MBA Fast Corrector Power Supply Development

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* No longer with APS
Outline

- Power supply requirement for the APS-U
- Technical requirement and challenges
- Choice of power circuit and regulation algorithm
- Prototype design
- Initial test results
Scope of APS-U Storage Ring Power Supplies

- 2082 power supplies for the APS-U magnets
  - Two large power supplies up to 1000A for L-bend (M1/M2) dipole magnets
  - One thousand 10 ppm stability-class and 230A unipolar DC power supplies for Q-bend (M3/M4) dipole, quadrupole, and sextupole magnets
  - 760 ±15A DC bipolar power supplies for trim/correction and skew quad coils
  - 320 ±15A bipolar power supplies for fast correctors

- 400 power supply controllers
  - 200 Unipolar power supply controllers
  - 200 Bipolar power supply controllers

- Pre-installation test
  - All the power supplies and the power supply controllers will be 100% tested in a temperature-elevated environment before the installation starts

New SR requires 2082 power supplies and 400 power supply controllers. All need to be pre-tested and ready before shutdown starts.
## Fast Corrector PS Specifications and Parameters

<table>
<thead>
<tr>
<th>Specifications/Design Parameters</th>
<th>Fast Corr PS</th>
<th>Exiting PS*</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximun operating current</td>
<td>±13</td>
<td>±150</td>
<td>A</td>
</tr>
<tr>
<td>Maximun output voltage</td>
<td>40</td>
<td>40</td>
<td>V</td>
</tr>
<tr>
<td>Maximun output power</td>
<td>0.52</td>
<td>6</td>
<td>kW</td>
</tr>
<tr>
<td>Current stability (AC RMS)</td>
<td>TBD</td>
<td>300</td>
<td>ppm</td>
</tr>
<tr>
<td>Initial accuracy after installation</td>
<td>100</td>
<td></td>
<td>ppm</td>
</tr>
<tr>
<td>Magnet-to-magnet repeatability</td>
<td>100</td>
<td>700</td>
<td>ppm</td>
</tr>
<tr>
<td>Reproducibility after shutdown</td>
<td>10</td>
<td>600</td>
<td>ppm</td>
</tr>
<tr>
<td>Small-signal -3dB bandwidth</td>
<td>10</td>
<td></td>
<td>kHz</td>
</tr>
<tr>
<td>Current ripple</td>
<td>TBD</td>
<td>1000</td>
<td>ppm</td>
</tr>
<tr>
<td>Voltage ripple</td>
<td>TBD</td>
<td></td>
<td>ppm</td>
</tr>
<tr>
<td>Magnet inductance</td>
<td>16.5</td>
<td>3.48/4.28</td>
<td>mH</td>
</tr>
</tbody>
</table>

* Parameters from 1992 power supply design review

- **Fast Communications Requirements**
  - 22.6 kHz update rate
  - 10 µs latency
Challenges and Issues

- Fast corrector magnet is very inductive
  - 16.5 mH in the design by BNL
  - High impedance at 10 kHz

\[ Z = \omega L = 2\pi f L = 2\pi \times 10000 \times 0.0165 = 1036.7 \, \Omega \]

- For 130 mA (1% of full rating) peak-to-peak current at 10 kHz, required peak-to-peak voltage is

\[ V = Z \times I = 1036.7 \times 0.13 = 134.7 \, V \]

- No commercial bipolar power supplies meet this requirement

Example:
Kepco 20-10 (±20V, ±10A) linear power supply
With a 10 mH load, -3dB at 3.7 kHz
R&D Goals

- Choose appropriate power supply circuit topology
- Choose appropriate hardware for the power circuit
- Design control loop
- Stay within constrains
  - Use existing 40V DC bus
- Deliver a 75 mA peak-to-peak current at 10 kHz
- Keep the design simple for reliability
Some of Basic Power Circuits

- Switching mode power supplies
  - Buck converters
    - Simple topology
    - Output voltage less than input voltage
    - Output can be unipolar or bipolar
    - All APS storage ring power converters are buck converters
  - Boost converter
    - Simple topology
    - Output voltage greater than the input voltage
    - Unipolar output only
  - Buck-boost or Boost-buck converters,
    - Output voltage can be either higher or lower than the input
    - Output can be unipolar or bipolar

- Linear power amplifiers
  - Works like operational amplifiers
  - High bandwidth, hundreds kHz
  - High power consumption, good for AC, not good for DC
Proposed Circuit for Bipolar Power Supply

- An H-bridge with four semiconductor switches
- Bipolar output
- Output voltage ≤ input voltage – a buck converter
- Output filter to reduce ripple voltage and ripple current
Semiconductor Switches

- **Discrete MOSFET switches**
  - Small size
  - Low conduction resistance
  - Low cost

- **Switching (class D) amplifiers**
  - Full bridge package
  - Built-in PWM generator
  - Built-in gate drive circuit
  - Built-in protection circuit
  - High conduction losses
  - High cost

Example:
- IRFB 4610, 100V, 73A,
  - 11 mΩ on resistance
  - TO-220 package
  - Less than $2.50 per MOSFET

Example:
- APEX SA12, 200V, 15A,
  - 400 mΩ on resistance
  - 200 kHz built-in PWM
  - $400 - $600 per unit

In comparison, existing SR corrector power supplies use two IGBTs, each rated 600V, 300A, and cost ~ $200
Power Supply Regulator Design

- **Pulse width modulation (PWM) methods**
  - A reference signal is compared with a periodic signal
  - Switches under control are turned on or off according to the comparison result
  - There are many PWM methods available
  - The simplest uses sawtooth or triangular waveforms
  - The power supply output voltage is proportional to the switch on time during the cycle, a.k.a. duty cycle or duty ratio

- **Closed feedback loop for the current regulation**
  - Proportional and integral (P-I) compensator
  - Lead-lag compensator to improve high frequency performance

\[
\begin{align*}
Y &= \frac{(s + z_1)(s + z_2)}{(s + p_1)(s + p_2)} \\
|p_1| &> |z_1| > |z_2| > |p_2|
\end{align*}
\]
Sawtooth PWM

Switch Q1 or Q2 is modulated to regulate the output while switch Q3 or Q4 is held on to control the polarity

- Only two switches are used for a given output polarity
- Very simple and easy to implement
- Does not work well for very small duty ratio or around zero for bipolar output
- Used in the storage ring quad, sext, and original corrector power converters

\[ V_{DC} = D \times V_o \]

Duty Ratio \( D = \frac{T_{on}}{T} \)
Unipolar PWM - choice for the design

- $V_{DC}$ can be positive or negative
- Ripple frequency is twice the PWM frequency
- Zero output at $D = 0.5$
- Smooth transition around zero

Duty Ratio $D = \frac{T_{on}}{T}$, $V_{DC} = (2D-1) \times V_o$
Switching sequence: assume Q1 and Q4 on initially

Positive I, 0 < t < T₁
Switching 1: Q1 off and Q3 on

Q3 does not need to be gated on. But, with MOSFETs, gate-on may result in lower conduction losses.
Switching 2: Q1 on and Q3 off

Positive I, \( T_2 < t < T_3 \)
Switching 3: Q4 off and Q2 on
Switching 4: Q4 on and Q2 off, back to initial condition
Simulation with PLECS (piecewise linear electrical circuit simulation)

At 10 kHz, 75 mA pk-pk sine reference, output current attenuation -2.05dB, phase shift 44.3°
1. Input capacitor bank
2. MOSFET heat sink
3. Cooling fan
4. MOSFET gate drive circuit
5. Output filter
6. Current sensor, LEM
7. Triangular waveform generator
8. P-I and lead-lag compensators
9. Interlocks for over current and over temperature
10. Reference input

16.5 mH high frequency magnet
Initial Test Results - MOSFET Gate Signals

115 kHz triangular waveform

Q1 on
Q3 off

Q2 on
Q4 off

Q1 off
Q3 on

Q2 off
Q4 on
MOSFET Drain-Source Voltage - no shoot-through condition
Step Function Response

Current slew rate = $0.15 \div 59.0\mu s = 2542 \text{ A/s}$
Calculated slew rate = $\frac{V}{L} = \frac{40}{0.0165} = 2424 \text{ A/s}$

* Delay in the existing SR fast corrector power supply is 10 times longer
150 mA (1%) Peak-peak Reference at 1 kHz

Regulator output

Output voltage, 20V/div

150 mA
150 mA (1%) Peak-peak Reference at 5 kHz

\[ \Delta t = 18 \mu s = 32.4^\circ \]

Current Reference (yellow)
Output Current (blue)
Regulator Output
Output Voltage, 20V/div
150 mA (1%) Peak-peak Reference at 10 kHz

Both regulator and output voltage saturate at 10 kHz
75 mA (0.5%) Peak-peak Reference at 10 kHz

\[ \Delta t = 18.5 \mu s = 66.6^\circ \]

Current Reference (yellow)
Output Current (blue)
Regulator Output
Output Voltage
Frequency Response (24.8981 mVpk, zero offset drive)

Test equipment: Dynamic signal analyzer HP35670A
24.8981 mVpk = 37.35 mApk, ~1 µrad bend
Summary

- A prototype MOSFET-based fast bipolar power supply is developed
- Achieved 10 kHz bandwidth for a 0.5% small signal
- Prototype is under redesign to
  - Reduce switching noise in the circuit
  - Clean up the mistakes
- Retune control loop parameters for real magnet, which is a laminated magnet and may have a very different characteristic at high frequency
Questions?