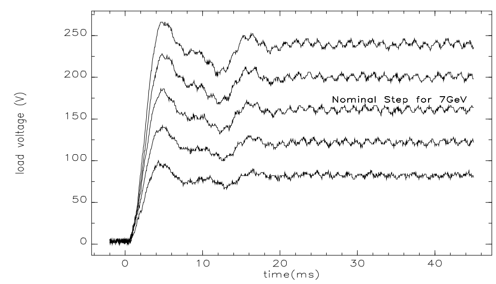

Figure 3: Step Response Family of Quadrupole Power Supply

In order to artificially extend the system bandwidth, the nominal voltage reference is modified to accommodate the inverse response of the power supply, thereby cancelling transients in the output voltage.

For a general linear system having the response vector Y to an input vector X, the response matrix A is:

$$Y = A \times X$$

By inverting the response matrix, it becomes possible to calculate the input vector required to produce a given output, where A^{-1} is the matrix inverse of A:

$$X = A^{-1} \times Y$$

In practice, straightforward determination of a single inverse response matrix useful over a broad range of conditions has proven difficult. So far, the approach has been to iteratively correct the voltage reference by hand until errors in the output current are reduced to allowable tolerances [1].

An approach which is currently being pursued is the use of adaptive signal processing techniques. Such techniques have already been used to create a forward model of the power supply from its measured response. The least-mean-square (LMS) algorithm [2] was used to determine the coefficients of a 60-element finite impulse response (FIR) digital filter which accurately modelled the measured response of the power supply. The intention is to use similar techniques to determine the coefficients for an FIR filter with the required inverse response.

VI. RAMP STABILITY

In addition to the single-cycle performance, cycle-to-cycle repeatability and long term stability are essential if the machine is to operate on a daily basis without significant operator intervention. Two effects are apparent: slow drift of the ramp parameters and cycle-to-cycle random jitter. The most apparent cause of drift has been changes in the AC line voltage. Figure 4 shows the effect of the AC line voltage on the slope of the dipole ramp without (software) feedback. The large steps seen in the AC line occur when the booster 1MW rf power system is turned on and off.

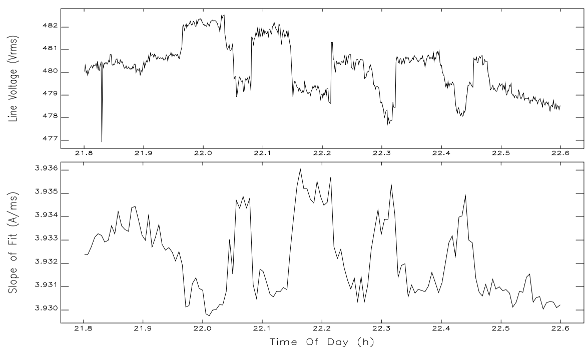

Figure 4: Effect of AC Line Voltage on Dipole Slope

Whilst in a normal operating mode such sudden changes in the line voltage are unlikely, slow changes over a much wider range are common. Since the changes in slope are relatively small in real terms, a high regulator gain would be required, and this cannot be achieved on our system.

The most significant contribution to cycle-to-cycle jitter has been the condition of the power supply just prior to the start of the ramp cycle. Since the power supply is unable to regulate to a 'zero' reference, it is necessary to run with a small positive DC bias. This puts the regulator at a consistent and defined position at the start of the ramp.

A further improvement of about a factor of two in cycle-to-cycle jitter has been achieved by smoothing the initial step in the voltage reference waveform, making it close to a cubic turn-on. This has the effect of reducing the integrated voltage error since the power supply is better able to track the smoother reference.

VII. SOFTWARE FEEDBACK

In addition to the software techniques used to automatically tune the ramps [1], a software feedback system known as 'Bcontrol' is used to continuously correct for drift in the slope and zero crossing of the linear fit parameters. A background process carries out the least-squares linear fit at the end of every ramp cycle. These fit parameters are then made available to the remainder of the control system. Corrections to the zero-crossing time are made by moving the trigger point for the appropriate waveform generator; small corrections to the slope are made by an overall scaling of the voltage reference waveform. Both of these actions can occur between each cycle and are therefore transparent to beam operation. The effect of using 'Bcontrol' on the zero crossing can be seen in Figure 5.

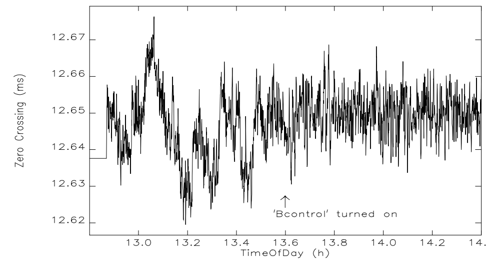

Figure 5: Effect of 'Bcontrol' on the Ramp Zero Crossing

VIII. OPERATING EXPERIENCE

The APS booster has been routinely producing 7GeV beam since January 1995. Throughout this time, only a 12-bit waveform generator has been available. However, it has still been possible to manually tune the ramps to well within 0.5% $\Delta I/I$ (limited by the patience of the operator). Early on, it was found that whilst the waveform generator provided 12-bit resolution, it only provided around 10-bit stability which proved inadequate for reliable beam operation. Thermal drift was found to be the major cause of the limited stability, and by close control of the electronics temperature, it has been possible to significantly improve the stability of the reference.

Cycle-to-cycle jitter is now the biggest problem, it being around 10-20μs rms. The most significant improvements in stability are expected to come from the new 16-bit waveform generator and from the implementation of the current loop.

IX. FUTURE ENHANCEMENTS

Presently, the three magnet systems are independent and there is no direct attempt to correct the quadrupole waveforms from dipole tracking errors. This will be implemented in the coming months. The ultimate level of control would come from feeding back directly from the measured betatron tunes, particularly during the early part of the ramp cycle when the beam is most sensitive. Simple feedback based on the tunes at injection is already underway, using the beam position monitors to measure the tunes. However, a full tune measurement system is currently being commissioned, and the intention is to ultimately make this part of the ramp control scheme.

X. ACKNOWLEDGMENTS

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XI. REFERENCES

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[2] B. Widrow, S. Stearns, Adaptive Signal Processing, (Prentice Hall, 1985).