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STATUS OF MAGNET POWER SUPPLY DEVELOPMENT FOR THE APS STORAGE RING*

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Abstract

To simplify installation and speed testing of the Advanced Photon Source (APS) storage ring magnets, vacuum chambers and magnet power supplies, a modular approach was developed. All but the dipole magnets are independently controlled. Pulse width modulated dc-to-dc converters are used to power the individual magnets, with 12-pulse power supplies providing the raw dc to the converters. A magnet support base is the heart of a module and may hold as many as 7 magnets with 8 individually powered coils. The dc-to-dc converters are part of each magnet base module. This paper will show the modular approach which is used for the storage ring magnet systems and will give the test results of the prototype topology for the dc-to-dc converters that are being built and tested to power 680 quadrupole and sextupole magnets.

Introduction

There will be 200 magnet/power supply modules in the storage ring. A typical module is shown in Fig. 1. This module will consist of a magnet base, magnets, water lines/headers, dc-to-dc converters, a control microprocessor and 4 sets of dc bus. The module will be completely assembled with magnets, vacuum chambers and dc-to-dc converters such that it needs only connections to 4 dc sources, main water lines, 115 V ac control power and the communications cable to the microprocessor to operate the magnets. When assembled, each module will be connected to a test stand where all magnets will be operated for 8 hours, 4 hours operating at rated power and 4 hours with each magnet's settings changing randomly. Once this test run is complete, the modules will be stored until installation into the storage ring.

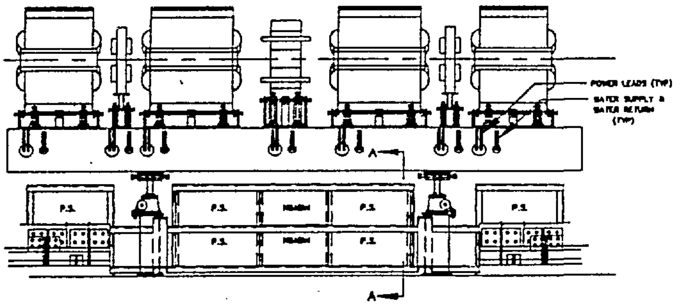

Fig. 1

The APS storage ring is made up of 40 sectors. Five modules make up 1 sector, with the dc bus and water lines connected in series from magnet base to magnet base for the sector's length. Two sectors are connected in parallel to 4 dc sources. This is repeated 20 times around the ring.

Due to their small profile, switch-mode power converters allow the use of the modular approach. A prototype unidirectional switch-mode dc-to-dc power converter is being constructed and tested at ANL to power each of the 680 quadrupole and sextupole magnets in the storage ring. The only differences in the converter for the quadrupoles and sextupoles are the digital-to-analog converter used for reference, the current transductor and the switching elements. The topology chosen for unidirectional converters has the least part count but requires full current switching. The storage ring vacuum chamber[1] is an effective low pass filter.[2] Eddy current shielding attenuates vertical ripple fields above 8 Hz by 6 dB/octave, and horizontal ripple fields are attenuated above 25 Hz at the same rate. Because of this filtering effect, the ripple specifications are much less demanding than the stability requirements at the converter's operating frequency. The less stringent requirement for ripple current allows the use of unregulated dc power supplies, as shown in Fig. 2.

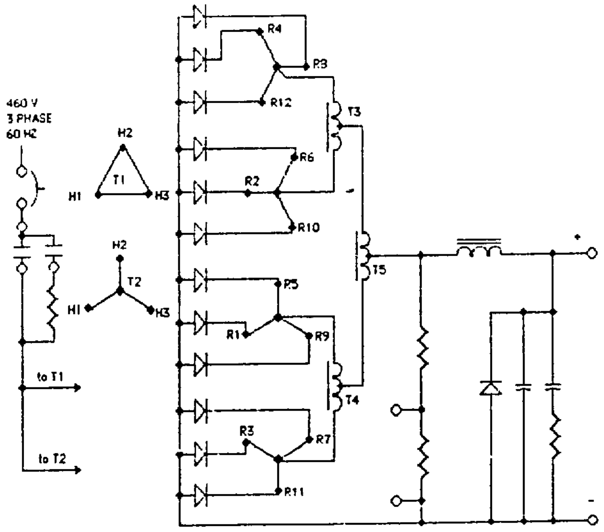

Fig. 2

Raw dc Power Supply

The unregulated 12-pulse dc power supply's output voltage was chosen to be equal to 2 times the magnet's IR drop (at rated current) plus 20% for losses and line voltage functions. There are 9 different types of magnet loads to be powered from these power supplies. These loads were grouped through an iterative process, where the highest voltage calculated above was used to calculate a current step change in each of the other magnets, and these current steps compared with the allowable ripple current. If they were less, they were grouped on one raw power supply; if more, the process was repeated with the remaining magnets until they were all grouped, thus setting the number and voltage of raw power supplies. The power supply configuration shown in Fig. 2 gives the minimum rectifier losses. As operation will be with output currents of 1000 to 5000 A, the difference in losses for this circuit over a full-wave-bridge for the 80 power supplies in the storage ring will be approximately 240 kW.

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DISCLAIMER

dc Bus Filter

This filter is designed to minimize the dc bus voltage fluctuations and current fluctuations on the ac mains.[3]

dc-to-dc Converter

Two types of dc-to-dc converters will be used to power the 1436 multipole and correction magnets in the storage ring. They are converters with unidirectional or bidirectional outputs. Table 1 shows the specifications for the storage ring magnet power supplies. Unidirectional circuits are used to power the quadrupoles, sextupoles and the correction magnets' bidirectional circuits. The unidirectional circuit is shown in Fig. 3, and the bidirectional circuit is shown in Fig. 4. Both function in the same manner, except that the bidirectional circuit can reverse polarity when the magnet current reaches zero. The basic operation of both circuits is shown in Figs. 5 and 6. There are 2 regulator loops, which are both current loops: one using a fast hall plate current transductor[4], and the other using a slow current transformer. The current transformer has a small signal bandwidth of 10 kHz and overall stability of a few p.p.m. This allows us to meet the quadrupole stability requirements of $\pm 3\mathrm{x}10^{-5}$ listed in Table 1. The hall plate current transductor shown in Fig. 7 has a small signal bandwidth of $\geq$500 kHz. This allows the use of pulse width modulation (PWM) to regulate the dc-to-dc converters. In an effort to uniformly load the dc source bus, the converters will be synchronized with clock pulses from the module's microprocessor. If the bus is uniformly loaded, the rms current will decrease to approximately the average current, thus increasing the efficiency.

Table 1 Magnet Power Supplies for Storage Ring

	Rating								Regulation $\Delta I/I_{max}$				
Magnet Circuit	No. of P.S.	I (A)	No. of Magnets	Resistance of Magnet	Inductance of Magnet	V (V)	P (kW)	Σp	Stability	Reproducibility	Current Ripple*	Tracking Error	Resolution of Reference (bit)
Main Dipole	1	549	81	0.038	0.051	1835	1006.6	1006.6	$\pm 3\mathrm{x}10^{-5}$	$\pm 5\mathrm{x}10^{-5}$	$\pm 4\mathrm{x}10^{-4}$	$\pm 1\mathrm{x}10^{-4}$	17
Trim Dipole	80	60	80	0.234	0.016	15	0.9	73.2	$\pm 3\mathrm{x}10^{-4}$	$\pm 6\mathrm{x}10^{-4}$	$\pm 1\mathrm{x}10^{-2}$	$\pm 7\mathrm{x}10^{-4}$	13
Quadrupole, 0.5m	240	458	240	0.03	0.017	15	6.9	1661.3	$\pm 3\mathrm{x}10^{-5}$	$\pm 5\mathrm{x}10^{-5}$	$\pm 2\mathrm{x}10^{-3}$	$\pm 2\mathrm{x}10^{-4}$	17
Quadrupole, 0.6m	80	458	80	0.035	0.02	18	8.1	646.1	$\pm 3\mathrm{x}10^{-5}$	$\pm 5\mathrm{x}10^{-5}$	$\pm 2\mathrm{x}10^{-3}$	$\pm 2\mathrm{x}10^{-4}$	17
Quadrupole, 0.8m	80	458	80	0.044	0.027	22	10.2	812.2	$\pm 3\mathrm{x}10^{-5}$	$\pm 5\mathrm{x}10^{-5}$	$\pm 2\mathrm{x}10^{-3}$	$\pm 2\mathrm{x}10^{-4}$	17
Sextupole	280	214	280	0.098	0.036	23	4.9	1382.3	$\pm 3\mathrm{x}10^{-4}$	$\pm 6\mathrm{x}10^{-4}$	$\pm 2\mathrm{x}10^{-3}$	$\pm 7\mathrm{x}10^{-4}$	13
Sextupole Dipole V-Correction	280	125	280	0.187	0.009	26	3.2	896.2	$\pm 3\mathrm{x}10^{-4}$	$\pm 6\mathrm{x}10^{-4}$	$\pm 1\mathrm{x}10^{-2}$	$\pm 5\mathrm{x}10^{-4}$	13
Dipole H-Correction	240	99	240	0.12752	0.0122	14	1.4	332.3	$\pm 3\mathrm{x}10^{-4}$	$\pm 6\mathrm{x}10^{-4}$	$\pm 1\mathrm{x}10^{-2}$	$\pm 7\mathrm{x}10^{-4}$	13
Dipole H & V Correction (H)	78	148	78	0.095	0.003	19	2.4	187.1	$\pm 3\mathrm{x}10^{-4}$	$\pm 6\mathrm{x}10^{-4}$	$\pm 1\mathrm{x}10^{-2}$	$\pm 7\mathrm{x}10^{-4}$	13
(V)	78	128	78	0.133	0.004	15	2.3	178.4	$\pm 3\mathrm{x}10^{-4}$	$\pm 6\mathrm{x}10^{-4}$	$\pm 1\mathrm{x}10^{-2}$	$\pm 7\mathrm{x}10^{-4}$	13

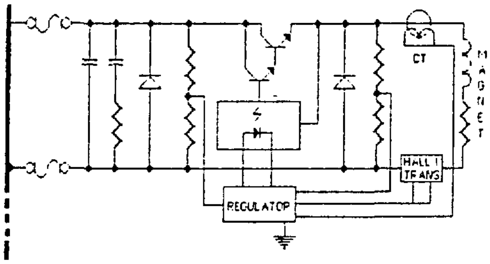

Fig. 3

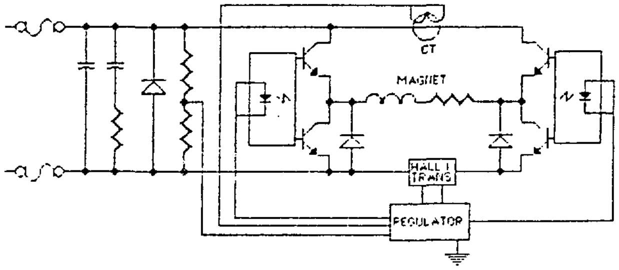

Fig. 4

Current Regulator Circuits

Since the dc-to-dc converters are PWM, the regulator operates by turning the switching element on or off to maintain the magnet current. The current regulator is composed of 2 error loops, a 14- or 18-bit, digital-to-analog converter (DAC) and a clock synchronization circuit. The first error loop uses a hall current transductor for feedback, and the second loop uses a high-precision current transformer. This differs from the normal unidirectional phase-controlled or series-pass-regulated power supply, which has a fast voltage and a slow current loop. However, because the voltage across the magnet is either the freewheeling diode drop or the raw dc source voltage,

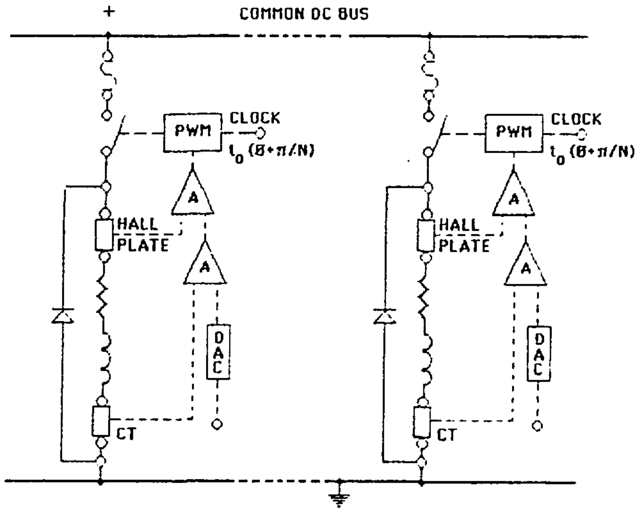

Fig. 5

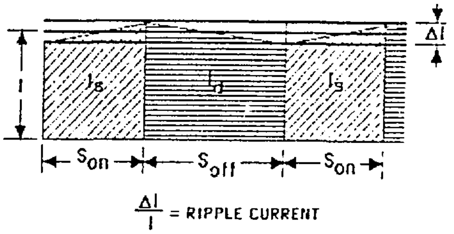

Fig. 6

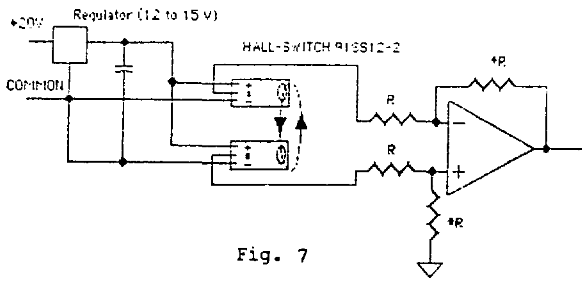

Fig. 7

it doesn't represent the magnet current, due to the nonlinearity of the freewheeling diode at low currents. In the case of a short circuit on the output of the converter, the voltage loop would call for more current until the slower current transformer indicates overcurrent and trips the interlock, shutting the converter down. A short circuit case is worse in this topology, because the circuit inductance is kept low for the full current switching . The voltage across the diode will be monitored for polarity, reversing at zero current in the bidirectional converters.

Four possible regulator topologies are being constructed and tested, all having 20-kHz square-wave clock signals from the module's microprocessor. The simplest regulator, shown in Fig. 8, turns on, if at all, when the clock signal goes positive, and stays on until the clock signal goes negative. The second regulator, shown in Fig. 9, turns on when the clock signal goes positive and stays on until either the clock signal or error amplifier goes negative. The third regulator, shown in Fig. 10, turns on any time during the positive clock cycle and stays on until the clock signal goes negative. The fourth regulator, shown in Fig. 11, turns on any time after the clock signal goes positive and stays on until either the clock signal or error amplifier goes negative.

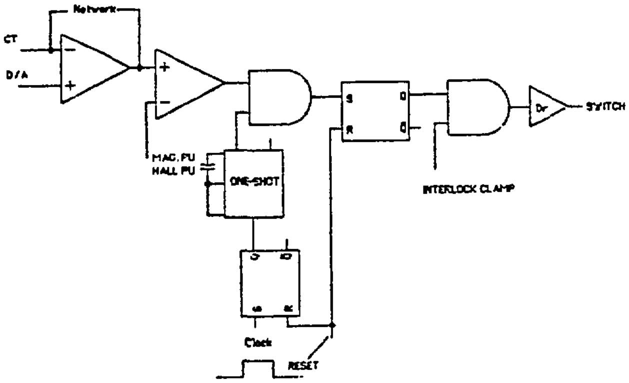

Fig. 8

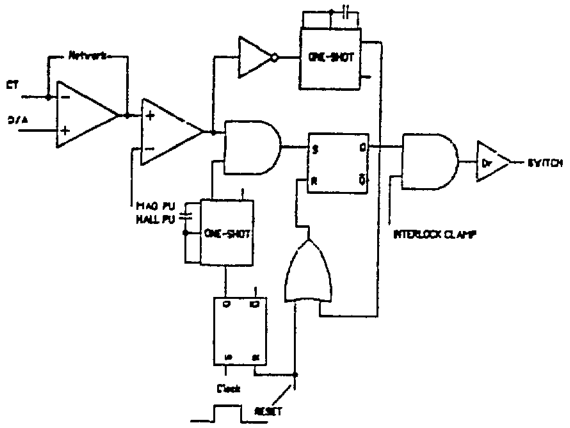

Fig. 9

Conclusions

1. The magnet/power supply modules for the storage ring will speed installation, improve testing, allow for correction of problems on the test pad where materials are close at hand, and reduce the congestion in the ring tunnel during installation.

2. The simple ac-to-dc converters (power supplies) will improve system reliability.

3. The aluminum vacuum chambers attenuate the ripple currents but also reduce the effective inductance of the magnet, thereby increasing the ripple current. At the operating frequency of the converters, the net effect is to improve the signal-to-noise ratio and attenuation of field ripple inside the vacuum chamber.

References

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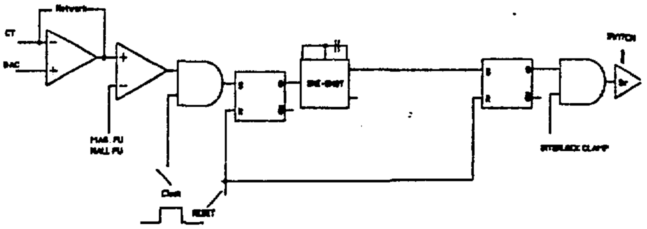

Fig. 10

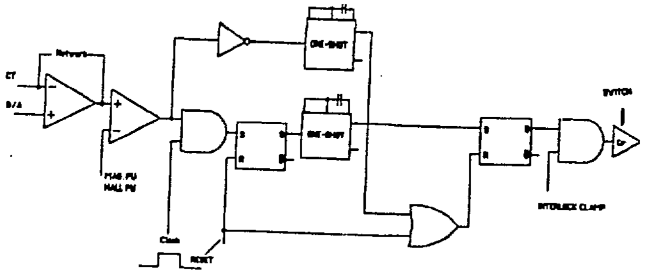

Fig. 11