# 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.
Tne 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
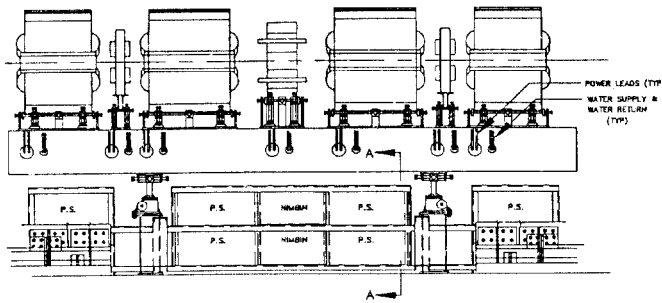shown in Fig. 1. This module will consist of a magnet



Fig. 1

base, magnets, water lines/headers, dc-to-dc conver-
ters, 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.

The APS storage ring is made up of 40 sec-
tors. 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 switch-
ing 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 strin-
gent requirement for ripple current allows the use of
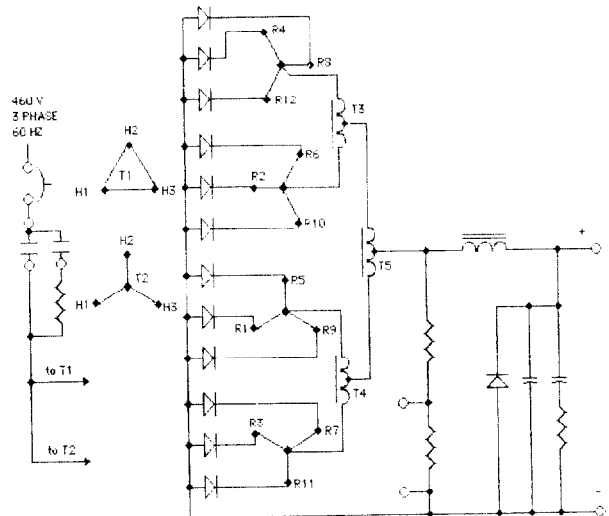unregulated dc power supplies, as shown in Fig. 2.



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 los-
ses 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 itera-
tive 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.

## 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

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.

## 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

Table 1  Magnet Power Supplies for Storage Ring

| | | | | Rating | | | | | Regulation ΔI/Imax | | | | Resolution of Reference (bit) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | |
| Main Dipole | 1 | 549 | 81 | 0.038 | 0.051 | 1835 | 1006.6 | 1006.6 | $\pm 3 \times 10^{-5}$ | $\pm 5 \times 10^{-5}$ | $\pm 4 \times 10^{-4}$ | $\pm 1 \times 10^{-4}$ | 17 |
| Trim Dipole | 80 | 60 | 80 | 0.234 | 0.016 | 15 | 0.9 | 73.2 | $\pm 3 \times 10^{-4}$ | $\pm 6 \times 10^{-5}$ | $\pm 1 \times 10^{-2}$ | $\pm 7 \times 10^{-4}$ | 13 |
| Quadrupole, 0.5m | 240 | 458 | 240 | 0.03 | 0.017 | 15 | 6.9 | 1661.3 | $\pm 3 \times 10^{-5}$ | $\pm 5 \times 10^{-5}$ | $\pm 2 \times 10^{-3}$ | $\pm 2 \times 10^{-4}$ | 17 |
| Quadrupole, 0.6m | 80 | 458 | 80 | 0.035 | 0.02 | 18 | 8.1 | 646.1 | $\pm 3 \times 10^{-5}$ | $\pm 5 \times 10^{-5}$ | $\pm 2 \times 10^{-3}$ | $\pm 2 \times 10^{-4}$ | 17 |
| Quadrupole, 0.8m | 80 | 458 | 80 | 0.044 | 0.027 | 22 | 10.2 | 812.2 | $\pm 3 \times 10^{-5}$ | $\pm 5 \times 10^{-5}$ | $\pm 2 \times 10^{-3}$ | $\pm 2 \times 10^{-4}$ | 17 |
| Sextupole | 280 | 214 | 280 | 0.098 | 0.036 | 23 | 4.9 | 1382.3 | $\pm 3 \times 10^{-4}$ | $\pm 6 \times 10^{-4}$ | $\pm 2 \times 10^{-3}$ | $\pm 7 \times 10^{-4}$ | 13 |
| Sextupole Dipole V-Correction | 280 | 125 | 280 | 0.187 | 0.009 | 26 | 3.2 | 896.2 | $\pm 3 \times 10^{-4}$ | $\pm 6 \times 10^{-4}$ | $\pm 1 \times 10^{-2}$ | $\pm 5 \times 10^{-4}$ | 13 |
| Dipole H-Correction | 240 | 99 | 240 | 0.12752 | 0.0122 | 14 | 1.4 | 332.3 | $\pm 3 \times 10^{-4}$ | $\pm 6 \times 10^{-4}$ | $\pm 1 \times 10^{-2}$ | $\pm 7 \times 10^{-4}$ | 13 |
| Dipole H & V Correction (H) | 78 | 148 | 78 | 0.095 | 0.003 | 19 | 2.4 | 187.1 | $\pm 3 \times 10^{-4}$ | $\pm 6 \times 10^{-4}$ | $\pm 1 \times 10^{-2}$ | $\pm 7 \times 10^{-4}$ | 13 |
| (V) | 78 | 128 | 78 | 0.133 | 0.004 | 15 | 2.3 | 178.4 | $\pm 3 \times 10^{-4}$ | $\pm 6 \times 10^{-4}$ | $\pm 1 \times 10^{-2}$ | $\pm 7 \times 10^{-4}$ | 13 |

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
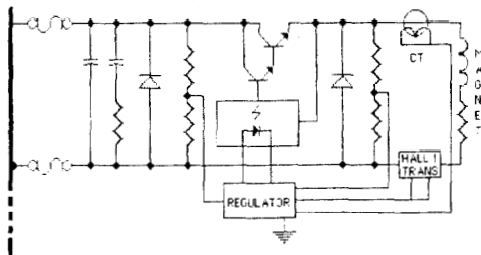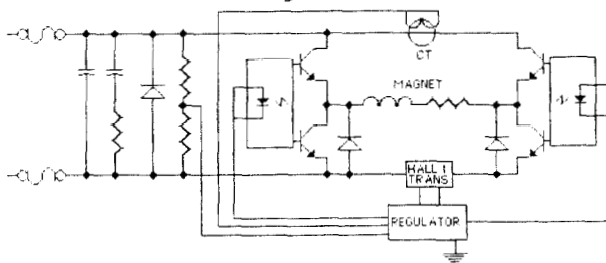


Fig. 3



Fig. 4

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 $\pm 3 \times 10^{-5}$ 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

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
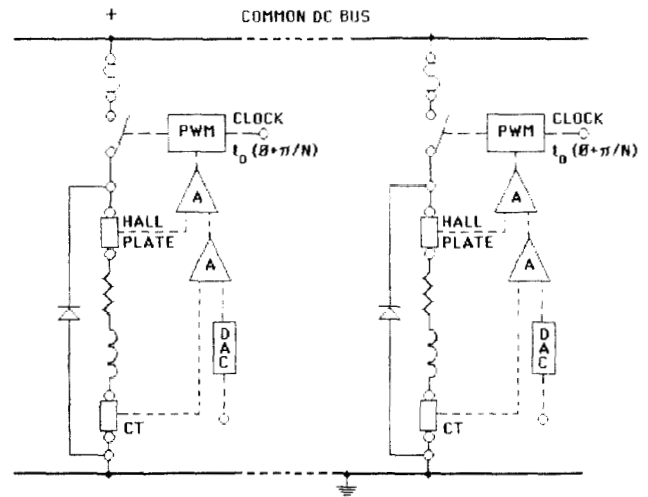


Fig. 5
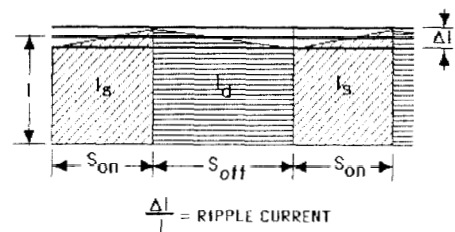


$\dfrac{\Delta I}{I}$ = RIPPLE CURRENT

Fig. 6

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,
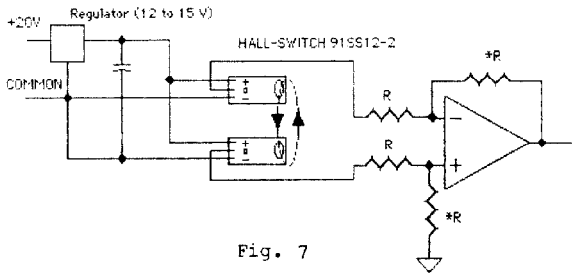
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Fig. 7

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.

## 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

1. R. Wehrle et al., "Ring Magnets for the Synchrotron X-Ray Source at Argonne," Particle Accelerator Conference (March 1987).

2. W. Praeg, "Frequency Response of SR Ring Magnets, Eddy Current Shielding of Vacuum Chamber," ANL Light Source Note LS-45 (Dec. 1985).

3. W. Praeg, "A High-Current Low-Pass Filter for Magnet Power Supplies," IEEE Trans. on Industrial Electronics and Control Instrumentation, Vol. IECI-17, No. 1 (Feb. 1970).

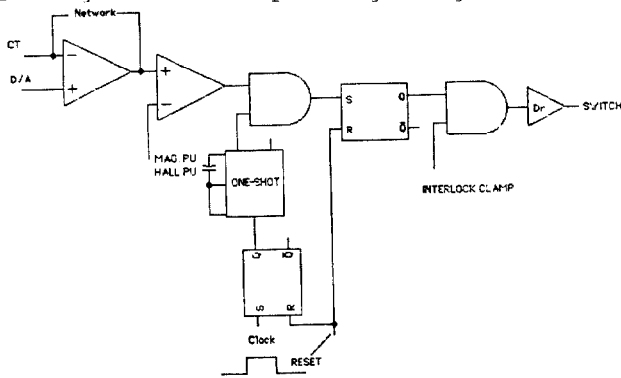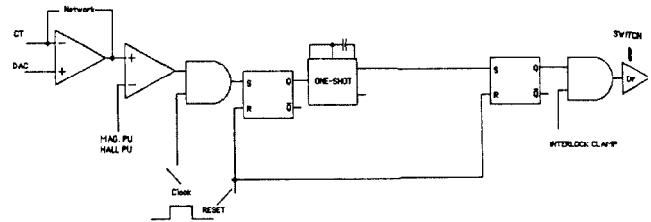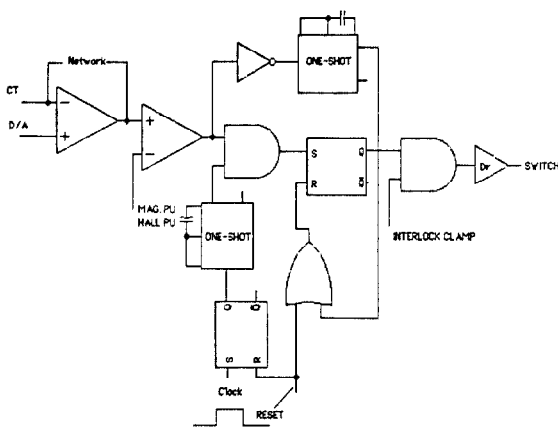4. W. Ripple, "A High Performance, Integrable Current Sensor," SATECH Conference (Sept. 1987).

Fig. 8



Fig. 10



Fig. 9



Fig. 11