Power Supplies for the Ring Magnets of the Synchrotron X-Ray Source at ANL*

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Abstract: For the storage ring (SR) a stability of ±10 ppm is required for the main bending and focusing magnets; for the correction magnets, the requirements range from ±100 ppm for sextupole to 300 ppm for dipole magnets. The main dipole magnets are connected in series and energized from a 12-phase power supply. All other magnets have individual pulse-width-modulated (PWM) power supplies. The load of the 1436 PWM power supplies on the ac line is distributed as evenly as practicable. For the power supplies of the bending and focusing magnets of the injector synchrotron, stringent requirements are met for flat injection and ejection currents and for current tracking during acceleration.

Introduction

The main bending magnets of the SR are connected in series and energized from one 1.2-MW, 12-phase power supply. For maximum flexibility in adjusting the lattice functions, all other magnets are energized from individual power supplies.[1] For the multipole magnets, the power supplies are unidirectional for the correction dipoles, they are bipolar. Table 1 lists the power supplies and their performance; storage ring magnet parameters are given in Ref. [2]. The current regulation includes effects due to normal power-line fluctuations, load variations, component drifts, and temperature coefficients over the range from 10° to 40° C. The aluminum vacuum chamber[3] of the storage ring is an effective low pass filter.[4] Eddy current shielding attenuates vertical ripple fields above 8 Hz by 6 dB/octave; horizontal ripple fields are attenuated above 25 Hz at the same rate. Because of this filtering effect, the ripple specifications for the power supplies are much less demanding than the stability requirements. An 81st dipole magnet, located outside the storage ring and connected in series with the storage ring magnets, is used to monitor the field with a nuclear magnetic resonance probe. There will be 20 three-phase 2400 V/460 V, 600 kVA, power distribution transformers spaced uniformly around the periphery of the ring to provide ac power for the PWM power supplies.

The ring magnets of the injector synchrotron are pulsed at a 1-Hz repetition rate. The stainless steel vacuum chamber of the synchrotron does not attenuate the predominent power supply ripple frequency of 720 Hz appreciably. Table 2 lists the power supplies and their performance.

All power supplies are shown for 7.7 GeV operation.

Storage Ring Power Supplies

Main Dipole Power Supply: Power supplies with a true current regulation of 10 ppm and power ratings up to 2 MW are commercially available.[5] Having only one power supply for 81 magnets reduces cost as compared to multiple feedpoints. The voltage to ground of ≤ ±1050 V causes current leaks through the cooling water paths. Magnet unbalances caused by these leakage currents are compensated with the dipole trim coils. The magnet cooling water inlet temperature is regulated for 32° C ± 1.1° C. The corresponding dimensional changes of the dipole (~ 12 ppm/°C) do not change ∫Bdl; the changes in gap heights are compensated by equal changes in magnet length.

Table 1

Magnet Circuit	No. of Units	Rating I (A)	Rating V (V)	Rating P (kW)	ΔI/Imax Stability	ΔI/Imax Reproducibility	ΔI/Imax Current Ripple	ΔI/Imax Tracking Error	Ref. Resol. (bit)
Main Dipole	1	570	2100	1200	$\pm 1\times10^{-5}$	$\pm 4\times10^{-5}$	$\pm 5\times10^{-5}$	$\pm 1\times10^{-4}$	18
Trim Dipole	80	60	± 16	1.0	$\pm 3\times10^{-4}$	$\pm 6\times10^{-4}$	$\pm 1\times10^{-2}$	$\pm 5\times10^{-4}$	13
Quad., 0.5 m	240	500	18	9.0					
Quad., 0.6 m	80	500	21	10.5	$\pm 1\times10^{-5}$	$\pm 4\times10^{-5}$	$\pm 2\times10^{-3}$	$\pm 2\times10^{-4}$	17
Quad., 0.8 m	80	500	27	13.5					
Sextupole	280	235	28	6.6	$\pm 1\times10^{-4}$	$\pm 3\times10^{-4}$	$\pm 2\times10^{-3}$	$\pm 4\times10^{-4}$	14
V-Corr.Sex.Dip.	280	125	± 26	3.3					
H-Corr. Dip.	240	15	± 51	0.8	$\pm 3\times10^{-4}$	$\pm 6\times10^{-4}$	$\pm 1\times10^{-2}$	$\pm 5\times10^{-4}$	13
H&V Corr Dipole	78H	150	± 15	2.3					
	78V	130	± 20	2.6					

Table 2

Magnet Circuit	Units	I_{max} (A)	V_{max} (V)	P_{max} (kW)	P_{rated} (kW)	ΔI/Imax Reproducibility	ΔI/Imax Current Ripple	ΔI/Imax Tracking Error	Ref. Resol. (bit)
Dipoles	2	650	+4600 / -3600	2990	664	$\pm 1\times10^{-4}$	$\pm 2\times10^{-4}$	$\pm 5\times10^{-4}$	15
Quadrupoles	2	760	+ 670 / - 500	510	235	$\pm 1\times10^{-4}$	$\pm 2\times10^{-4}$	$\pm 5\times10^{-4}$	15
Sextupoles	2	245	+1090	267	44	$\pm 2\times10^{-4}$	$\pm 3\times10^{-4}$	$\pm 1\times10^{-4}$	14
H&V Corr.Mag.	80	±30	± 15	0.45	±0.5	$\pm 1\times10^{-3}$	$\pm 1\times10^{-3}$	$\pm 5\times10^{-3}$	12

*This work is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

Quadrupole and Sextupole Power Supplies: A total of 680 unidirectional power supplies having power ratings from 6.6 to 13.5 kW are required. Two types of high-frequency (HF) PWM power supplies are being considered. The first, a dc-dc converter, uses a solid-state switch to interrupt the current at frequencies above the audio range and regulates by varying the ratio of the on-to-off time.[1] Power supplies of magnets with similar voltage ratings are energized from a common dc source, as shown in Fig. 1a. A monotonic digital-to-analog converter (DAC) is the reference for the current regulator, which obtains its feedback from a precision current transductor (CT). Fast changes in the dc bus voltage are corrected by an inner voltage loop controlled by the current loop. The switch stays closed until the current exceeds the value called for by the DAC. The current then decays through the diode with the L/R time constant of the magnet until it falls below the value set at the DAC. This causes closure of the switch, and the above cycle repeats. Figure 1b shows the variations of switching frequency versus dc input voltage for various current ripple parameters.[6] At ~ 20 kHz, eddy currents in the vacuum chamber attenuate vertical ripple fields by 68 dB and horizontal fields by 58 dB[4], therefore, no separate ripple filter is required. The pulse load on the line is distributed by arranging the power supplies into smaller groups and by phase-shifting the clock frequency of the PWM of these groups.

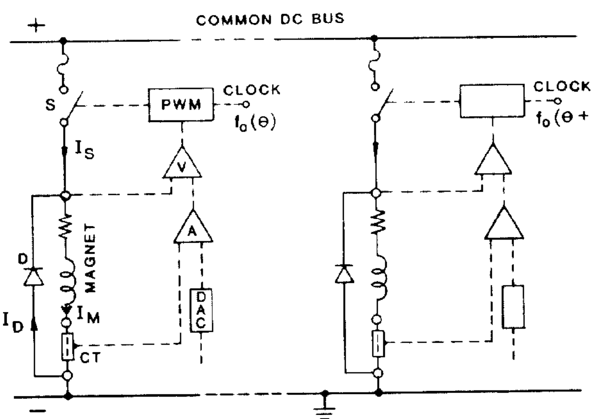

Fig. 1a. PWM DC Power Supply.

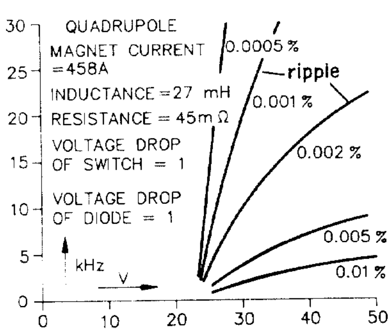

Fig. 1b. Switching Frequency vs DC Input Voltage for Various Percentages of Ripple Currents.

The second type of PWM power supply, a dc-ac-dc converter, uses series-resonant circuits; the spacing between sine waves is controlled. The transformer provides electrical isolation and the dc bus voltage can be higher and the switching current correspondingly lower than the magnet current and voltage. As shown in Fig. 2, the circuits consist of half- or full-wave bridges driving the primary of an HF transformer.[7],[8],[9] On the transformer secondary is a full-wave rectifier to which the magnet load is connected. Thyristors or transistors may be used as switching elements.

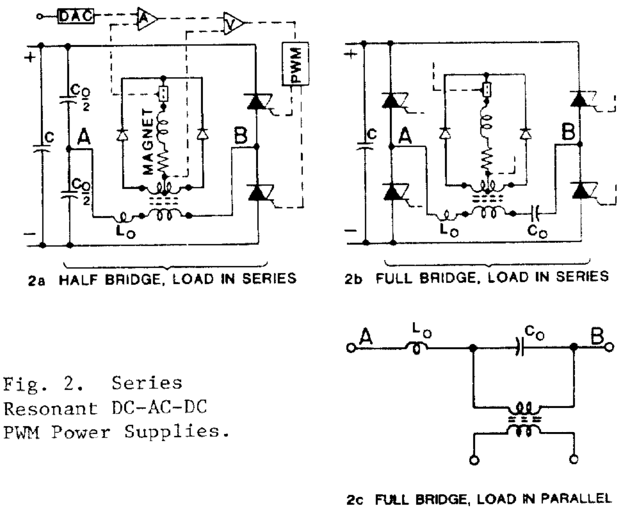

Fig. 2. Series Resonant DC-AC-DC PWM Power Supplies.

Correction Magnet Power Supplies: A total of 756 power supplies are required with power ratings of 0.8 kW to 3.3 kW. The need for smooth control of the current through zero requires bipolar supplies. Linear amplifiers with push-pull output stages are used for loads ≤ 1 kW. For the larger loads, bipolar converter circuits are considered. They operate at frequencies between 20 and 50 kHz and use, as switching elements, power transistors and diodes or reverse conducting thyristors (RCTs). Figure 3 shows a block diagram of one possible bipolar power supply system. Twenty 100-kW dc power supplies are provided uniformly spaced around the SR periphery for a total of 280 vertical correction magnets. Each of these dc sources energizes 14 half-bridge HF resonant inverters. The inverter output is connected to two pairs of phase-controlled full-wave rectifier circuits. The polarity of the current is determined by which pair of rectifiers is selected, the magnitude by changing the phase delay α on the selected thyristor pair.

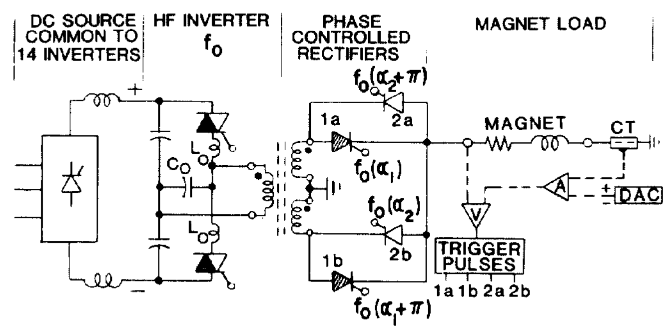

Fig. 3. Bipolar DC-AC-DC Power Supply

The principle of the one-quadrant converter of Fig. 1 can be applied to two-quadrant operation as shown in Fig. 4. For positive magnet current, Q_1 and Q_2 are turned on. When Q_1 is turned off, the current decays through the still turned-on Q_2 and D_1. For current control in the negative direction, Q_3, Q_4, and D_2 are used in a similar fashion.[6]

High Precision Current Control: For a precision of several ppm of full scale, each power supply control loop is placed in an oven in which the

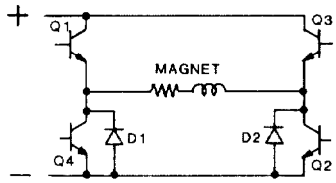

Fig. 4 Bipolar DC-DC Power Supply.

temperature is maintained within ≤ .5° C. The high gain, high stability, low noise input amplifier of this control loop receives an input signal that is the difference of the reference voltage V_r (magnet current value set with a DAC) and a voltage V_i which is proportional to the magnet current. The cost of the reference voltage and the current measuring device is a major part of the total price of the PWM power supplies. Commercially available high precision zero-flux CT's will measure the magnet currents.

Synchrotron Ring Power Supplies

Dipole Power Supply: Two identical 12-phase power supplies will energize the chain of 64 dipoles from feed points 180° apart. The desired voltage and current shapes are produced by rectifier phase control of the 12-phase system, with a regulator comprising current and voltage feedback loops. Figure 5 shows current and voltage shapes of one power supply for two operating conditions, together with a block diagram. In Fig. 5a, the injection and extraction times are nominally 1/6 s. These times can be increased, without changing the pulse repetition rate, by shortening the current decay time by means of rectifier phase control as illustrated by Fig. 5b. The injection current is only 7.6% of maximum magnet current. At this low current level, the current stability, ripple, and reproducibility are degraded. Therefore, a separate 150-V, 50-A dc power supply, regulated to 0.01%, is used during injection. At the start of acceleration, the main power supply output voltage of 1674 V back-biases the silicon controlled rectifiers (SCRs) in series with the injection power supply. After flat-top, when the current has decayed to close to the injection level, i.e., 46 A, the trigger pulses to the power supply SCRs are set for zero output voltage and the crowbar SCRs, in parallel with the power supply filters, are turned on to discharge the filter capacitors. This causes the magnet current to decay exponentially, reaching the injection level of 42 A after ~ 23 ms. The injection current is maintained by turning on the SCRs in series with the injection power supply. During standby, the injection power supply operates into a light-load resistor in parallel with a low-inductance capacitor bank, both operating at the injection voltage of 138.1 V.

Quadrupole Power Supply: Two 12-phase power supplies are provided. One will energize 36 focusing magnets, the other 36 defocusing magnets. Except for the power rating, the power supply circuit is similar to the one shown for the dipole power supply.

Sextupole Power Supply: Two identical 12-phase power supplies are used to energize the two strings of sextupoles. Since the regulation requirements are not very stringent, no separate injection power supply is needed.

Correction Magnet Power Supply: A total of 80 bipolar ≤ 500-W power supplies are provided, they are commercially available.

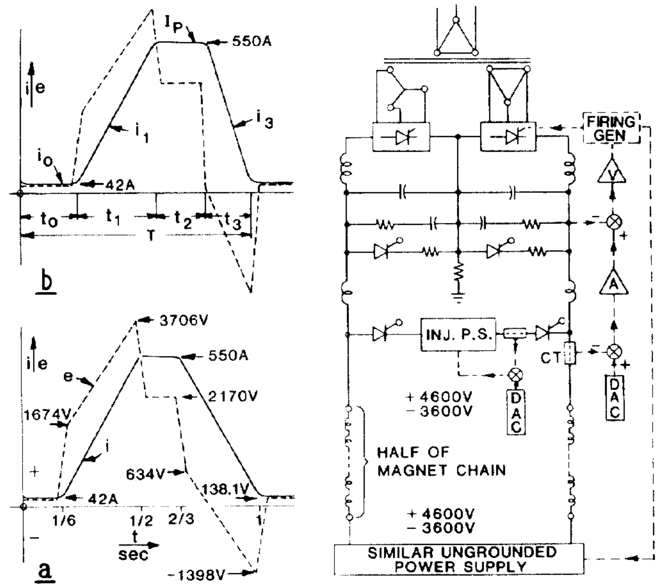

Fig. 5. Dipole Power Supply.

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