Study of 1 MW Neutron Source Synchrotron Dual Frequency Power Circuit for the Main Ring Magnets

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ABSTRACT

This paper describes the proposed design of the resonant power circuits for the 1-MW neutron source synchrotron's main ring magnets. The synchrotron is to have a duty cycle of 30 Hz with a maximum upper limit of operation corresponding to 2.0 GeV and a maximum design value of 2.2 GeV. A stability of 30 ppm is the design goal for the main bending and focusing magnets (dipoles and quadrupoles), in order to achieve an overall stability of 100 ppm when random field and position errors of the magnets are included. The power circuits of this design are similar to those used in Argonne's Intense Pulsed Neutron Source (IPNS) where the energy losses during each cycle are supplied by continuous excitation from modulated multiphase DC power supplies. Since only 50% of the 30-Hz sinewave is used for acceleration, a dual-frequency resonant magnet circuit is used in this design. The 30-Hz repetition rate is maintained with a 20-Hz magnet guide field during acceleration and a 60-Hz reset field when no beam is present. This lengthens the guide-field rise time and shortens the fall time, improving the duty factor for acceleration. The maximum B dot is reduced by 33% during acceleration and hence, the maximum rf voltage/turn is reduced by 56%.

I. INTRODUCTION

The main bending and focusing magnets, dipoles and quadrupoles, have an upper limit of operation corresponding to 2.1 GeV and a maximum design corresponding to 2.2 GeV for both the magnets and power supplies. The main dipole magnets are connected in series with six parallel resonant cells and six feed points as shown in Fig. 1. The energy losses for this circuit total 9 MW and are supplied continously through the six feed points. The quadrupole magnets are divided into two families and connected in the same manner but with three feed points per family as shown in Fig. 2. The total energy loss for both quadrupole families, connected as shown, is 11 MW.

The energy loss in the resonant circuits is made up by three 12-pulse power supplies phase shifted 10° by an autotransformer for each of the feed points. These power supplies are phase-controlled with their reference voltage digital-to-analog converters being serially counted up and down, creating the desired arbitrary current shape between a base current and the maximum current in each cycle.

Main Dipole Power Circuit

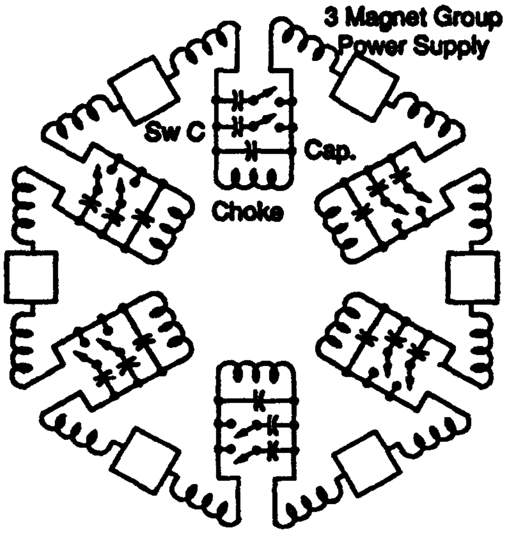

Fig. 1 Six parallel resonant cells and feed points

One Quadrupole Family Power Circuit

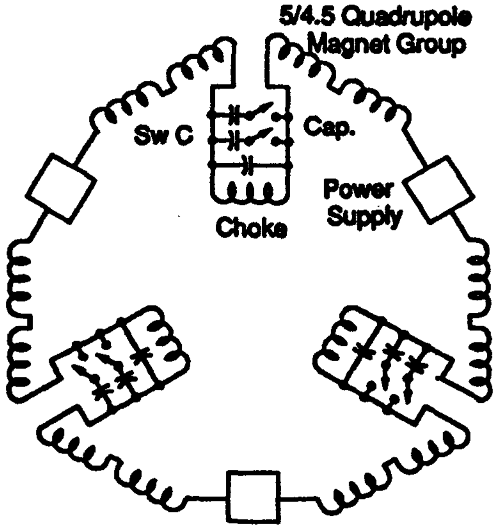

Fig. 2 Three parallel resonant cells and feed points

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II. GENERAL CONSIDERATIONS

The rapid cycling synchrotron is excited by a DC-biased sinewave current. Capacitors and chokes are used to resonate the magnets in order to save energy. The energy losses during each cycle are made up by a power source which provides continuous excitation from a modulated multiphase DC power supply, providing both DC and AC excitation from one source. It can operate over a wide frequency range and be readily phase-locked to the line or to a stable oscillator. Figure 3 illustrates the AC-DC power source comprised of three identical 12-pulse DC power supplies connected in series.

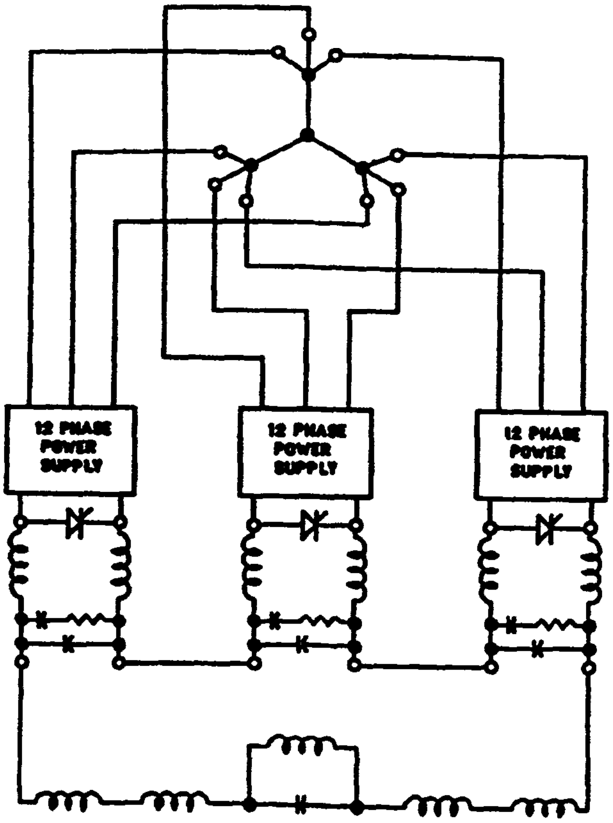

Fig. 3 Autotransformer, power supplies, and filter for one feed point.

An autotransformer is used to phase-shift the 3-phase AC inputs to each power supply by 10 electrical degrees with respect to each other. This combination provides a 36-pulse, phase-controlled DC power supply generating the desired wave shape. It operates into a slightly under-damped filter. The filter attenuates ripple above the circuit's operating frequency f_o. This configuration is repeated once for each feed point around the ring to reduce peak operating voltages. The circuit has been modified with the addition of capacitor switching for dual frequency operation, reducing the rf voltage required.

III. DUAL FREQUENCY CIRCUIT

Since only 50% of the 30-Hz sinewave is used for acceleration, a dual-frequency resonant magnet circuit has been chosen for the main magnets. The 30-Hz repetition rate is maintained with a 20-Hz magnet guide field during acceleration and a 60-Hz reset field when no beam is present. This lengthens the guide-field rise time and shortens the fall time, improving the duty factor for acceleration. The maximum B dot is reduced by 33% during acceleration and hence, the maximum rf voltage/turn is reduced by 56%. Figure 4 shows the comparison of magnet voltage and current between 30-Hz operation and the 20/60-Hz dual-frequency operation.

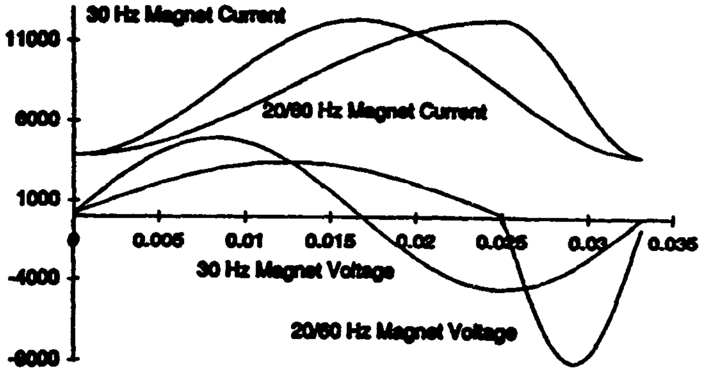

Fig. 4 Comparison of magnet voltage and current between 30 Hz and 20/60 Hz dual frequency operation.

A frequency f_1 during acceleration and a frequency f_2 during magnet reset results in a synchrotron repetition rate equal to frequency

$$f_o = \frac{2 \times f_1 \times f_2}{f_1 + f_2}. \qquad (1)$$

The fixed capacitors shown in Figs. 1 and 2 each represent capacitor bank C_2, and the sum of C_2 plus the switch capacitors per cell in Figs. 1 and 2 represent capacitor bank C_1.

The peak magnet voltage (during reset) is proportional to f_2. As f_o/f_1 increases, the capacitance value of capacitor C_1 increases while the capacitor voltage decreases. The opposite is true for the smaller capacitor bank C_2, the value of which decreases as f_o/f_1 increases, but with an ever higher voltage rating for capacitor C_2 and switch SwC, which is proportional to f_2.

For equal inductance values of the chokes and magnets, Fig. 5 shows the current waveforms and Fig. 6 shows the energy stored.

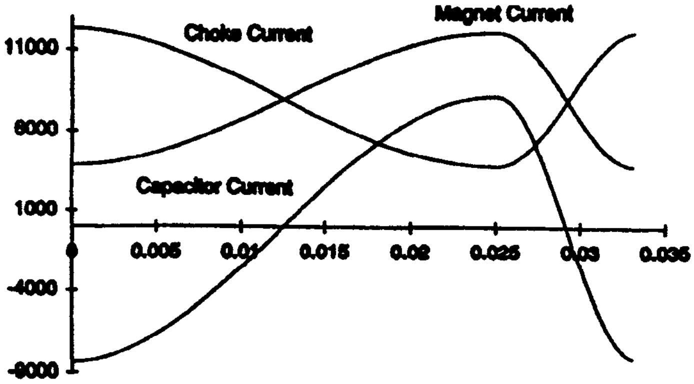

Fig. 5 Magnet, choke, and capacitor currents for circuits shown in Figs. 1 and 2.

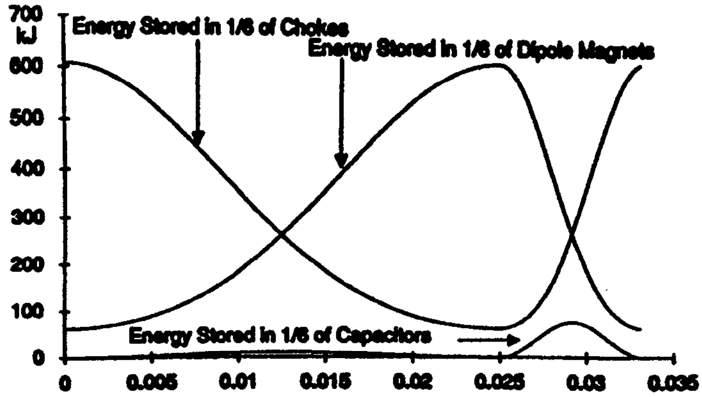

Fig. 6 Magnet, choke, and capacitor stored energy for the circuits shown in Figs. 1 and 2

The currents in the magnets and chokes are 180° out of phase. The magnet-stored energy is transferred to the choke and back again, once per cycle, through the resonant capacitor.

For equal inductance values for the choke and magnet we have

$$L_{ch} = L_m = L, \tag{2}$$

$$C = \frac{L_m + L_{ch}}{L_m \times L_{ch} \times \omega^2}. \tag{3}$$

Neglecting saturation effects, the time-variation of the magnet current during acceleration is

$$i_{magnet} = I_{dc} - I_{ac} \times Cos\ \omega t. \tag{4}$$

The choke and capacitor currents are given by

$$i_{choke} = I_{dc} + I_{ac} \times Cos\ \omega t, \tag{5}$$

$$\begin{aligned} i_{capacitor} &= i_{magnet} - i_{choke} \\ &= -2I_{ac} \times Cos\ \omega t \end{aligned}. \tag{6}$$

The capacitor and magnet voltages are given by

$$e_c = \frac{2I_{ac}}{\omega C} Sin\ \omega t, \tag{7}$$

$$e_m = E_{dc} + e_c. \tag{8}$$

IV. CIRCUIT LOSS BUDGET

To estimate the circuit parameters, a loss budget was established for the circuits in Figs. 1, 2, and 3 based on the dipole and quadrupole magnet designs. Table 1 shows the budget for the dipoles (Figs. 1 and 3). Table 2 shows the budget for the quadrupoles (Figs. 2 and 3).

Table 1 Synchrotron dipole resonant power circuit loss budget.

Ring Dipole Magnets	Chokes	Capacitors	Inter-connections	Filters	Power Supplies	Number of Magnets
0.32	0.32	0.05	0.10	0.05	0.16	
79765	79765	12463	24927	12463	39883	1
478591	478591	74780	149560	74780	239296	6
2871548	2871548	448679	897359	448679	1435774	36

There are six feed points, each has three 12-pulse power supplies, with their input phase shifted 10° from the next (see Fig. 3).
Each group of three power supples is required to make up 1495598 W.
Total system losses are 8973589 W.

Table 2 Synchrotron quadrupole resonant power circuits loss budget.

Ring Dipole Magnets	Chokes	Capacitors	Inter-connections	Filters	Power Supplies	Number of Magnets
32%	32%	5%	10%	5%	16%	
60101	60101	9391	18781	9391	30050	1
601005	601005	93907	187814	93907	300503	10
3606031	3606031	563442	1126885	563442	1803015	60

There are two families of quadrupoles, each having three feed points (this assumes half the quads per family). Each family's magnets are divided into six equal groups for a total of 4.5 magnets per group. To maintain symmetry, an extra magnet is added to make each group equal five magnets, for a total of 60. Each feedpoint has three 12-pulse power supplies, with their input phase shifted 10° from the next (see Fig. 3).

Each group of three power supples is required to make up 1878141 W.
Total system losses are 11268846 W.

From the loss budget and Eqs. 1 through 8, design values were established. They are listed in Table 3 for the dipole circuits and Table 4 for the quadrupole circuits.

V. FLAT-BOTTOM INJECTION

At injection into the synchrotron, a constant magnet field, $\dot{B} \approx 0$, may be required for 1 ms to 1.5 ms to reduce beam loss during injection. If this is needed, it is accomplished with either a passive or active crowbar as shown in Figs. 7a and 7b.

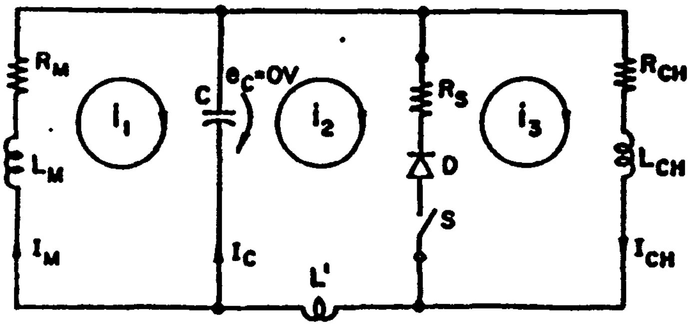

Fig.7a Passive crowbar for flat-bottom.

A flat-bottom magnet current for beam injection is initiated at times t_0, t_5, etc. when switch S is closed, as shown in Fig. 8. As illustrated in this figure, the power supply voltage maintains the magnet current until time t_1.

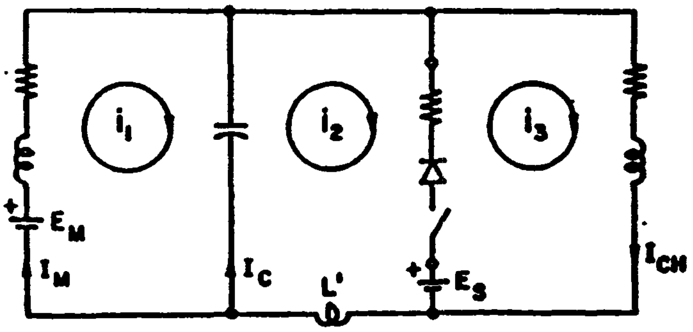

Fig. 7b Active crowbar for flat bottom.

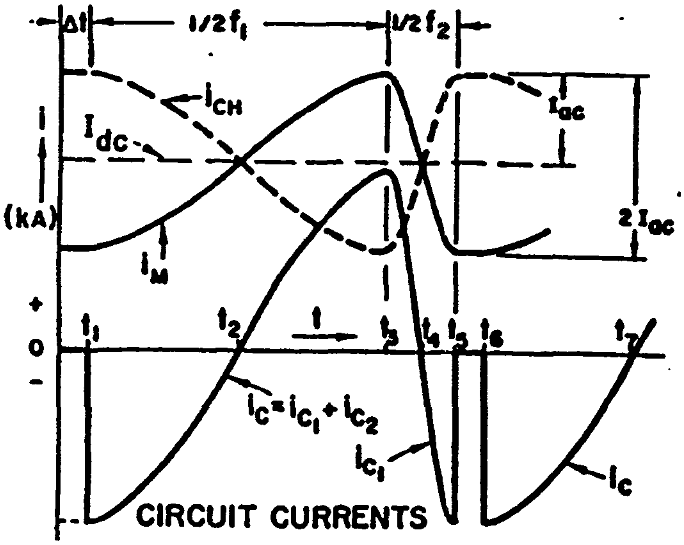

Fig. 8 Timing and circuit currents with flat bottom.

It is not essential to also maintain the choke current constant between times t_0 and t_1, which can be accomplished with a power source, E_S, in the crowbar.

Depending on the values of the DC voltages, $\dot{B}$ values of zero, positive, or negative, are possible.

For $t_0 \leq t < t_1$, all the energy is stored in the circuit inductances. Crowbaring the ring magnets and the chokes requires the crowbar to carry the difference between these currents

$$i = i_{CH} - i_M = (I_{dc} + I_{ac}) - (I_{dc} - I_{ac}) = 2I_{ac}. \quad (9)$$

The crowbar may or may not contain a power source in addition to the 36-pulse power supply, requiring beam to be injected into:

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

For magnets with a large L/R time constant, a passive crowbar is sufficient to keep the current flat within 0.1% for 1.5 ms. Magnets with small time constants require a DC driving voltage in the power supply and/or in the crowbar. Figs. 7a and 7b show equivalent circuits for passive and active crowbars. In these circuits, the crowbar switch S in series with diode D (unidirectional current flow) and resistor R_S is, for practical purposes, constant during the 1-ms injection time. The nominal crowbar current has the same value as the capacitor current at time $t = t_0$,

$$I = I_{CH} - I_M = 2I_{ac}.$$

Table 3 Operating parameters for the synchrotron dipole resonant circuit.

Circuit Values	20 Hz	60 Hz
Inductance of a magnet	0.001345	1.35E-03
Inductance of 1/6 of the total magnet	0.00807	8.07E-03
Magnet rms current	8616	8616
Magnet DC current	8092	8092
Magnet peak AC current	4181	4181
Capacitor bank peak AC current	-8362	-8362
Number of feedpoints	6	6
Total number of power supplies	18	18
Number of magnet families	1	1
Total number of magnets	36	36
Total DC resistance of 1/6 magnets, chokes, filters, interconnections.	0.0130308	0.0130308
Total AC resistance of 1/6 magnets, chokes, filters, interconnections and capacitors.	0.0654197	0.06541977
f_0	20	60
W_0	125.6637	376.9911
1/6 total capacitance	0.15694	0.001744
Select 550 kW (one power supply)	529	529
Voltage rms of one power supply based on the KW rating selected	64	64
Voltage peak of one power supply based on power supply selected	171	171
AC voltage peak across the tank	3318	9303
DC voltage across 1/6 of the magnets, chokes, interconnections, and filters	105	105
e_pT	3371	9356

Passive Crowbar

Without a driving voltage in the crowbar and with zero voltage on the capacitor, the magnet and choke currents change at time $t = t_0$ at the following rates. The magnet's current rate of change corresponds to

$$\frac{di_M}{dt} = -\frac{I_M R_M}{L_M},$$

and the choke's current rate of change corresponds to

$$\frac{di_{CH}}{dt} = -\frac{I_{CH} R_{CH}}{L_{CH}}.$$

With L' = 0, the current transfers form the capacitor to the crowbar in about 6 µs. With L' > 0, this transfer takes longer and is oscillatory with a frequency of

$$f = \frac{1}{2\pi\sqrt{L'C}}.$$

For L' = 0.2 µH the capacitor current i_C oscillates at 1 kHz around its steady state value of zero, for about 200 µs; the crowbar current oscillates at the same frequency and for the same duration with a steady state value of -8 kA. For L' = 1 µH, the oscillations are at 0.4 kHz for about 8 ms. These oscillations have a negligible effect on the magnet and choke currents. After the capacitor current has been transferred to the crowbar, the rate of change in

Table 4 Operating parameters for the synchrotron quadrupole resonant circuit.

Circuit Values	20 Hz	60 Hz
Inductance of a magnet	1.08E-03	1.08E-03
Inductance of 1/6 of the total magnet	1.08E-02	1.08E-02
Magnet rms current	4729	4729
Magnet DC current	4442	4442
Magnet peak AC current	2295	2295
Capacitor bank peak AC current	-4590	-4590
Number of feedpoints	6	6
Total number of power supplies	18	18
Number of magnet families	2	2
Total number of magnets	60	60
Total DC resistance of 1/6 magnets, chokes, filters, interconnections.	0.038759	0.038759
Total AC resistance of 1/6 magnets, chokes, filters, interconnections and capacitors.	0.31027	0.31027
f_0	20	60
W_0	125.6637	376.9911
1/6 total Capacitance	0.011727	0.001303
Select 550 kW (one power supply)	664.2688	664.2688
Voltage rms of one power supply based on the KW rating selected	142	142
Voltage peak of one power supply based on power supply selected	396	396
AC voltage peak across the tank	3153.991	7448
DC voltage across 1/6 of the magnets, chokes, interconnections, and filters	172	172
e_pT	3240	7534

the magnet current is,

$$\frac{di_M}{dt} = -\frac{I_M R_M - E_{crowbar}}{L_M}, \qquad (10)$$

while the choke current changes as

$$\frac{di_{CH}}{dt} = -\frac{I_{CH} R_{CH} + E_{crowbar}}{L_{CH}}. \qquad (11)$$

Note that the crowbar voltage drop reduces the current decay in the magnets but increases the current decay in the chokes.

Active Crowbar

For magnets with small L/R time constants, an active power source is required to hold the injection current to within 0.1%. The power source may be in the crowbar, the magnet circuit, or both, as shown in Fig. 7a.

Inductance of the crowbar power source must be small to not delay transfer of the current from the capacitor to the crowbar. This requires a low voltage capacitor bank in parallel with the crowbar power supply.

As in the passive crowbar circuit, L' causes an oscillatory delay during the transfer of current from the capacitor to the crowbar.

VI. CONCLUSIONS

The circuits covered in this paper meet the requirements for an IPNS upgrade to 1 MW.

The power loss estimates are conservative.

Effort should be made to reduce the losses in the final design.

A 1-1.5 ms zero $\dot{B}$ for injection should be obtainable.

VII. REFERENCES

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