RESONANT PULSE POWER SUPPLY FOR COMPACT PROTON 
AND/OR HEAVY ION SYNCHROTRON
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Abstract
A resonant type pulse power supply, for an application 
to a compact proton and/or heavy ion synchrotron with a 
several Hz repetition rate, is attractive from the view 
point of attaining large average beam current that is 
enough for the radiation therapy. Maximum ampere-turn 
of the dipole magnet is as large as 200 kA to make the 
bending radius as small as possible. Pulse current is 
generated by discharging the stored energy in a capacitor 
bank through a pulse transformer. The current pulse width 
can be adjusted by the circuit elements including dipoles 
to a desired value to limit the heat load to the excitation 
coil. Its circuits and behaviors are treated for the realistic 
parameters.

1 INTRODUCTION
To realize the small hospital-based accelerator called a 
table-top proton synchrotron (TTPS) using a normal 
conducting high field magnet as presented at EPAC2000 
[1], magnets should be excited by a large half-sinusoidal 
current in a short time to avoid the heating of the 
conductor. An extracted average proton beam intensity 
required by a medical treatment is 10 nA or more to 
administrate the prescribed radiation dose to the target 
volume in a few minutes. The small synchrotron with a 
limited beam aperture and a short injection time cannot 
afford to attain the beam intensity requirement with a 
small repetition rate. A beam repetition rate should be 
increased as large as the conductor can bear. According to 
the temperature increase of the water-cooled conductor, the 
5 to 10 Hz operation will be possible depending on the 
conductor cross-section. It also imposes the same 
repetition rate to the power supply system.

To energize all magnets to a peak field by a half-
sinusoidal current pulse in 10 ms or less, a large capacitor 
bank is required. Considering the energy in the form of 
the magnetic field, the stored energy is about 100 kJ and 
it is restored in a short time for the next excitation. As 
soon as attaining the peak field the discharge circuit is 
disconnected to establish the recovery circuit to restore the 
remaining energy in the secondary circuit that includes the 
magnets. And the consumed energy must be supplemented 
from the primary line.

The same power supply with the increased stored 
energy can be used to the next stage project to develop a 
heavy ion synchrotron of a moderate scale for the carbon 
ion beam therapy adopting the same components except 
for dipoles after the actual proof test of the compact 
proton synchrotron.

2 BASIC CIRCUIT
A basic circuit of the power supply including a magnet is 
simplified as in Fig.1.

Figure 1: Simplified circuit of the power supply.

Using notations in Fig.1, the circuit equations are 
expressed as follows,

\[ V_1 = j\omega L_1 I_1 + j\omega M I_2 \]  
\[ V_2 = j\omega M I_1 + j\omega L_2 I_2 = -j\omega L_2 I_2 \],

where \( L_1 = n^2 L \quad L_2 = L \) and
\[ M = k\sqrt{L_1 L_2} \equiv \sqrt{L_1 L_2} \] (k \( \equiv 1 \))

assuming the primary to secondary winding turn ratio of a 
matching transformer as \( n :1 \). The \( L_B \) is the inductance of 
the magnet to be excited, \( C \) the energy storage capacitor 
and \( k \) the coupling coefficient. For the sake of 
simplicity, the parasitic inductance \( L_{\text{para}} \), the resistance 
\( R \) and \( R_B \) are neglected. Therefore the secondary current is

\[ I_2 = -M I_1 (L_2 + L_B) \],

and the input impedance \( Z_i \) is

\[ Z_i = \frac{V_2}{I_1} = j\omega n^2 L \left( \frac{1}{L + L_B} \right) \].

Considering the relative value of \( L \) and \( L_B \) when 
designing the whole circuit, \( L << L_B \) and \( L \equiv L_B \) cases 
may be realized. The \( L >> L_B \) case gives the infinitesimal 
impedance from (4).

(1) When \( L << L_B \),

\[ Z_i = j\omega n^2 L \]

and

\[ V_2 = \omega n L_B I_1 \].

In this case the total effective impedance is \( L_{\text{total}} = n^2 L_B \)
and the resonant frequency is
\( \omega = \frac{1}{n \sqrt{C L_B}} \). (7)

Assuming 50Hz the turn ratio is \( n = 3.2 \times 10^{-5} / \sqrt{C L_B} \).
Let the magnet with multi-turn coil windings have 100 \( \mu \)H for TTPS. Then, \( n = 0.32 / \sqrt{C} \) is obtained. For an example, \( n = 7 \) for 2.1 mF, \( I_1 = 3000 \) A and \( V_1 = 4500V \) to attain the peak secondary current of 20 kA for 10 turn coil corresponding to 3 T.

(2) When \( L \equiv L_B \),
\[ Z_r = 0.5 j n^2 L, \]
and
\[ V_r = 0.5 j n^2 L I_1, \]
The total effective inductance in this case is \( L_{\text{total}} \equiv 0.5 n^2 L_B \) which resonates with the capacitor \( C \). Then, the resonant frequency is
\[ \omega = \sqrt{2 / n^2 C L_B}. \] (10)

Letting \( L = L_B = 1 \) \( \mu \)H for 50 Hz, \( n = 4.5 / \sqrt{C} \) which leads to \( n = 100 \) for 2.1 mF, \( V_1 = 6300 \) V and \( I_1 = 2000 \) A to attain the same peak magnetic field.

The turn ratio of the matching transformer and the primary voltage are small for larger \( L_B \). Assuming above parameters in both cases, comparisons are given in Fig.2.

As the inductance of the multi-turn coil is larger than the parasitic one, problems associated with the cabling and electrical connection will be avoided in addition to simplification in manufacturing the matching transformer. However, the coil becomes complicated and requires more its space to built in.

### 3 MULTI-MESH CIRCUIT

The proton synchrotron ring magnets system is composed of 4 dipoles and 4 defocusing and 8 focusing quads [2]. The quadrupole field must track the dipole field precisely although the dipole is excited by the method mentioned above. As all dipoles assure the same instantaneous current all the time during acceleration, the multi-mesh circuit of Fig.3 is evaluated by the numerical simulation and its current and voltage behaviors are shown for the case of the multi-turn coil in Fig.4. The first peak attains 20 kA and the current trace shows the 50 Hz sinusoidal dumping oscillation due to the ohmic loss.

![Figure 3: Multi-mesh circuit to assure the same instantaneous current for all dipole magnets with 10 turn coils.](image)

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![Figure 4: Current and voltage behaviors of the multi-mesh circuit. (a) Terminal voltage of each dipole, and (b) currents and voltages at the probe points in Fig.3.](image)

By putting the earth point at the middle of one of the coils, the phantom null voltage point is generated at the middle of others and the peak terminal voltage of every dipole is about ±340 V as shown in Fig.4.

![Figure 5: Multi-mesh circuit to assure the same instantaneous current for all dipole magnets with one turn coils.](image)

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Similar simulations are also performed for the circuit of single turn coil dipoles of Fig.5 and results are shown in Fig.6 where the peak current is almost 200 kA which corresponds to the magnetic field of 3 T. The maximum terminal voltage of each magnet is about ±40 V for this case.

**Figure 6:** Current and voltage behaviors of the multi-mesh circuit. (a) Terminal voltage of each dipole, and (b) currents and voltages at the probe points in Fig.5.

**4 ENERGY RECOVERY AND CAPACITOR CHARGING**

Immediately after finishing the acceleration the residual energy in the secondary circuit should be recovered to increase the repetition rate of the synchrotron. By forced switching of the power switching elements from the discharge to the recovery mode, most of the energy initially stored in the capacitor can be restored except for the resistive loss. It is easily demonstrated by using a simple circuit of Fig.7 where the switch elements are replaced with relays which are sequentially operated for two cycles. In the real system they are replaced with the fast switch elements such as IGBT or MOSFET as shown in Fig.9 for a case of the push-pull circuit. The switching rate will be selected between 5~20 kHz according to the charging rate.

As the charge and discharge are repeated during the accelerator operation, the charging circuit supplies the dissipated energy to the preset voltage after recovering the residual energy of the secondary circuit except for the initial cycle.

**Figure 7:** Demonstration circuit for the energy recovery to increase the repetition rate. Mode changes from discharge to recovery and recovery to discharge are performed by relays only for two cycles.

**Figure 8:** Energy is recovered every 10 msec in coincidence with the resonant frequency of 50 Hz.

**Figure 9:** Simulation of the simplified charging circuit. In this case MOSFET is used as a switching element.

**REFERENCES**
