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.

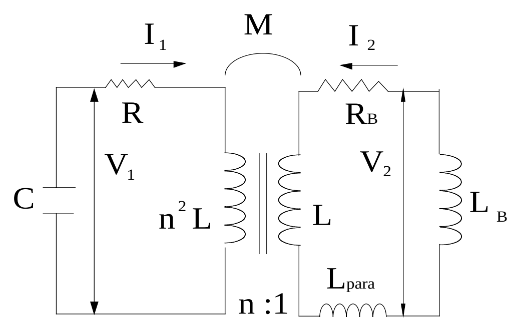

Figure 1: Simplified circuit of the power supply.

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

$$V_1 = j\omega L_1 I_1 + j\omega M I_2 \quad (1)$$

$$V_2 = j\omega M I_1 + j\omega L_2 I_2 = -j\omega L_B I_2, \quad (2)$$

where $L_1 = n^2 L$, $L_2 = L$ and

$$M = k\sqrt{L_1 L_2} \cong \sqrt{L_1 L_2} \ (k \cong 1)$$

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_{para}, the resistance R and R_B are neglected. Therefore the secondary current is

$$I_2 = -MI_1/(L_2 + L_B), \quad (3)$$

and the input impedance Z_i is

$$Z_i = \frac{V_1}{I_1} = j\omega n^2 L\left(1 - \frac{L}{L + L_B}\right). \quad (4)$$

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

(1) When $L << L_B$,

$$Z_i = j\omega n^2 L \quad (5)$$

and

$$V_2 \cong \omega n L_B I_1. \quad (6)$$

In this case the total effective impedance is $L_{total} = n^2 L_B$ and the resonant frequency is

$$\omega = 1/n\sqrt{CL_B}\,. \qquad (7)$$

Assuming 50Hz the turn ratio is $n = 3.2\times10^{-3}/\sqrt{CL_B}$. Let the magnet with multi-turn coil windings have 100 μH 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 $L \cong L_B$,

$$Z_i \cong 0.5 j\omega n^2 L, \qquad (8)$$

and

$$V_1 \cong 0.5 j\omega n^2 L I_1. \qquad (9)$$

The total effective inductance in this case is $L_{total} \cong 0.5 n^2 L_B$ which resonates with the capacitor C. Then, the resonant frequency is

$$\omega = \sqrt{2/n^2 CL_B}\,. \qquad (10)$$

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

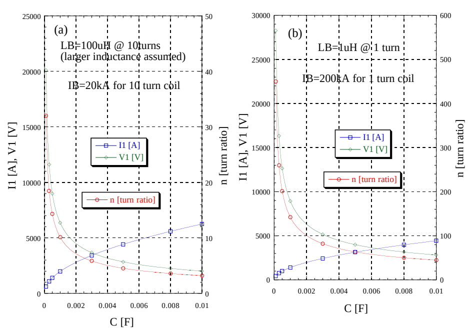

Figure 2: Estimations of capacitor, turn ratio of the matching transformer, primary current and capacitor voltage for exciting one dipole magnet up to the maximum field for (a) 10 turn coil and (b) 1 turn coil.

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.

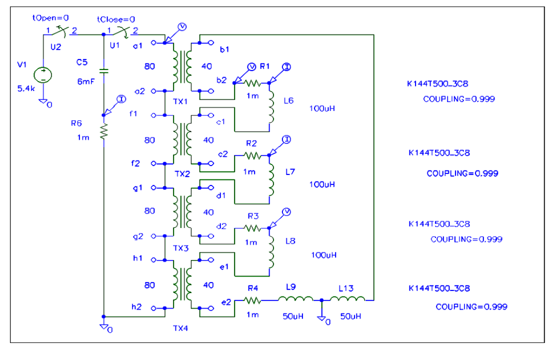

Figure 3: Multi-mesh circuit to assure the same instantaneous current for all dipole magnets with 10 turn coils.

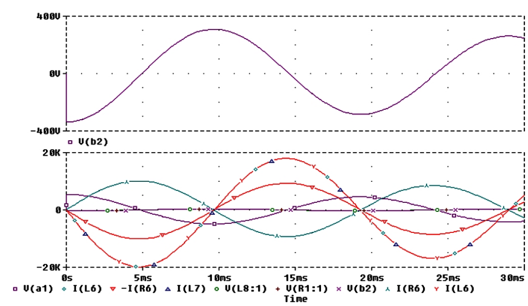

Figure 4: Current and voltage behaviors of the multi-mesh circuit. (a) Terminal voltage of each dipole, and (b) currents and voltages at the probe points in Fig.3.

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.

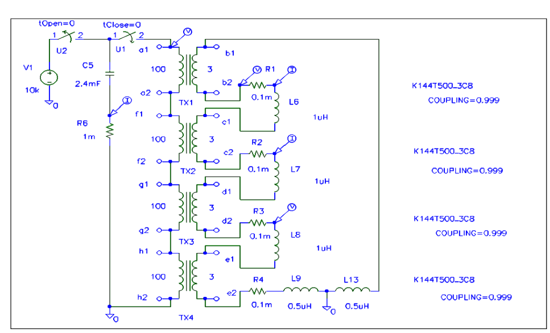

Figure 5: Multi-mesh circuit to assure the same instantaneous current for all dipole magnets with one turn coils.

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.

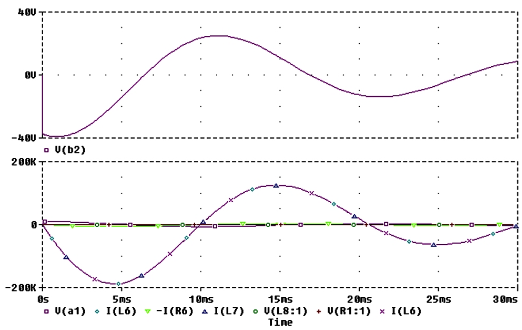

Figure 6: Current and voltage behaviors of the multi-mesh circuit. (a) Terminal voltage of each dipole, and (b) currents and voltages at the probe points in Fig.5.

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 SCR.

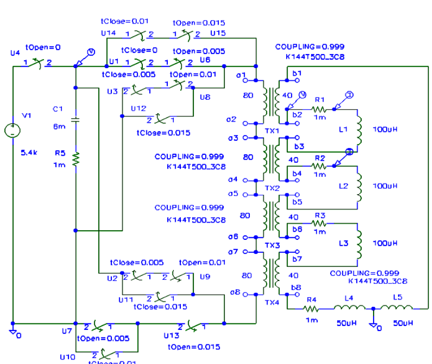

Figure 7: Demonstration circuit for the energy recovery to increase the repetition rate. Mode changes from discharge to recovery and recovery to discharge are performed by relays only for two cycles.

As for the capacitor charging, the dc voltage rectified with diodes is used to charge the capacitor through the inverter circuit of the switching 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.

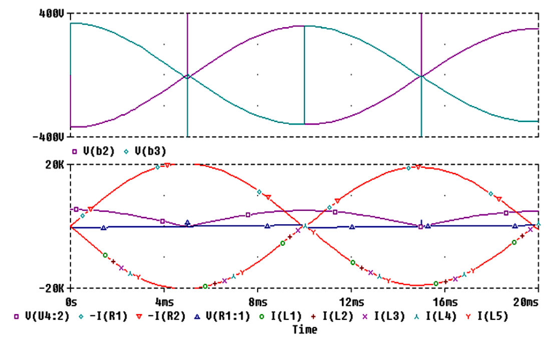

Figure 8: Energy is recovered every 10 msec in coincidence with the resonant frequency of 50 Hz.

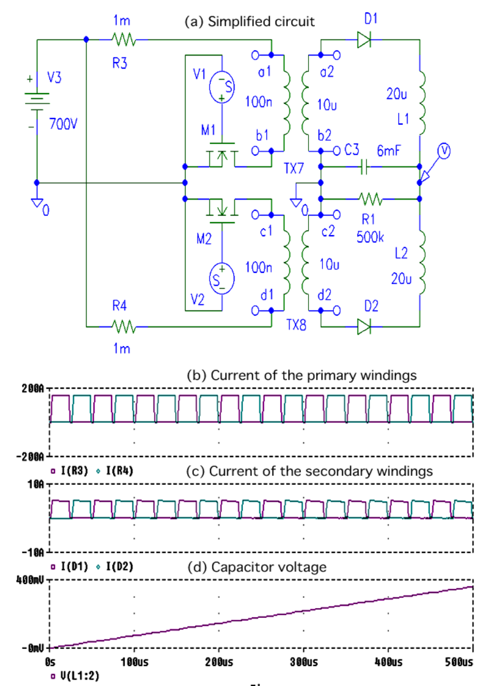

Figure 9: Simulation of the simplified charging circuit. In this case MOSFET is used as a switching element.

REFERENCES

[1] K. Endo et al, "Table-Top Proton Synchrotron Ring for Medical Applications," EPAC2000, Wien, pp.2515-7.

[2] K. Endo et al, "Compact Proton and Heavy Ion Synchrotron for Cancer Therapy and Bio-Science," to be appeared in the Proc. of 13th Symp. Acc. Sci. and Tech., Osaka, 2001.