

A VERSATILE DC/PULSE SWITCHING MODE POWER SUPPLY FOR AN INTERLEAVING DIPOLE MAGNET*

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Abstract

A special interleaving operation of the Advanced Photon Source's injector requires three dipole magnets to selectively direct linac beam bunches into the storage ring during "top-up" operation. A versatile switching mode power supply has been designed and built for the magnets to meet that requirement. This paper presents the main circuit, the circuit analysis, and the test results.

1 REQUIREMENT

The APS storage ring requires a beam injection about every two minutes in top-up mode [1]. The so-called interleaving operation allows beam pulses between injections to be used for machine studies. It also allows more sophisticated diagnostic techniques than otherwise would be possible. Three pulsed dipole magnets are required to interleave the storage ring top-up injection and noninjection studies. The beam is delivered for the storage ring injection when these magnets are energized and is available for studies when the magnets are off. One mode of operation is to run the injector at up to 10 Hz, while only injecting into the booster at 2 Hz. In order to do so, the dipole magnet current has to rise or fall within 100 ms and the pulse has to complete within 200 ms. There are also times when the continuous booster injection is required. Then those magnets will be running in DC mode. The switch between modes needs to be smooth and fast. Table 1.1 is a summary of the specifications.

Table 1: Power Supply Specifications

Modes of operation	Pulsed or DC
Switch between modes	< 1 s
Maximum pulse rep-rate	2 Hz
Rise and fall times	< 0.1 s in pulsed mode < 1 s in DC mode
Maximum current	350 A
Flat top in pulsed mode	> 1 ms
Flat top or DC regulation	±100 mA
Load parameters	58 mH, 45 mΩ

2 MAIN CIRCUIT

A circuit consisting of a diode rectifier, a boost converter, and an H-bridge has been developed. Figure 1 shows a diagram of the main circuit.

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Since the magnet current is unidirectional, the H-bridge only needs two controllable switches, IGBTs S_1 and S_2 . Diodes D_1 and D_2 are used for other switches.

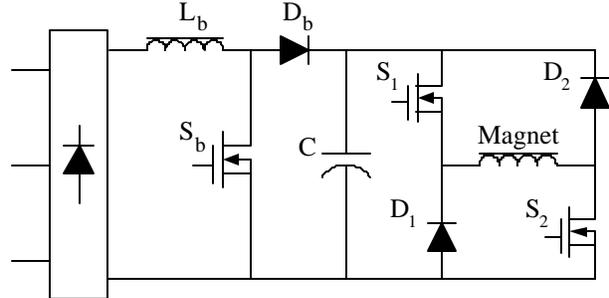


Figure 1. Main circuit.

The circuit has four operation stages.

2.1 Stage One: Charge

Before the supply is ready to send a current pulse to the magnet, the capacitor C has to be charged to a proper voltage required by the expected current. During this time, the boost converter switch S_b is operating. When S_b is on, the energy is accumulated in the boost choke L_b . This energy is transferred to the capacitor after S_b is turned off. The boost converter charges the capacitor and maintains the voltage until it is time to discharge the capacitor into the magnet.

2.2 Stage Two: Discharge

When it is time to start the pulse, the boost converter is turned off and switches S_1 and S_2 in the H-bridge are turned on. The capacitor and the magnet form a resonant circuit. The current in the magnet increases sinusoidally while the capacitor voltage decreases. The discharge finishes when the current reaches the desired level.

2.3 Stage Three: Flattop/DC Regulation

After the current reaches the desired level, the H-bridge starts to regulate the current at a constant level, flattop or DC. Both switches S_1 and S_2 can be PWM-controlled to regulate the current, or alternatively only one is PWM-controlled while the other is held on all the time. The former scheme provides faster regulation and the latter saves switching losses. The duration of this stage can be long or short. A short duration means the output is a pulse. A long duration means the supply is operating in DC mode.

2.4 Stage Four: Recovery

At the end of the flattop or DC mode, switches S_1 and S_2 are turned off. The magnet current goes through diodes D_1 and D_2 back to the capacitor. Similar to the discharge,

the circuit for the recovery is also a resonant circuit. The recovery time is the same as the discharge time.

Figure 2 shows the four operating stages versus time.

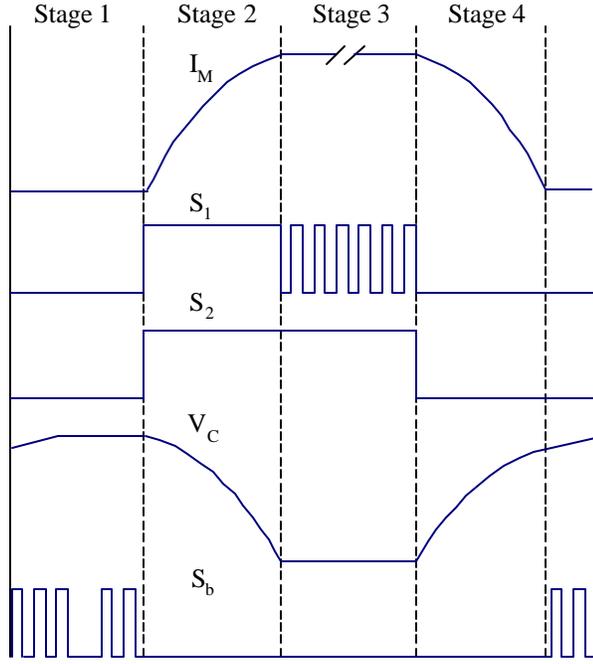


Figure 2. Operation stages vs. time.

A switch from the pulsed mode to the DC mode can be made instantly simply by extending the flattop indefinitely. However, it takes up to 0.5 second from the end of the DC mode to the first pulse.

3 CIRCUIT ANALYSIS

There are two components critical for the circuit to produce a magnet current that meets the requirement. One is the capacitor bank. Its capacitance determines the rise time and fall time of the pulse. The other is the boost converter. It charges the capacitor bank to a voltage that determines the peak of the magnet current.

3.1 Calculation of Required Capacitance

There are several factors to consider in determining the capacitor size. The rise time or the fall time of the pulse has to be less than 0.1 second. The maximum capacitor voltage has to be high enough to produce the maximum magnet current, 350 amperes, but not so high that it threatens the safe operation of the capacitor and other circuit components. The capacitance should also be readily available with commercial capacitors.

The rise time or fall time of an LC resonant circuit can be calculated from (circuit resistance is ignored for easy calculation)

$$T_{rise} = T_{fall} = \frac{p\sqrt{LC}}{2} < T_{rise,max} = 0.1 \text{ s.} \quad (1)$$

If the desired capacitor operation voltage is less than 600 volts to produce 350 amperes in the magnet, then

$$V_C = \sqrt{\frac{L}{C}} I_M < V_{C,max} = 600 \text{ V.} \quad (2)$$

Solving inequalities (1) and (2) for C , we have

$$\frac{L I_M^2}{V_{C,max}^2} < C < \frac{4 T_{rise,max}}{p^2 L}. \quad (3)$$

With $L = 58 \text{ mH}$, $T_{rise,max} = 0.1 \text{ s}$, $V_{C,max} = 600 \text{ V}$, and $I_M = 350 \text{ A}$, the range of the capacitance obtained from Eq. (3) is between 19.7 mF and 69.9 mF.

A capacitor bank of 23.5 mF has been chosen. The bank has twenty 4.7-mF capacitors, rated at 450 V, connected as two in series and ten in parallel. With this capacitor bank, the rise time or fall time is equal to 58 milliseconds, well below the 0.1-second requirement.

3.2 Capacitor Operating Voltage

The capacitor voltage required for a given magnet current can be calculated with an energy balance equation, i.e.,

$$\frac{1}{2} C V_{C,0}^2 = \frac{1}{2} L I_M^2 + \left(\frac{p\sqrt{LC}}{4} R I_M^2 + 2 V_{IGBT} \sqrt{LC} I_M \right) + \frac{1}{2} C V_{DC}^2, \quad (4)$$

where $V_{C,0}$ is the capacitor voltage before the discharge and V_{DC} is the DC voltage at flattop or in DC mode. The terms in the parentheses present the losses in the magnet and the switches. Solve Eq. (4) for $V_{C,0}$ to obtain

$$V_{C,0} = \sqrt{\frac{L}{C} I_M^2 + \left(\frac{p}{2} \sqrt{\frac{L}{C}} R I_M^2 + 4 V_{IGBT} \sqrt{\frac{L}{C}} I_M \right) + V_{DC}^2}. \quad (5)$$

Similarly, the capacitor voltage $V_{C,f}$ after the recovery can be calculated from

$$V_{C,f} = \sqrt{\frac{L}{C} I_M^2 - \left(\frac{p}{2} \sqrt{\frac{L}{C}} R I_M^2 + 4 V_{diode} \sqrt{\frac{L}{C}} I_M \right) + V_{DC}^2}. \quad (6)$$

In the above equation, the losses during the recovery are subtracted from the energy stored in the magnet, and the voltage drop across the diode instead of the IGBT is used.

Assuming that in the DC mode or at flattop the capacitor voltage is 30 volts and the IGBT and diode on-state voltage drops are 3 volts and 2 volts, respectively, then using the parameters of the magnet and the capacitor bank, Eqs. (5) and (6) can be simplified to

$$V_{C,0} = \sqrt{2.579 I_M^2 + 18.852 I_M + 900} \quad (7)$$

and

$$V_{C,f} = \sqrt{2.357 I_M^2 - 12.568 I_M + 900}. \quad (8)$$

At the maximum current 350 amperes, $V_{C,0} = 568.7 \text{ V}$ and $V_{C,f} = 534.1 \text{ V}$.

3.3 Boost Converter

The boost converter has to supply the energy lost during the discharge and the recovery. From Eqs. (5) and (6), the relation between the lost energy and the magnet current is

$$E_{loss} = \frac{1}{2} \sqrt{LC} \{ p R I_M^2 + 4(V_{IGBT} + V_{diode}) I_M \}. \quad (9)$$

The maximum energy loss happens at the maximum magnet current and is equal to 448.3 J.

The energy supplied to the capacitor bank by the boost converter in each pulse is equal to $0.5 L_b I_b^2$. If the booster current is the same as the magnet current and a 30- μ H choke is used, the maximum energy supplied by the boost converter in each pulse is 1.838 J. The number of pulses required to supply the maximum energy 448.3 J is 244. Since the boost converter has to charge up the capacitor bank within 0.3 second, its switching frequency has to satisfy

$$f_b \geq \frac{\text{Number of pulses}}{\text{charging time}} = \frac{244}{0.3} = 813.3 \text{ Hz}. \quad (10)$$

A switching frequency of 1200 Hz is chosen for the boost converter to guarantee that the capacitor bank is recharged in time.

3.4 Other Circuit Parameters

The output voltage of the rectifier is chosen as 32.4 V at no load. The corresponding input AC line-to-line voltage is 24 V and can be obtained through a step-down transformer from the 480-V AC line. The maximum input power is 11.86 kV·A, which occurs when the supply is running at 350 A in DC mode. A 15-kV·A, Δ -Y, three-phase transformer is selected as the step-down transformer.

Since the magnet has a large time constant, 1.289 s, the switching frequency of the H-bridge can be relatively low. The spice simulation shows that with a 4-kHz switching frequency the ripple current is less than one-half of the specification.

A digital controller/regulator has been designed to control the power supply using TI TMS320C6711 DSP. A digital proportional-integral regulator is implemented with the DSP to control the output current. The boost converter switching duty cycle is determined such that the booster peak current is equal to the magnet current. After the capacitor bank is charged to the required voltage, a digital bang-bang regulator with a fixed duty cycle of 15% is used to maintain the voltage.

4 TEST RESULTS

Three supplies have been built and installed in the APS injector and the performances of those supplies have been very satisfactory. Figures 3 through 5 show some test results. The boost converter switch was turned off during the flat-top. The booster current at this time was the magnet current plus the ripple current into and out of the

capacitor bank. The current in Figure 5 was measured with an external transductor.

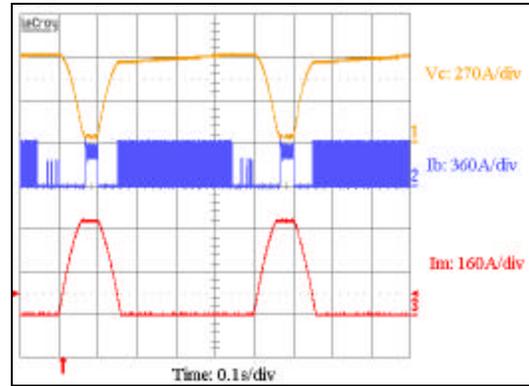


Figure 3. Waveforms in the pulsed mode.

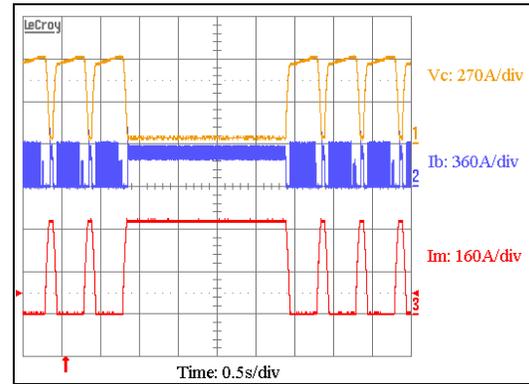


Figure 4. Transition between two modes.

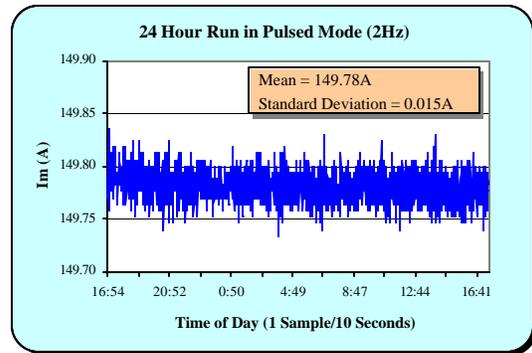


Figure 5. Result of the stability test.

5 ACKNOWLEDGEMENT

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6 REFERENCES

- [1] L. Emery, "Recent Operational Data on Continuous Top-up Operation at the Advanced Photon Source," Proceedings of the 2001 Particle Accelerator Conference, P. Lucas, S. Webber (Eds.), 4, IEEE, (2001) pp. 2599-2601.