Circuit Description of the Power Systems for Pulsed Septum Magnets at APS *

D. G. McGhee
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439-4814

ABSTRACT

This paper describes the design and simulation of power circuits for the 4 Advanced Photon Source (APS) pulsed septum magnets which will be transformer type or transformer coupled to their switching circuits. Three are for synchrotron injection, extraction and Storage Ring injection, operating at a 2 Hz pulse rate; one is for the Positron Accumulator Ring (PAR) operating at a 60 Hz pulse rate for both injection and extraction. The septum current pulse is approximately a half-sine-wave with a base width of approximately 1/3 ms and a peak current, repeatable within ± 0.05%, in the transformer primary between 3.5 kA and 4.7 kA. The septum magnets have a primary inductance between 16 µH and 23 µH. Circuit design considerations of the switching, logic and simulations are presented.

I. INTRODUCTION

The transformer septum magnets must be pulsed at a 60 Hz rate to inject beam from a 450 MeV positron linac into the PAR and extract beam. Of the 60 pulses per second, the first 24 are used for injection, 25 through 29 are not used and 30 is used for extraction.

The other 3 septum magnets will be operated at a repetition-rate of 2 Hz. Two of the magnets are identical transformer type septum magnets which operate at the same values. These are the synchrotron extraction and the storage ring injection magnets with a primary inductance of 23 µH and resistance of 6.3 mΩ, and must be pulsed at 2 Hz to extract beam from the synchrotron and inject beam into the storage ring at 7.7 GeV. The third septum magnet is used to inject electrons into the synchrotron at 650 MeV or positrons at 450 MeV, and is also a transformer septum magnet, with a primary inductance of 21 µH, a resistance of 6.7 mΩ, and must be pulsed at 2 Hz.

The power supplies are designed to produce pulses of approximately a half-sine-wave having a base width of about 1/3 ms and peak currents repeatable within ±0.05% and adjustable from 470 A to 4.7 kA. A few ms after the forward current pulse, the magnet steel is reset by a half-sine pulse of reverse polarity. Use of a transformer design minimizes the cost of the capacitors used for energy storage.

During injection and extraction from the PAR and the synchrotron, as well as injection into the storage ring, the septum magnets must be pulsed. The combined rise and fall time of the pulse should be ≤ 1/3 ms with a flat-top time of >1 µs. These requirements can be met with a capacitor discharge circuit that is resonant with the septum magnet at a frequency of approximately 1500 Hz. The peak currents in the transformer primaries range from 3800 A to 4227 A and ranges from 11400 A to 16888 A in the secondaries.

These requirements can be met with a half sine-wave pulse. This is accomplished by discharging the energy stored in capacitor bank C_2 into the magnet as illustrated in Figs. 1a and 1b. On triggering the forward thyristor S_3, the energy stored in C_2 between pulses is discharged into the magnet circuit. S_3 turns off at the end of the first half-cycle of the damped oscillation. C_2 is then left with a smaller charge of opposite polarity until reverse thyristor S_4 is triggered and the second half-cycle takes place with current flowing in the opposite direction. The difference between the initial and the final charges is furnished by the charging supply between septum pulses.

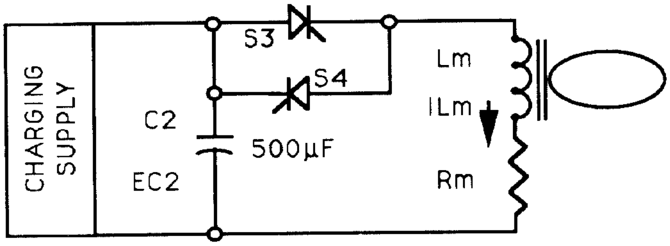

Fig. 1a. Magnet pulse switching circuit

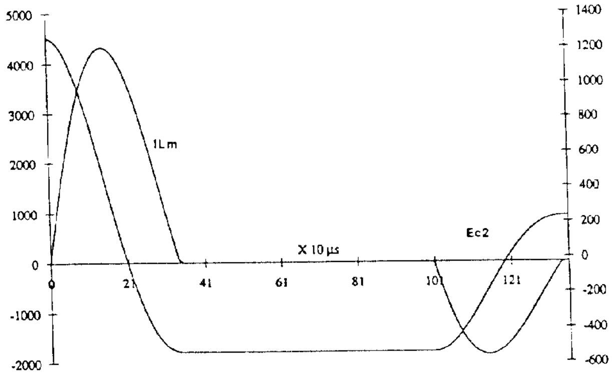

Fig. 1b. Magnet current and voltage waveforms

II. SWITCHING CIRCUITS

Circuit Equations

The switching circuits for these 4 septum magnets operate the same.[1] When capacitor C_2 of Fig. 1a is discharged into the load, an oscillatory current will result, provided the total resistance in the circuit is sufficiently low.

---

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

The resonant frequency of the circuit is:

$$fr = \beta/2\pi, \qquad [s^{-1}] \quad (1)$$

where $\beta = ((1/L_mC_2)-(R_m^2/4L_m^2))^{0.5}$, $[s^{-1}]$

C_2 = capacitor bank [F]

L_m = total circuit inductance [H]

R_m = total circuit resistance. [Ω]

The current at any time is:

$$i = (E/\beta L_m)\, e^{-at} \sin \beta t, \qquad [A] \quad (2)$$

where t = time after discharge starts, [s]

$a = R_m/2\, L_m$. $[s^{-1}]$

The required voltage on C_2 for the different peak operating currents is:

$$E_{c2} = i\beta L_m/e^{-at} \sin \beta t. \qquad [V] \quad (3)$$

The time where the current reaches its first peak is:

$$tp = 1/\beta \tan^{-1} \beta/a. \qquad [s] \quad (4)$$

The first current peak does not occur at precisely the first quarter period of the discharge cycle, but at a time before. The term $\tan^{-1} \beta/a$ describes the phase angle at which the peak current occurs.

In this application, R_m is made appreciably less than the value for critical damping. With $1/L_mC_2 > R_m^2 / 4L_m^2$, we can write $\beta \approx 1/(L_mC_2)^{0.5}$.

III. CONTROLLED CHARGING-CHOKE CIRCUIT

Fig. 2 shows the controlled charging-choke circuit and the capacitor discharge circuit of Fig. 1a combined. Discharge capacitor C_2 is charged and recharged to make up the circuit losses incurred by pulsing the magnet. These losses are made up from an unregulated dc power supply powered from a 3-phase line, for the PAR septum power supply. A commercial 1kW regulated dc power supply PS1 and capacitor bank C_f is used for the other 3 septum power supplies. PS1 has constant voltage and constant current mode of operation with automatic crossover. This allows the direct connection to C_f, as PS1 will operate in the constant current mode until crossover occurs at the output voltage setpoint. Capacitor bank C_f allows the losses to be made up at a fixed time before the next pulse of the main switching circuit. The controlled charging circuit is comprised of L_2, C_2, S_1 and S_2. Gating on of S_1 starts the charging of C_2 from the dc power supply. At time t_0 the supply voltage Ea begins to drive an essentially sinusoidal current through the charging circuit.

$$E = iR_2 + L_2(di/dt) + (1/C_2)\int_0^{t1} i_{c2}\, dt \qquad [V] \quad (5)$$

At time t_1, the current is at its peak and $L_2\, di/dt = 0$,

$$E = iR_2 + (1/C_2)\int_0^{t1} i_{c2}\, dt. \qquad [V] \quad (6)$$

Between t_1 and t_2 the decaying charging current generates a voltage L_2 (di/dt) which aids the supply voltage to charge capacitor C_2 to a voltage larger than Ea. In the case where R is 0, this voltage will be, at time t_2,

$$e_{c2} = E + L\, (di/dt) = 2E. \qquad [V] \quad (7)$$

By providing a thyristor across the charging choke as shown in Fig. 2, the charging cycle can be terminated at any instant between times t_1 and t_2. A fraction of capacitor voltage e_{c2} is compared with a reference voltage. When the capacitor voltage is ≥ to the supply voltage at time t_r, a pulse can be generated which turns on S_2. With S_2 conducting, driving voltage L_2 (di/dt) is removed from the circuit and capacitor voltage e_{c2} is larger than the power supply voltage Ea, thyristor S_1 is back-biased and charging current i_{c2} stops. The current i_{L2} flowing in choke L_2 at time t_r will decay with a time constant L_2/R_2, where R_2 is the resistance of the choke and thyristor S_2 circuit. Thyristor S_2 remains on until S_1 is gated on starting the charge cycle again or until the choke

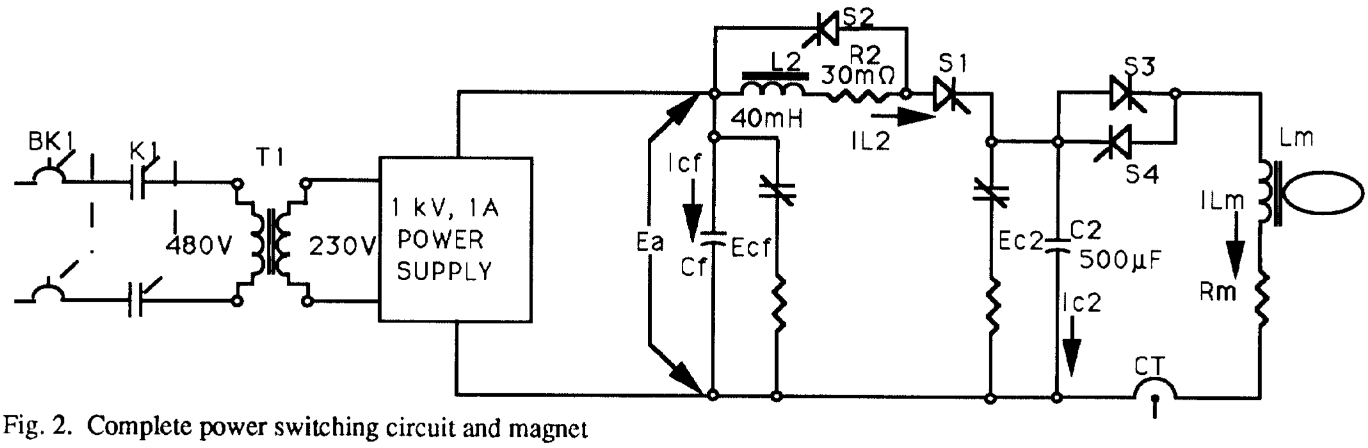

Fig. 2. Complete power switching circuit and magnet

current decays to 0. The current i_{L2} flowing in the choke when S_2 is turned off will aid in charging capacitor C_2 (the energy $0.5 L_2 i_{L2}^2$ is returned to the circuit). This makes the circuit very efficient.

It should be noted that the Q of the discharge circuit in Fig. 1a must be <5 for this charging circuit to operate properly. As the Q increases, current flowing in choke L_2 will decrease. This decreases the operating range of the charging circuit.

Pulsing the Magnet Without Resetting the Core

Heat losses in the magnet can be cut as much as 1/3 by not gating S_4, but the magnet core will not be reset. This mode of operation allows the dc power supply and filter to operate at a lower voltage. Also, the circuit Q could be increased, thus increasing the operating efficiency. Fig. 3 shows the change in charging time for the first 6 charge cycles of capacitor C2 with S4 gated, and Fig. 4 shows the first 9 charge cycles without S4 gated. It should be noted the first charge cycle is the longest in both cases, and the second is next longest without S4 gated and the shortest with S4 gated. Steady-state requires between 6 and 20 pulses, depending on the circuit Q.

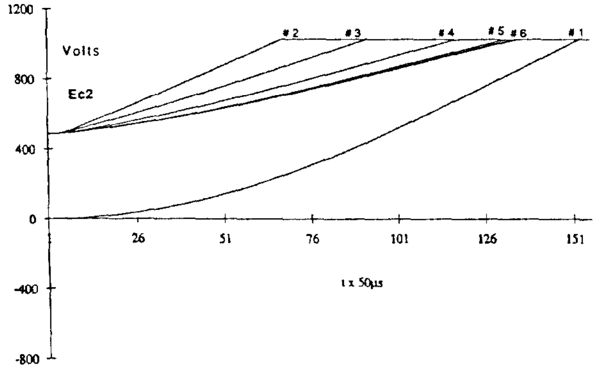

Fig. 3. Charging of C2 with S4 gated

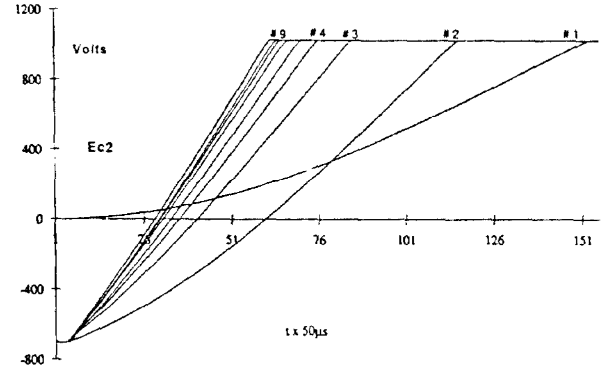

Fig. 4. Charging of C2 without S4 gated

VI. SIMULATION RESULTS

All 4 of the septum magnet and power supply circuits were simulated with a piecewise simulation program.[2] Typical waveforms for the pulsed septum magnets operating at 2 Hz are shown in Figs. 5a, 5b and 5c. The simulated waveforms have a varied time axis so that they show in detail what happens during the charge and discharge of C_2.

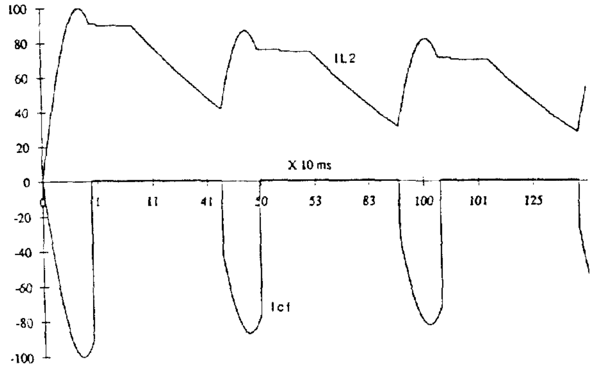

Fig. 5a. Simulation of current in inductor IL2, capacitor Cf

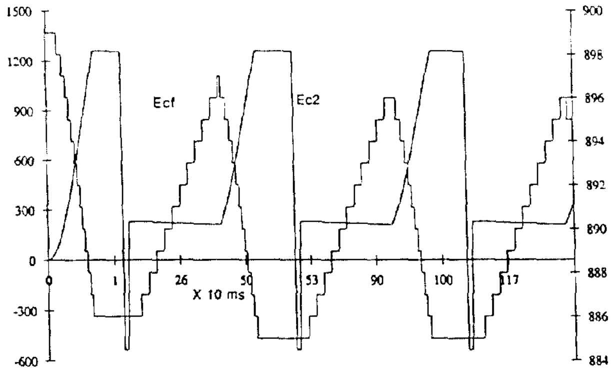

Fig. 5b. Simulation of voltages across capacitors Cf and C2

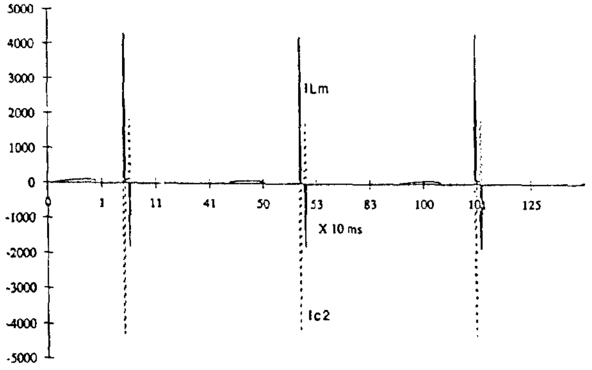

Fig. 5c. Simulation of current in inductor ILm and capacitor Cf

V. REFERENCES

1. D. G. McGhee, "Pulsed Power Supply for PAR Injection/Extraction Septum Magnet," ANL Light-Source Note, LS-159, September 23, 1990.
2. D. E. Piccone, I. L. Somos, and W. H. Tobin, "Piecewise Simulation (PS) Computation Method for Computing Transient Phenomena," *IEEE-IAS Annual Meeting*, September 1975, pp. 326--331.