DUAL FREQUENCY RING MAGNET POWER SUPPLY WITH FLAT-BOTTOM*

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Summary

A power supply is described that furnishes an essentially flat-bottom injection field, followed by a dual frequency cosine field. This results in efficient beam capture during injection and reduces significantly the peak rf power required during acceleration in a rapid-cycling synchrotron.

Introduction

Ring magnets of rapid-cycling synchrotrons are usually excited by a dc-biased sinewave current as shown in Fig. 1a. An ideal excitation current wave shape is shown in Fig. 1b which utilizes most of the machine cycle for injection and acceleration. The magnet reset time, Δt_3, is the unproductive part of the cycle, its duration is determined by the $\dot{B}$ values acceptable to the ring magnets. This ideal waveshape

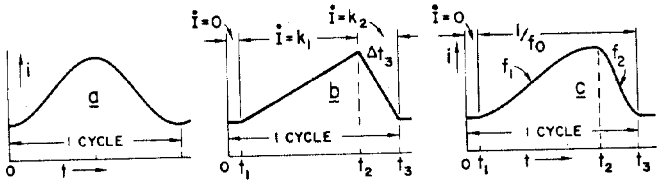

Fig. 1. Ring Magnet Excitation Shapes.

can be closely approximated by the shape shown in Fig. 1c where the flat-bottom is followed by a dual frequency cosine wave.[1] The circuit of Fig. 2 can generate the waveshape of Fig. 1c by modulating a 48-phase rectifier power supply. Capacitors resonate with the magnets at two frequencies, a choke provides a path around the capacitors for the dc bias current, and a crowbar produces the flat-bottom.

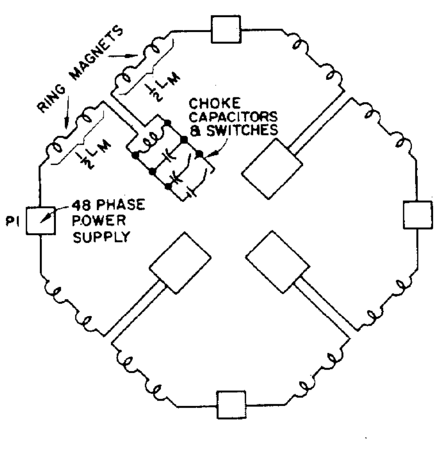

Fig. 2. Ring Magnets and Power Supply Circuit.

Neglecting saturation effects and for $L_M = L_{CH} = L$, the time-variation of the circuit currents during acceleration is

$$i_M = I_{dc} - I_{ac} \cos \omega t \qquad (1)$$

$$i_{CH} = I_{dc} + I_{ac} \cos \omega t \qquad (2)$$

$$i_C = i_M - i_{CH} = -2 I_{ac} \cos \omega t \qquad (3)$$

where

I_{dc} = dc bias current
I_{ac} = ac peak current
L_M = magnet inductance
L_{CH} = choke inductance
C = circuit capacitance

$$\omega = \left(\frac{2}{LC}\right)^{1/2} \qquad (4)$$

and

$$e_C = -\frac{2 I_{ac}}{\omega C} \sin \omega t \quad . \qquad (5)$$

The waveforms of the circuit in Fig. 2 are shown in Fig. 3.

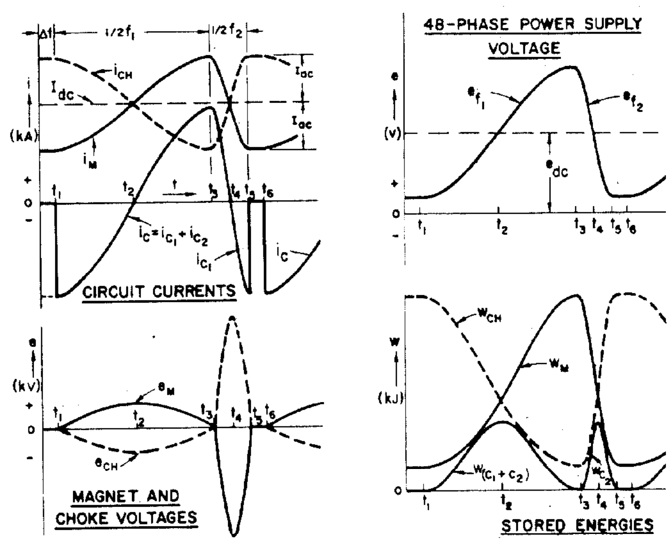

Fig. 3. Waveforms of Currents, Voltages, and Energies for the Circuit of Fig. 2.

Dual Frequency Ring Magnet Power Supply with Flat-Bottom

Ideal Switching Circuit

Figure 4a is a simplified diagram of the circuit of Fig. 2. It is initially energized with switches S_I

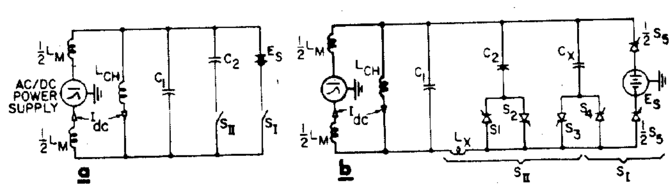

Fig. 4. Switching Circuits.

and S_{II} open; the circuit oscillates at frequency f_2. With reference to the waveforms shown in Fig. 3, a flat-bottom magnet current for beam injection is initiated at time t_o, when all the stored energy is in the inductances, by closing switch S_I. The power supply voltage maintains the magnet current until time t_1. It is not necessary to also maintain the choke current constant between times t_o and t_1, which could be accomplished with a power source, E_S, in the

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crowbar. Depending on the values of these dc voltages $\dot{B}$ values of zero, positive, or negative are possible. At time t_1 switch S_{II} is closed and switch S_I opens. With capacitors C_1 and C_2 connected in parallel the circuit oscillates at frequency f_1 until time t_3. At that time, with all the circuit energy in the inductances, switch S_{II} is opened and the circuit oscillates at frequency f_2; the decaying current resets the magnets to the injection field value. The above cycle repeats at time t_5.

General design curves for the dual frequency part of the circuit are shown in Fig. 5. A frequency f_1 during acceleration and a frequency f_2 during magnet reset correspond to an equivalent single frequency of $f_o = 2 f_1 f_2/(f_1 + f_2)$. Single frequency operation at f_o requires a capacitor bank C_o. The normalized curves f_1/f_o, f_2/f_o, C_1/C_o and C_2/C_o in Fig. 5 illustrate the trade-offs between single (f_o) and dual frequency operation (f_1, f_2) as a function of f_o/f_1.

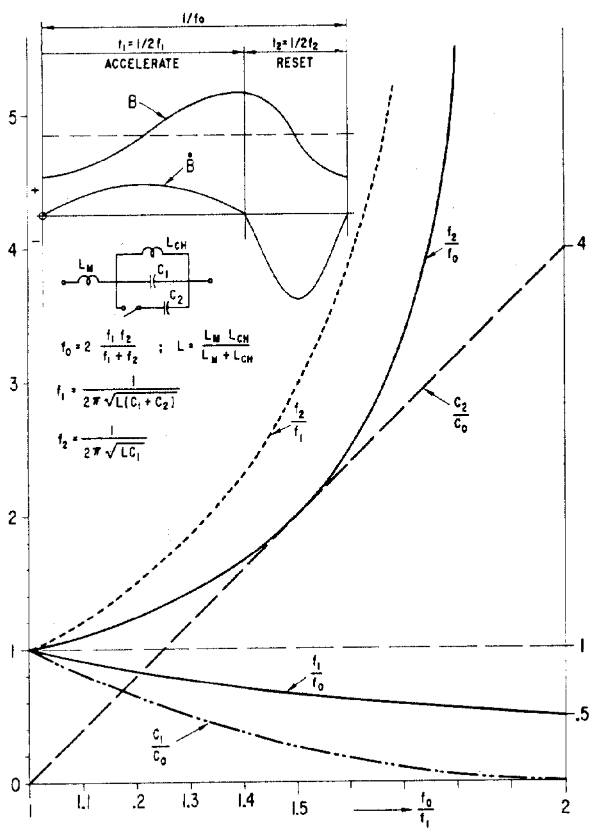

Fig. 5. Response of Dual Frequency Circuit vs f_o/f_1.

A Solid State Switching Circuit

A solid state switching circuit, is shown in Fig. 4b. For start-up it is run at frequency f_2. Just before normal circuit operation commences turn-off capacitor C_x is charged by turning on thyristor S_3 once when the choke current begins to rise. Circuit operation is described with reference to Figs. 3 and 6. In Fig. 6 heavy lines indicate current flow, a capacitor symbol drawn heavy indicates a charge on the capacitor. The following is the time sequence of events:

For $t_o < t < t_1$ (Fig. 6a) -- All the energy is stored in the circuit inductances. Thyristors S_5 are turned on, crowbaring the magnets and the choke. The crowbar current is $i = i_{CH} - i_M = (I_{dc} + I_{ac}) - (I_{dc} - I_{ac}) = 2\ I_{ac}$. Depending on the crowbar the beam may be injected into:

a) a falling field ($\dot{B} < 0$, passive crowbar),
b) a rising field ($\dot{B} > 0$, active crowbar),
c) a constant field ($\dot{B} = 0$, active crowbar),
d) a combination of the above.

At $t = t_1$ (Fig. 6b) — Thyristors S_1 and S_4 are turned on. Thyristor S_4 provides discharge paths for turn-off capacitor C_x via crowbar S_5 (current i_x') and via C_1 and L_x (current i_x''). Inductance L_x limits current i_x''. Thyristor S_1 is back biased until the charge on C_x reverses.

At $(t + 25\ \mu s) < t < t_2$ (Fig. 6c) -- The reverse current i_x' has turned off thyristors S_5. The charge on C_x is reversing and thyristor S_1 connects capacitor C_2 in parallel with C_1. The choke energy discharges at frequency f_1 into the magnets and the parallel connection of C_1, C_2 and C_x.

At $t = t_2$ (Fig. 6d) -- The capacitor current is zero, $i_M = i_{CH}$, and thyristors S_1 and S_4 turn off. All capacitors are at their frequency f_1 peak voltage.

At $t_2 < t < t_3$ (Fig. 6e) -- With thyristor S_2 turned on, the currents of capacitors C_1 and C_2 reverse. The charge on C_x remains at its value obtained at time t_2.

At $t = t_3$ (Fig. 6f) -- The capacitor current is at its peak; capacitors C_1 and C_2 are discharged. The circuit energy is stored in the inductances. At this time S_3 is turned on. This provides discharge paths for turn-off capacitor C_x via S_2 and C_2 (current i_x') and via L_x and C_1 (current i_x'').

At $(t_3 + 25\ \mu s) < t < t_4$ (Fig. 6g) -- Reverse current i_x' has turned off S_2 disconnecting C_2 from the circuit. The magnet discharges at frequency f_2 into the choke and the parallel connected capacitors C_1 and C_x.

At $t = t_4$ (Fig. 6h) -- The capacitor current is zero, $i_M = i_{CH}$, thyristor S_3 turns off. Capacitors C_1 and C_x are charged to the frequency f_2 peak voltage.

At $t_4 < t < t_5$ (Fig. 6i) -- The capacitor current reverses. At time t_5 capacitor C_1 is discharged. With all the circuit energy stored in the inductors and with the charge on C_x as shown, the circuit is ready to repeat the above cycle.

Flat-Bottom Crowbar Circuits

For magnets with large L/R time constants a passive crowbar will keep the current sufficiently flat. Magnets with small time constants require a dc voltage in the power supply and/or in the crowbar. Figure 7 shows equivalent circuits for passive and for active crowbars. Crowbar thyristors are represented by a switch S, a diode D, and a resistor R_S. The crowbar current, I_S, has the same value as the capacitor current at $t = t_o$, $I_S = I_C = I_{CH} - I_M = 2\ I_{ac}$.

Passive Crowbar. The transient response of the circuit of Fig. 7b to closure of switch S at time $t = t_o$ is shown in Fig. 8b for the circuit component values as shown on Fig. 8. The initial conditions are:

I_M = magnet current = 1.44 kA,
I_C = capacitor current = 2.60 kA,
I_{CH} = choke current = 4.04 kA.

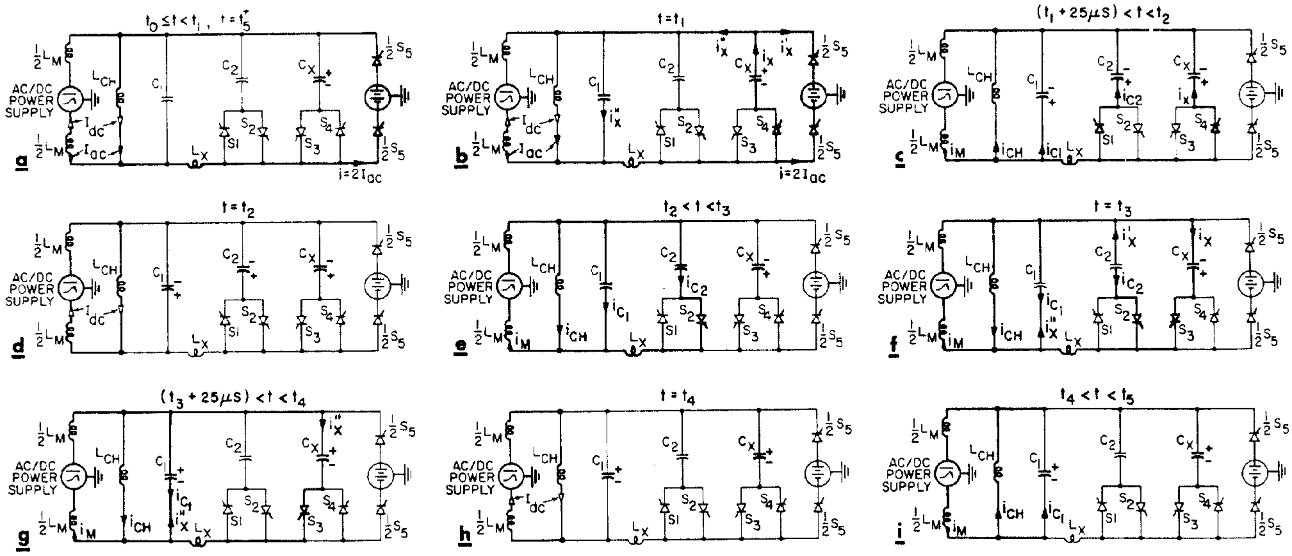

Fig. 6. Diagrams of Circuit Response at Various Times During a Cycle.

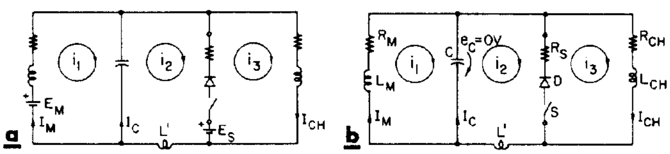

Fig. 7. Crowbar circuits.

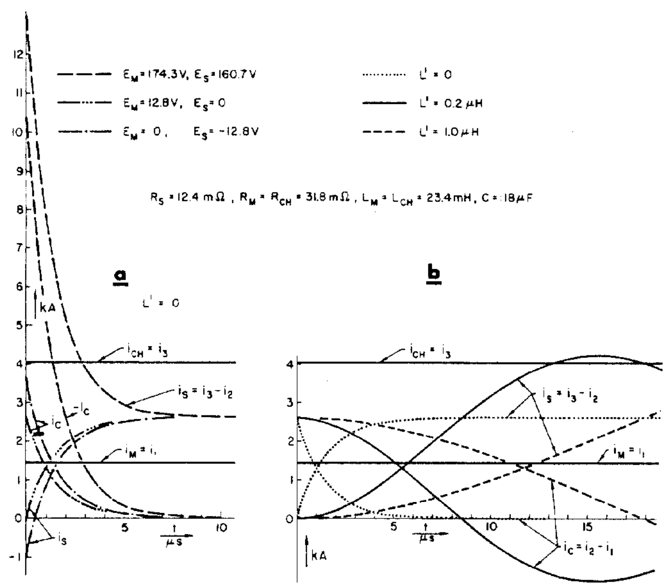

Fig. 8. Transient Response of Crowbar Circuits.

At time $t = t_o$ the magnet and choke currents change at the following rates:

$$\frac{di_M}{dt} = \frac{-I_M R_M}{L_M} = \frac{-1.44\ kA \times 31.8\ m\Omega}{23.4\ mH} = -1.96\ kA\ s^{-1} \quad (6)$$

$$\frac{di_{CH}}{dt} = \frac{-I_{CH} R_{CH}}{L_{CH}} = \frac{-4.04\ kA \times 31.8\ m\Omega}{23.4\ mH} = -5.5\ kA\ s^{-1}. \quad (7)$$

With $L' = 0$ the current transfers from the capacitor to the crowbar in about 6 µs. With $L' > 0$ this transfer takes longer and is oscillatory with a frequency of $f = 1/2\pi\ (L'C)^{1/2}$. For $L' = 0.2$ µH the capacitor current, i_C, oscillates at 32.7 KHz above and below its steady state value of zero for about 200 µs; the crowbar current, i_S, oscillates at the same frequency and for the same time around its steady state value of 2.6 kA. For $L' = 1$ µH the oscillations are at 14.6 KHz and last for about 1 ms. These oscillations have a negligible effect on the magnet and on the choke current. After the capacitor current has been transferred to the crowbar, the rate of change in the magnet current is,

$$\frac{di_M}{dt} = -\frac{I_M R_M - I_S R_S}{L_M}, \quad (8)$$

while the choke current changes as

$$\frac{di_{CH}}{dt} = -\frac{I_{CH} R_{CH} + I_S R_S}{L_{CH}}. \quad (9)$$

Note, the crowbar voltage drop, $I_S R_S$, reduces the current decay in the magnets but increases it in the choke.

Active Crowbar. For magnets with small L/R time constants, a power source is required to hold the current constant. The power source may either be in the crowbar, E_S, or in the magnet circuit, E_M, or in both as shown in Fig. 7a. The transient response of the circuit of Fig. 7a is shown in Fig. 8a for $L' = 0$. It illustrates the effects of the different power source arrangements as indicated in Fig. 8a. A circuit inductance L' would cause an oscillatory delay of the transfer of the current from the capacitor to the crowbar as was illustrated for the passive crowbar.

References

1. M. Foss, W. Praeg, "Shaped Excitation Current for Synchrotron Magnets," IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981.