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A High-Current, High-Voltage Power Supply with Special Output Current Waveform for APS Injector Synchrotron Dipole Magnets¹

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Abstract

This paper describes a high-voltage, high-current power supply for the injector synchrotron dipole magnets at APS. In order to reset the dipole magnets in each cycle two different current waveforms are suggested. The first current waveform consists of three sections, namely: dc-reset, linear ramp, and recovery sections where injection is done "on the fly". The second current waveform consists of six different sections, dc-reset, transition to injection level, injection flat level, parabolic, linear ramp and recovery sections. The effect of such waveforms on the beam is discussed and the power supply limitations to follow such waveforms are given. The power supply limitations are due to the power components and control loops. The reference for the current loop is generated by a DAC which is discussed.

I. INTRODUCTION

The injector synchrotron of the Advanced Photon Source consists (APS) of 68 dipole magnets connected in series. Two identical 12-phase power supplies are used to energize the chain of 68 magnets from two feed points 180° apart. To monitor the current in the magnets only one transducer is used. Two control loops are utilized to regulate the current in the magnets. Fast correction for the line transients is provided by a fast-response voltage loop controlled by a high-gain, slow-response current loop. The regulator card controls the firing pulses for two sets of identical 12-phase wye group power supplies. These pulses are transmitted to the second power supply via optical links.

The injector synchrotron boosts the positron beam energy from 450 MeV to 7.0 GeV. It has a circumference of 368 m (one third of the storage ring) and operates at a repetition rate of 2 Hz. The magnetic field must change from a certain low value to a certain high value. Several waveforms can be used to accommodate this change of magnetic field. Common waveforms used are ramp, sinusoidal, parabolic or a combination of these. However, quick changes of the magnetic field can cause large eddy currents resulting in the disruption of the beam and consequent loss of control. Therefore, the magnetic field must change gradually from 450 MeV to 7.0 GeV within 250 ms.

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II. WAVEFORM REQUIREMENT

The field in the injector synchrotron magnet must rise from 0.045 T (450 MeV) to 0.7 T (at 7 GeV) within 250 ms. If the rate of change of the field remains constant, then after a short initial time, the induced eddy current in the 1-mm thick stainless steel vacuum chamber will be constant. However, because of the shape of the of the vacuum chamber, the field produced due to the eddy currents, has sextupole and 10-pole components as well as the predominant dipole component. At the full field, (7.0 GeV, 0.7 T), the sextupole component from the eddy current constitutes a negligible fraction of the total dipole field, but at the injection level (450 MeV, 0.045 T) it can lead to an unacceptable tune shift in the synchrotron. The inhomogeneous eddy-current field is predicted to be:

$$B = -0.09 r^2 + 20 r^4 \quad (1)$$

where, r is the radius in meters and B is in teslas. At a reference radius of 0.025 m, the sextupole component predominates. At the full field (0.7 T) the sextupole to the dipole components ratio is acceptable, but at the injection level (0.045 T) this ratio is relatively large. If the field rises quadratically with time from 0.045 T at time zero to a level with slope equal to the slope of the linear ramp of 4 A/ms, then the field will be 0.09 T at time 33.5 ms. This will be followed immediately by a linear ramp to 0.7 T at time 250 ms. The ratio of the sextupole to dipole components would start at zero, gradually increase to a maximum at 33.5 ms, and then decrease during the linear ramp. If the field rises quadratically all the way to 0.7 T, then the maximum ratio of the sextupole to dipole will be twice that seen in the case of the linear ramp.

Two different waveforms are considered and are shown in Figures 1 and 2 respectively. In the Figure 1 the current waveform consists of a dc-reset value of 30 A, a ramp section and a recovery section. The injection is done "on the fly". In Figure 2, the current changes from a 30 A dc-reset value to a 60 A injection level via a ramp section. At injection, a parabolic section starts until its slope equals 4 A/ms where the current continues on a linear ramp to the extraction level of 1044 A, followed by the recovery section. The total resistance of the magnets is $R = 594 \text{ m}\Omega$, the total inductance of the magnets $L = 261 \text{ mH}$ and the power supply rating is calculated by the following equation with 10% cable drop allowance:

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$$V = L \frac{di}{dt} + Ri \quad (2)$$

Thus the power supply is rated 1100 A and 1900 V. The maximum deliverable current per millisecond of the power supply at the extraction level is only 4 A/ms. Thus, almost 8 ms is needed to change from 30 A to 60 A level. As shown, in Figure 2 the current starts out quadratically (section 1), followed by a linear ramp (section 2) up to the extraction level 250 ms later. Section 3 starts the recovery phase where the current ramps down to the reset level at about 8 A/ms. This increased rate will leave enough time for the reset period and the transition time to the injection level before the start of the next cycle without exceeding the dynamic capability of the magnet current regulator. About 115 ms are available to share between sections 4 and 6 in any desired ratio.

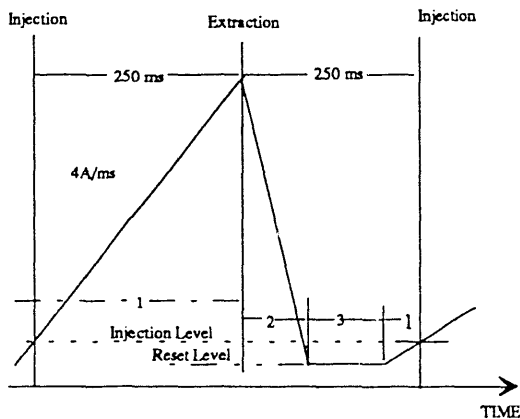


Figure 1 Power Supply Current Output "Injection on the fly"

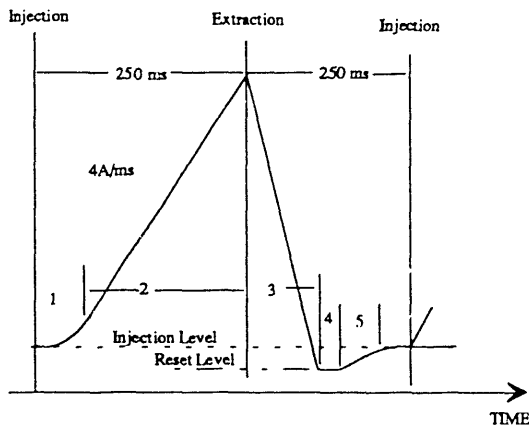


Figure 2 Power Supply Current Output with 60 A Injection Level.

Use of quadratic waveform can produce a smaller but variable sextupole component which may require a complicated correction if its effect still is not negligible. A linear ramp will produce a higher but constant value of the sextupole component which is simpler to compensate.

Based on a recent calculation [2], the horizontal chromaticity due to the eddy currents is +8 units with the natural chromaticity of -15 units. The vertical chromaticity due to the eddy currents is -8 units with the natural chromaticity of -12 units. Both in the horizontal and vertical motions, the higher momentums of the eddy currents will contribute to a tune shift of $10E-3$ at 1% of the momentum, which is considerably larger than the expected momentum. Therefore, a simple current waveform with the "injection on the fly" as shown in Figure 3 can be used.

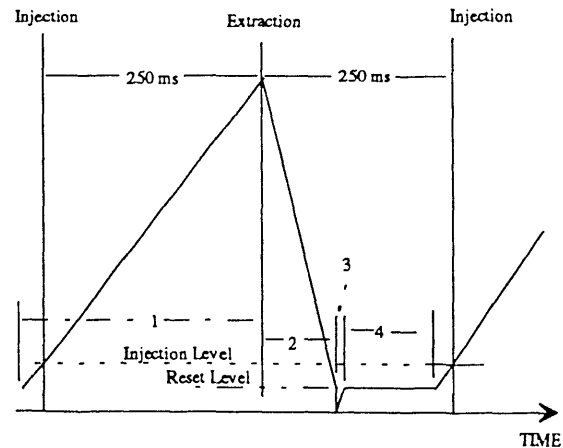


Figure 3 Selected Current Reference for Injector Synchrotron

III. DIGITAL TO ANALOG CONVERTER REFERENCE

The basic analog reference block (ARB) used by almost all the power supplies in the APS project is shown in Figure 4.

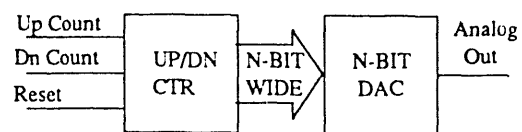


Figure 4 Analog Reference Block

It is seen that the analog output is generated by a digital to analog converter (DAC) fed from the output of an UP/DN counter. Therefore, the analog output can only be changed by counting up or down input pulses. This configuration was chosen to provide a reference block with the following highly desirable features: 1) soft/smooth changes of reference voltage, since counter output can only change by counting pulse inputs, 2) high noise rejection due to the integration effect of the counting process, and 3) a small number of cables between the counter and the remote power supply which simplifies the use of optical coupling, further reducing interference during signal transmission.

A. Reference DAC Specifications

The DAC used in the reference supply is an Analog Device AD1145A with the following specifications:

Resolution	16 bits
Differential & Integral Nonlinearity	1 LSB
Stability (Long Term, ppm FSR/1000 hrs)	0.2
(total drift, 0-50 deg C)	1 LSB
Settling time (1/2 LSB, 10 V step)	6 μ s

B. Waveform Generation for Injector Synchrotron

The generation of the voltage reference waveform used by the synchrotron dipole magnet current regulator is based on the arbitrary function generator (AFG) design used for the injector synchrotron correction magnets [3]. As described earlier, the synchrotron cycle is divided into two main phases of injection/acceleration and extraction/recovery. These phases are further divided into sub-segments as illustrated in Figure 3.

The AFG uses 2K x 9 first-in-first-out (FIFO) memory to store parameters of the desired function. The function is represented by a series of points P (time, pulse ENable) at each pulse of the scan clock. The other parameter associated with each clock tick is the direction information DIR. Hence only 2 bits are required to encode the value of the function at each clock time regardless of the DAC resolution. These two pieces of information are initially calculated in the power supply control unit (PSCU) that services the injector synchrotron dipole power supply, and then loaded into FIFO.

The Pulse ENable (PEN) status and DIR stored in the FIFO are scanned out in synchronism with the injection pulse. These data control the gating and routing of each pulse to the UP/DN counter. In this manner the particular waveform for the acceleration of the beam and recovery of the injector synchrotron dipole magnet is generated.

The ARB and AFG utilize programmable logic devices (PLD) to reduce count and wiring complexity in the hardware. This is expected to improve the reliability of the subsystems. Flexibility in updating the waveform for the acceleration phase is built into AFG. The update process itself is transparent to but in sync with the synchrotron cycle.

As mentioned earlier, two injection strategies are being considered for use: 1) injection "on the fly" at the initial linear ramp following a parabolic field rise starting at a dc reset level of about 30 A; 2) injection from a resting dc-level into a quadratically rising field for the initial portion of the acceleration phase followed by a linear ramp to full energy at extraction. Extraction occurs at the same energy level in both cases. In the second method the sum of the dwell times at the reset level, and the injection level plus the transition time between them, approximately equals the reset level dwell time in the first method. The advantage of the second method is its essentially zero value of the undesirable field components at injection time. This field is due to the

vacuum chamber eddy currents induced when acceleration occurs. The advantage of the first method is the simpler waveform required to generate the accelerating field. Except for the field states at injection (resting dc field for the first method versus dynamic ramping field for injection on the fly) and the short time for transition from reset level to dc resting level of the second method, the waveform for the rest of the synchrotron cycle is the same for both methods.

Results of later calculations [2] have shown that the effects of the eddy currents in beam injection are not as bad as earlier feared. Therefore, the simpler method of "injection on the fly" is the strategy that will be used.

C. SEGMENTS OF WAVEFORM

Segment 1 - Linear Ramp: This segment starts about 40 ms before the injection pulse from the nominal reset level of 30 A, rising at an average rate of 4 A/ms until extraction time, 250 ms after injection. Injection is about 60 A.

Segment 2 - Main Recovery: After beam extraction, the field is taken down to the value referred to as the reset level (about 30 A). The average rate of field decrease is about twice the acceleration rate in order to leave time for the other segments in the recovery phase.

Segment 3 - Return Reset: The UP/DN counter of the ARB is quickly reset to zero to provide a known absolute value of reference for the DAC and the counter. Error in pulse count from any source is therefore removed every cycle. The counter is then quickly pulsed to the reset level count. Since these pulses are high frequency and the count is small, the magnet current regulator essentially does not have sufficient time to react to the momentary change before the reference voltage is back at the reset level.

Segment 4 - Reset Dwell This is a time interval where the field is held at a steady value, the reset level. This level is adjustable to enable the operator to optimize the field. This process helps to produce stable and repeatable field patterns.

IV. CONCLUSION

The effect of the vacuum chamber eddy currents on the dipole field was discussed and it was noticed that the sextupole field is the dominant undesirable component. Several alternatives to correct the sextupole effect were examined. It was concluded that using a quadratic waveform can produce a smaller but varying sextupole components which may require a complicated correction if its effect still is not negligible. However, a linear ramp will produce a higher but constant value of the sextupole component which can be corrected in simpler fashion. Thus, the "injection on the fly" method using a linear ramp that starts from an adjustable reset level and ramps to the extraction level was selected.

V. REFERENCES

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