LS-170
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PULSED POWER SUPPLY FOR THREE APS SEPTUM MAGNETS

ABSTRACT

Three septum magnets will be operated at a repetition-rate of 2 Hz. Two of the septum magnets are identical and operate at the same values; these are the synchrotron extraction and the storage ring injection magnets. They are transformer septum magnets, with a primary inductance of 23 μH and resistance of 6.3 mΩ, and must be pulsed at a 2 Hz rate 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. It is also a transformer septum magnet, with a primary inductance of 21 μH and resistance of 6.7 mΩ, and must be pulsed at a 2 Hz rate. A design study was performed of the power supply proposed in the APS Title I design. This supply produces a pulse that is approximately a half-sine-wave with a base width of approximately 1/3 ms; its peakcurrent is adjustable from 470 A to 4.7 kA and is repeatable within ±0.05%. The septum steel is reset by a half-sine pulse of reverse polarity a few milliseconds after the forward current pulse. No beam is present during reset. The use of the transformer design minimizes the cost of the capacitors used for energy storage.

INTRODUCTION

The septum magnets could be operated dc from a beam perspective. If they were operating dc the current leads would be required to be 47 to 63 times as large and the power loss in the magnet would be 2209 to 3969 times the pulsed operation, this would increase the power density in the septum edge to a level that would result in unacceptable operating temperature.

During the injection of the 650 MeV electron or 450 MeV positron beam from the Linac or PAR into the Synchrotron the septum magnet will be pulsed. Also, during extraction of the 7.7 GeV electron or positron beam from the Synchrotron and the injection into the Storage Ring, 3 septum magnets will be used for each function, 2 are dc and 1 is pulsed. All 3 pulsed septum magnets have approximately the same rise and fall time. The septum's current pulse is required to be < 1 ms and the flattop time > 1 μs. These requirements are met with a capacitor discharge circuit that is resonant with the septum magnet at a frequency of approximately 1500 Hz. The peak current for the Synchrotron injection septum is 4227 A in the transformer primary and 16888 A in the secondary. The other 2 pulsed septums are identical and operate at approximately the same required current of 3800 A in the transformer primary and 11400 A in the secondary. These requirements can also be met with a half sinewave pulse. This is accomplished by discharging the energy stored in capacitor bank (C_2) into the magnet as illustrated by Fig. 1. 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 the reverse thyristor S_4 is triggered and the second half cycle takes place with current flowing in the opposite direction. The difference between the original and the final charge is furnished by the charging supply between septum pulses.

Switching Circuits

Circuit Equations

The switching circuits of these 3 septums operate in the same way as the injection/extraction septum for PAR.[1] When the capacitor, C_2, of Fig. 1 is discharged into the load, an oscillatory current will result provided that the total resistance in the circuit is sufficiently low.

The resonant frequency of the circuit is:

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

where $\beta = ((1/L_m C_2)-(R_m^2/4L_m^2))^{0.5} \qquad [s^{-1}]$

C_2 = capacitor bank [F]
L_m = total circuit inductance [H]
R_m = total circuit resistance [Ω]

The current at any time is:

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

where t = time after discharge starts [s]

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

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

$$E_{C2} = i\beta L_m / e^{-\alpha t} \sin \beta t \qquad [V] \qquad (3)$$

These values are shown in Table 1 for each of the 3 magnets operating at 2 different energies.

The time at which the current reaches its first peak is:

$$t_p = 1/\beta \tan^{-1} \beta/\alpha \qquad [s] \qquad (4)$$

The first current peak does not occur at precisely the first quarter period of the discharge cycle, but at a previous point in time. This is shown by the circuit simulation graphed in Fig. 2. The term $\tan^{-1}\beta/\alpha$ 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 $1/L_m C_2 > R_m^2 / 4L_m^2$ we can write $\beta \approx 1/(L_m C_2)^{0.5}$ and the above equations can be simplified to:

$$f_r \approx 1/(2\pi(L_m C_2)^{0.5}) \qquad [s^{-1}] \qquad (1')$$

$$i \approx E_{C2}\, (C_2/L_m)^{0.5}\, e^{-\alpha t} \sin t/(L_m C_2)^{0.5} \qquad [A] \qquad (2')$$

The peak current is then

$$I_p \approx E_{C2}(C_2/L_m)^{0.5}\, e^{-((\pi R_m/4)(C_2/L_m)^{0.5})} \qquad [A] \qquad (2'')$$

and the voltage on the first reversal becomes

$$E_{C2} \approx - E_{C2}\, e^{-((\pi R_m/2)(C_2/L_m)^{0.5})} \qquad [V] \qquad (5)$$

Critical damping occurs at a resistance:

$$R_m = 2(L_m/C_2)^{0.5} \qquad [\Omega] \qquad (6)$$

Controlled Charging-Choke Circuit

Fig. 3 shows the controlled charging-choke circuit and the capacitor discharge circuit of Fig. 1 combined. The discharge capacitor C_2 is charged and recharged to make up the circuit losses incurred in pulsing the magnet. These losses are made up from a commercial 1 kW regulated dc power supply, PS1, and a capacitor bank, C_f. 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 set point. The key power supply specifications are given in Table 2. The capacitor bank C_f is used to allow the losses to be made up at a fixed time before the next pulse of the main switching circuit. The controlled charging circuit consists of L_2, C_2, S_1 and S_2. Gating on of S_1 is used to start the charging of C_2 from the dc power supply. At time t_0 the supply voltage E begins to drive an essentially sinusoidal current through the charging circuit.

$$E = iR_2 + L_2(di/dt) + (1/C_2) \int_0^{t_1} i_{C2}\, dt \qquad (8)$$

At time t_1 the current is at its peak and

$$L_2\, di/dt = 0, \qquad (9)$$

$$E = iR_2 + (1/C_2) \int_0^{t_1} i_{C2}\, dt. \qquad (10)$$

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

$$e_{C2} = E + L\,(di/dt) = 2E.$$

By providing a thyristor across the charging choke as shown in Fig. 3 the charging cycle can be terminated at any instant between times t_1 and t_2. A fraction of the capacitor voltage e_{C2} is compared with a reference voltage. At time t_r when the capacitor voltage is ≥ the supply voltage, a pulse can be generated which turns on S_2. With S_2 conducting, the driving voltage L_2 (di/dt) is removed from the circuit and the capacitor voltage e_{C2} is larger than the power supply voltage E, thyristor S_1 is back-biased and the 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 the time S_1 is gated on starting the charge cycle again, or the choke 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.

Warning

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

Pulsing Directly Into the Load

Heat losses in the magnet can be cut by approximately 1/3 and the circuit efficiency can be increased by not gating S_4, and resetting the required output voltage of PS1.

Simulation Results

Two septum circuits with 2 beam energies per circuit were simulated with the magnets each having a Q of 2. The charge voltages used are given in Table 1. The peak and rms voltages/currents for all the pulsed septum magnets operating at 2 Hz and the waveforms for the synchrotron injection septum power supply at the different circuit nodes, are shown in Fig. 4 a, b and c. These simulations were done using a piecewise simulation program. [2]. The simulated waveforms have a varied time axis so that they show in detail what happens during the charge and discharge of C_2.

<u>Control and Interlock Logic</u>

Control logic is shown in Fig. 5. Control is accomplished with 3 gate pulses from the power supply control unit (PSCU) or a master clock and 3 interlock signals from the interlock circuit.

The "Start Charge" pulse is optically coupled to AND/1 with a signal from the interlock trip circuit. When the trip signal is low the power supply is completely shutoff and crowbarred. When both the "Start Charge" pulse and the interlock are logic 1s then the AND's output is true (1) setting the flip-flop, FF/1, causing single shot, (SS)/2's Q output to go high and stay there for 250 µs. This pulse is amplified and coupled with the pulse transformer to gate Thyristor S1. This starts the resonant charge of C2 from Cf through L2, as shown in Fig. 4.

At the time SS/2 is triggered, SS/3 is also triggered, which causes its Q/not output to go low. The pulse width of SS/3 is 5 ms and at the end of this pulse Q/not goes high triggering SS/4. The Q output pulse of SS/4 is 9 ms and is used as a window during which time Ec2 is compared to the DAC voltage and Ec2 is also compared with Ecf in the interlock circuit. If Ec2 is greater than both voltages, Ecf, and the DAC then all 3 inputs to AND/2 are 1s. This causes the AND's output to be true (1) setting the flip-flop, FF/2, causing single shot, (SS)/5's Q output to go high and stay there for 250 µs. This pulse is amplified and coupled with pulse transformer to gate Thyristor S2. This stops the resonant charge of C2 by crowbarring L2, as shown in Fig. 4.

At the end of the SS/5 Q output pulse SS/7 is triggered causing a Q output pulse of SS/7. The pulse is 15 ms and is used as a window during which time, as long as the trip circuit is satisfied, a "Magnet Current" pulse can wide. This causes the AND's output to be true (1) setting the flip-flop, FF/4, causing single shot, (SS)/8's Q output to go high and stay there for 150 µs. This pulse is amplified and coupled with the pulse transformer to gate Thyristor S3. This starts the resonant current pulse of Lm by discharging C2 and recharging with the other polarity, as shown in Fig. 2.

At the end of the SS/8 Q output pulse SS/10 is triggered causing a Q output pulse. Also at the time the "Magnet Current" pulse SS/11 is also triggered causing its Q/not output to go low. The pulse width of SS/11 is 0.5 ms and at the end of this pulse

Q/not goes high triggering SS/12. The Q output pulse of SS/12 is 10 µs wide and is used to cause the AND's output to switch to true (1) setting the flip-flop, FF/5, causing single shot, (SS)/13's Q output to go high and stay there for 150 µs. This pulse is amplified and coupled with pulse transformer to gate Thyristor S4. This starts the resonant current pulse of Lm by discharging C2 and recharging with the other polarity, as shown in Fig. 1. The current pulse resets the magnet core.

At the end of the SS/13 Q output pulse SS/16 causes its Q/not output to go low. The pulse width of SS/16 is 250 ms and at the end of this pulse Q/not goes high triggering SS/15. The Q output pulse of SS/15 is 10µs and is ORed with a "Magnet Reset" pulse. Either pulse will reset all flip/flops (FF) with a 10 µs pulse from SS/14.

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, Page 326--331.

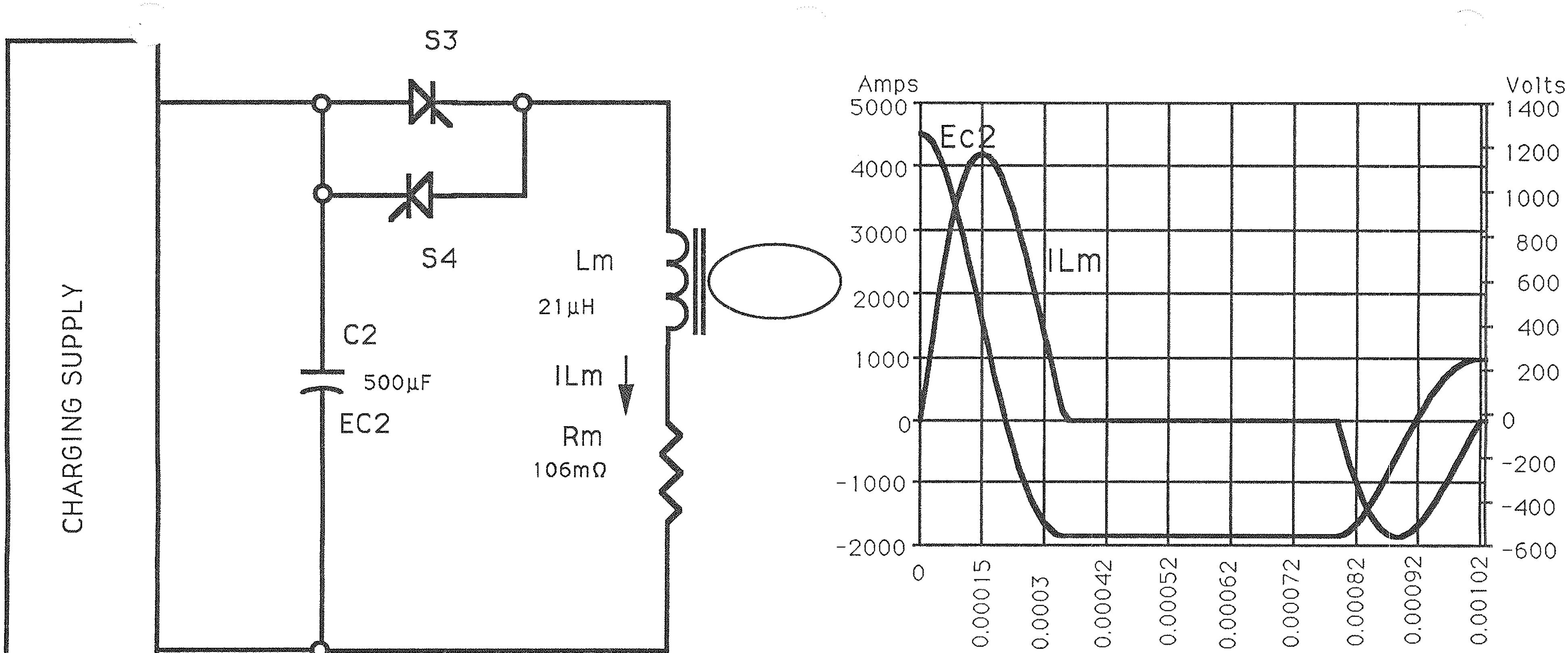

Fig. 1 The magnet switching circuit with its current and voltage waveforms during the magnet pulse and the reset pulse.

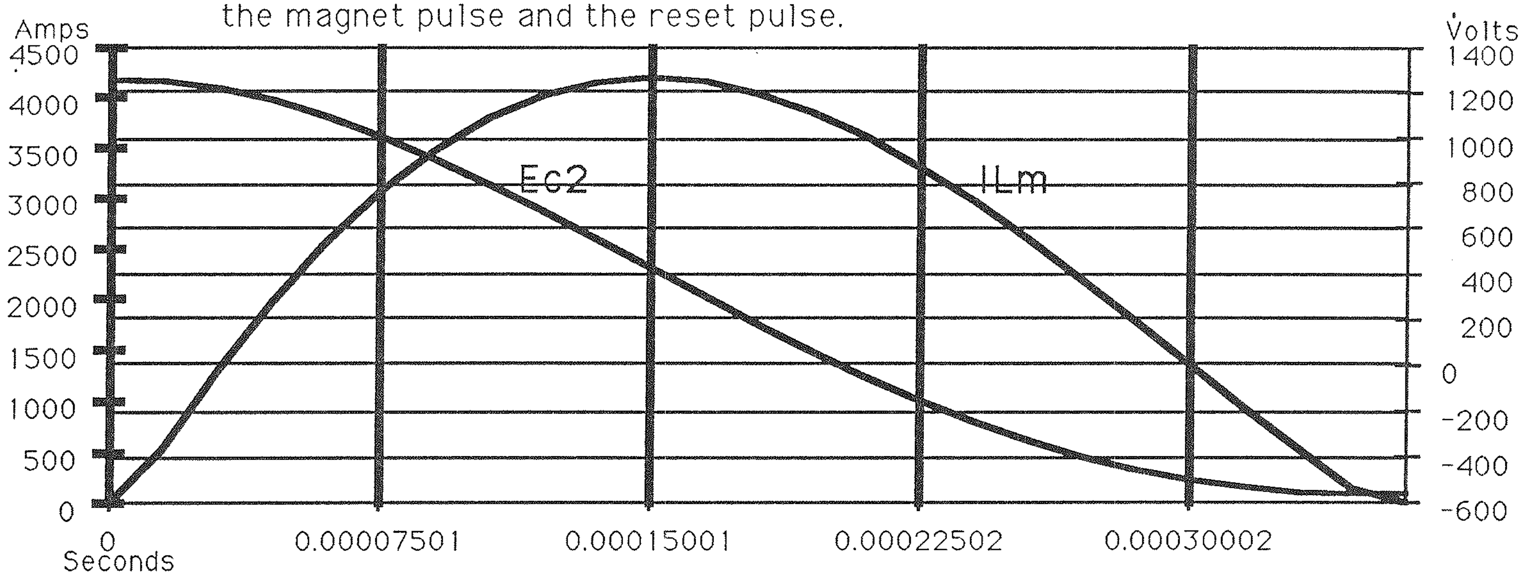

Fig. 2 The magnet current and voltage waveforms during the magnet pulse.

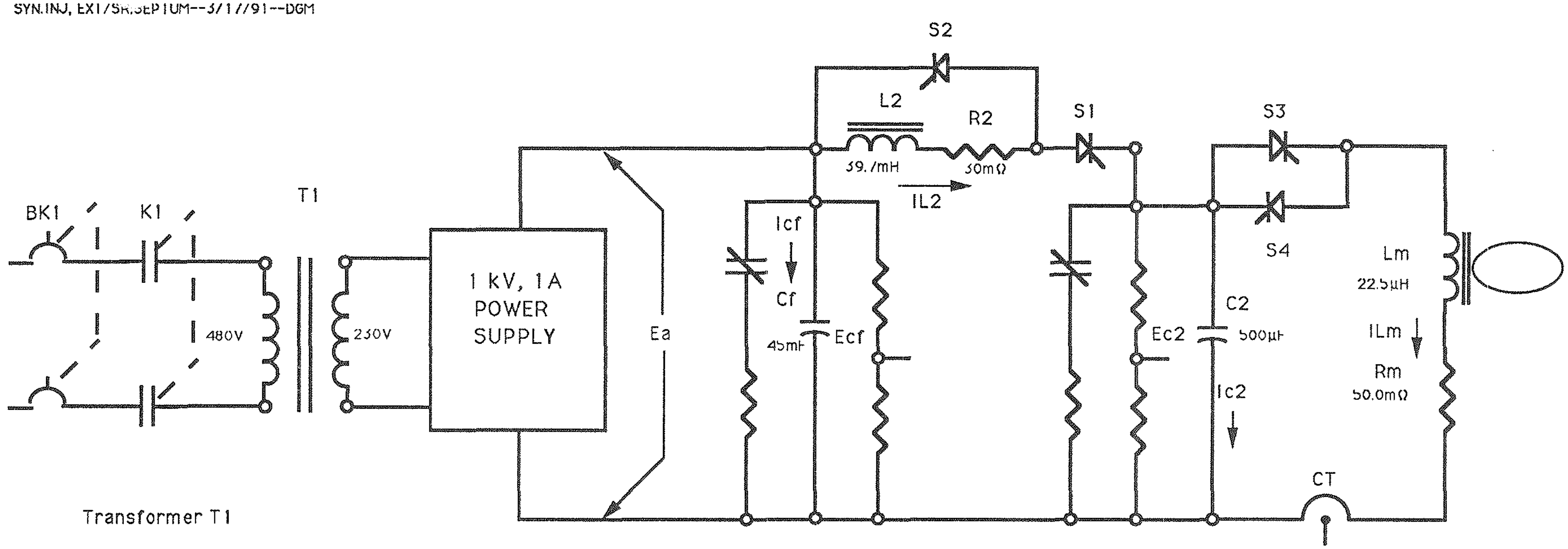

Fig. 3 Schematic of septum power supply and magnet.

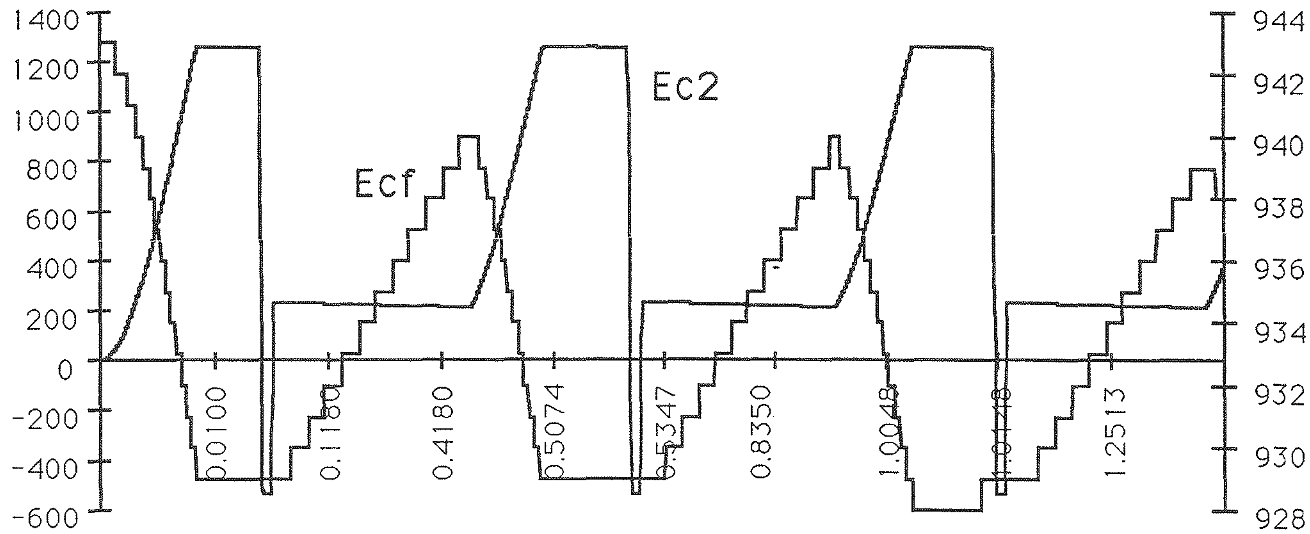

Fig. 4a Simulation results showing the voltages on capacitors Cf and C2

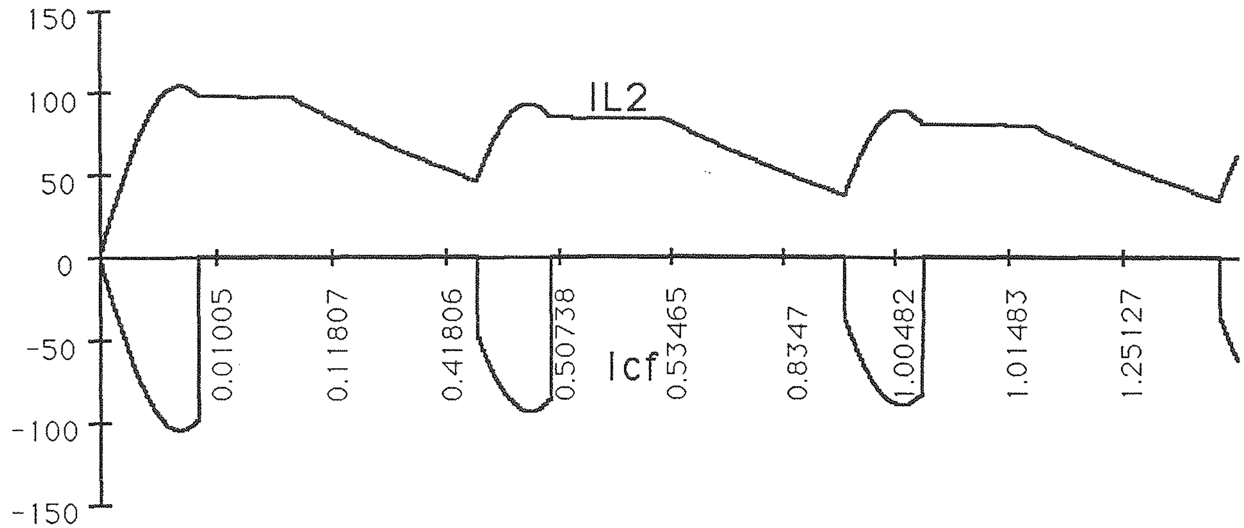

Fig. 4b Simulation results showing the currents in capacitor Cf and inductor L2

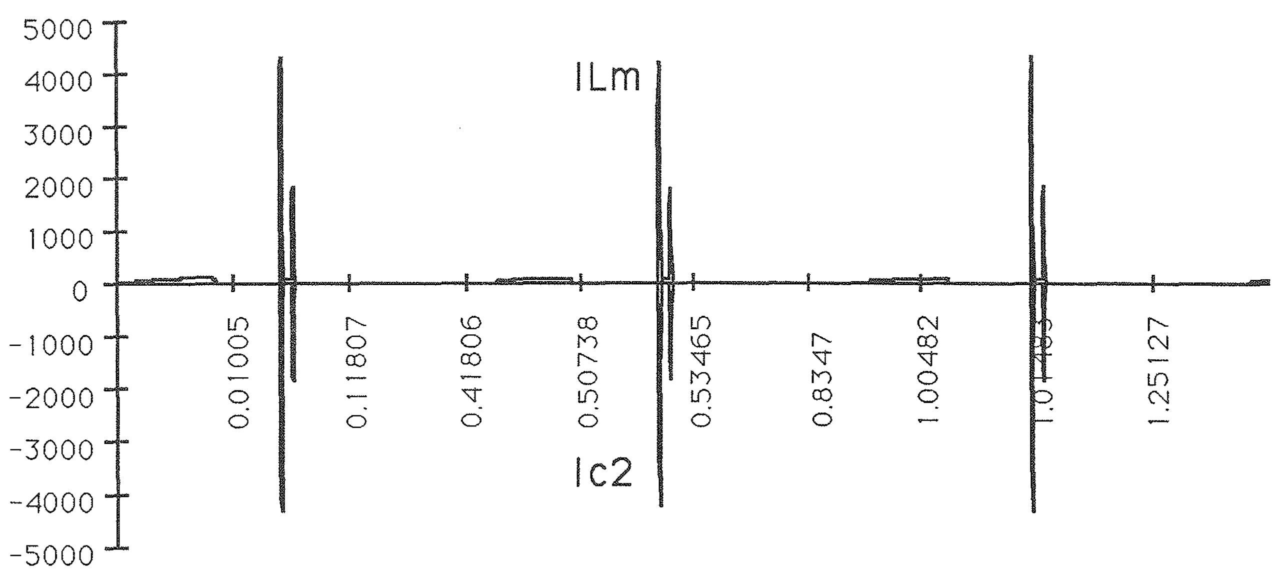

Fig. 4c Simulation results showing the currents in capacitor C2 and magnet Lm.

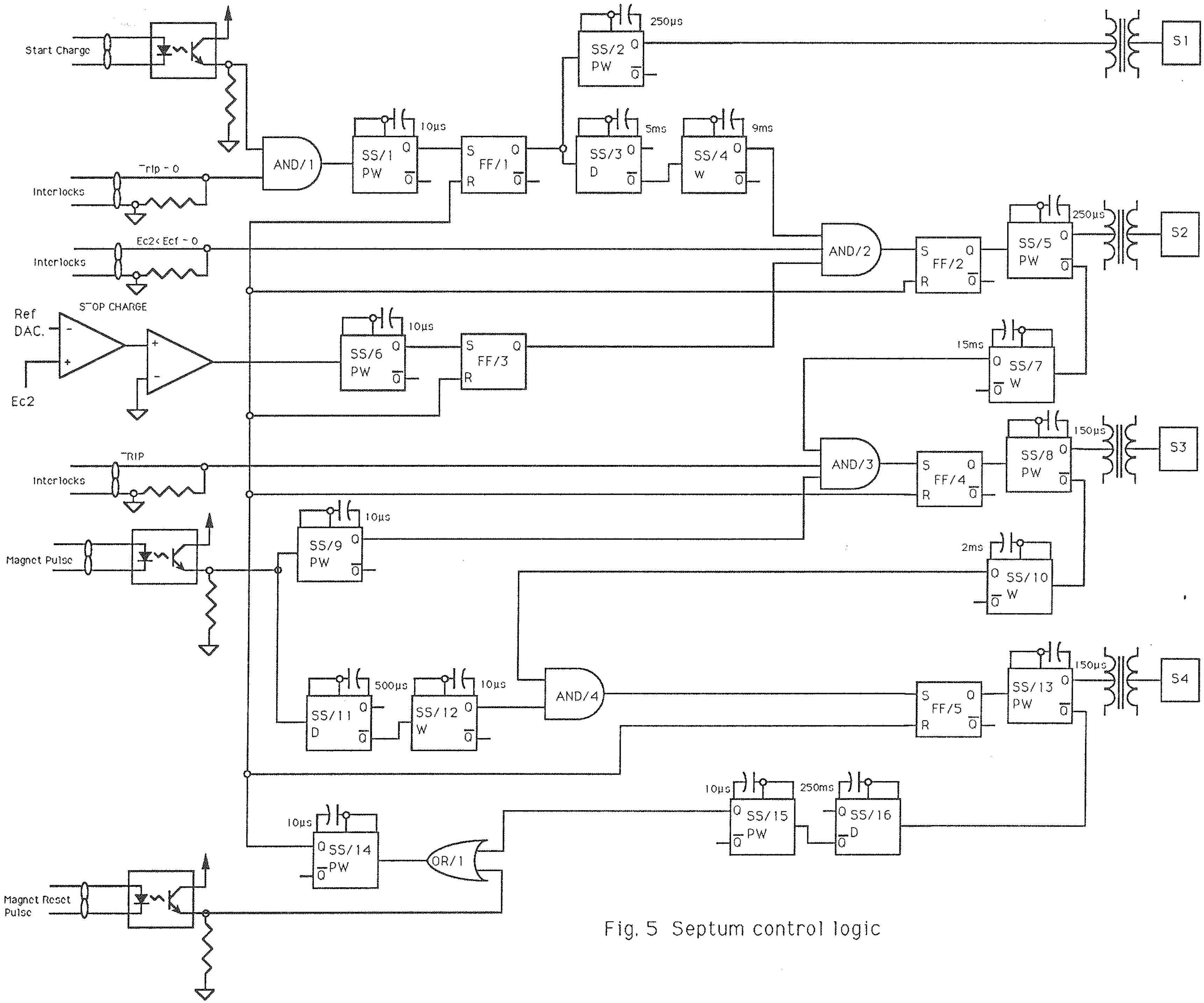

Fig. 5 Septum control logic

Table 1 APS's 2 Hz septum systems operating voltages and currents

Description						
Machine	Synchrotron	Synchrotron	Synchrotron	Synchrotron	Storage Ring	Storage Ring
Septum	Injection	Injection	Extraction	Extraction	Injection	Injection
Energy	650 MeV	450 MeV	7.7 GeV	7 GeV	7.7 GeV	7 GeV
Peak Primary Current	4227	2926	3800	3455	3800	3455
Primary Magnet Inductance	0.000021	0.000021	0.000023	0.000023	0.000023	0.000023
Capacitor Voltage C2 [Ec2.C	1258	871	1166	1060	1166	1060
PS1 Voltage	944	653	874	795	874	795
Simulation						
Voltages						
Ecf--{max}peak	943	653	874	795	874	795
Ecf--{min}peak	928	643	861	783	861	783
Ecf--rms	934	650	868	790	868	790
Ec2--{max}peak	1258	871	1166	1060	1166	1060
Ec2--{min}peak	-537	-371	-518	-471	-518	-471
Ec2--rms	288	198	280	254	280	254
Currents						
Icf--{max}peak	1	1	1	1	1	1
Icf--{min}peak	-105	-72	-97	-88	-97	-88
Icf--rms	10	7	9	8	9	8
Ic2--{max}peak	1849	1279	1732	1575	1732	1575
Ic2--{min}peak	-4322	-2990	-3888	-3535	-3888	-3535
Ic2--rms	91	63	84	77	84	77
ILm--{max}peak	4321	2989	3887	3534	3887	3534
ILm--{min}peak	-1850	-1280	-1733	-1576	-1733	-1576
ILm--rms	90	63	84	76	84	76
IL2--{max}peak	105	72	97	88	97	88
IL2--{min}peak	2	1	2	1	2	1
IL2--rms	64	40	57	50	57	50

Table 2 PS1 Specifications

Output		
1.	Power:	1kW
2.	Voltage:	0-1kV
3.	Current:	0-1A
4.	Voltage Regulation for ±10% input line:	0.02%
5.	Current Regulation for ±10% input line:	0.1%
6.	Ripple:	0.2% peak to peak
7.	Temperature Coefficient (0 to 50°C):	±200ppm/°c
8.	Automatic Crossover from constant current to constant voltage	
9.	Efficiency:	85% typical
Input		
10.	Power	115V ±10% @16A, 60Hz 230V ±10% @10A, 60Hz
11.	Control Interface	IEEE 488