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A MULTI-FUNCTION RING MAGNET POWER SUPPLY FOR RAPID-CYCLING SYNCHROTRONS*

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Abstract: Ring magnet power supply (RMPS) circuits that produce a wide range of magnet current waveshapes for rapid-cycling synchrotrons (RCS) are described. The shapes range from long flat-tops separated by a biased dual frequency cosine wave to those having a flat-bottom (injection), followed by a lower frequency cosine half wave (acceleration), a flat-top (extraction), and a higher frequency cosine half wave (magnet reset). Applications of these circuits for proposed synchrotrons are outlined. Solid-state switching circuits and the results of proof-of-concept tests are shown.

Introduction

Ring magnets of RCSs are usually excited by a dc-biased sinewave of frequency f_0.[1] In 1980 I proposed a circuit for dual frequency excitation.[2,3] A half cosine wave of frequency $f_1 < f_0$ is applied during acceleration, thereby reducing significantly the peak rf power required as compared to single frequency, f_0, operation. After acceleration, the magnets are reset with a half cosine wave of frequency $f_2 > f_0$. The repetition rate of the dual frequency circuit is the same as for a single frequency circuit operating at $f_0 = 2 f_1 f_2/(f_1+f_2)$. Figure 1, without switch S_{II}, is a block diagram of the circuit. Later I added switch S_{II} to provide constant current during beam injection or during beam extraction.[3,4] This paper describes further circuit developments for generating a wide variety of RMPS current shapes. Their application should minimize the cost of new RCSs, and in some cases permit to build and operate facilities in stages and perhaps to upgrade existing facilities. To simplify the wave shape diagrams, the inductance values of ring magnets, L_M, and of energy storage chokes, L_{CH}, are assumed to have equal values.

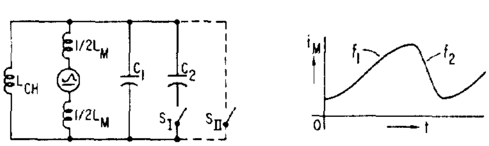

Fig. 1 Dual frequency resonant circuit.

Long Flat-Tops Separated by Dual Frequency Cosine Wave

The waveshapes of Fig. 2 are proposed for a synchrotron with a 100 pps repetition rate and 5 ms flat-tops for the Daresbury Laboratory in England. They can be generated by the circuit of Fig. 3. At time t_0, all circuit energy is stored in the inductances; the magnet current i_M is at beam injection level, the choke current i_{CH} is at its peak value. At this time, solid-state switch S_I is closing, switch S_{II} remains open. Between times t_0 and t_2, the circuit resonates at frequency f_1 while the energy stored in choke L_{CH} is being transferred to the magnets L_M via capacitors $C_1 + C_2$. At time t_2 the capacitors are discharged, switch S_{II} is closing and S_I is opening. Between times t_2 and t_3, the magnet current is held constant by dc power supply $E_M = i_M R_M$ while the beam

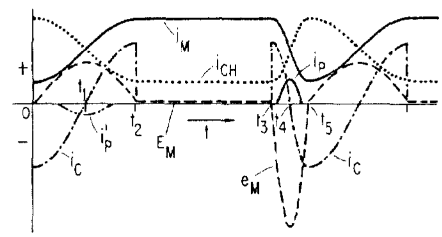

Fig. 2 Long flat-tops separated by dual frequency cosine wave.

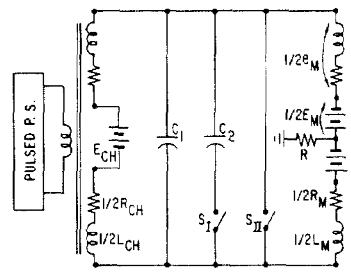

Fig. 3 Circuit to generate the waves of Fig. 2

is being extracted; the choke current is being maintained by dc power supply $E_{CH} = i_{CH} R_{CH}$. The difference of the two currents, $\Delta i = i_M - i_{CH}$ flows through switch S_{II}. At time t_3 switch S_{II} opens causing the circuit to oscillate at frequency f_2 until time t_5 when the magnet current has decayed to its injection level. At time t_5, the above cycle is repeated. The ac power losses of the resonant circuits are made up by a current pulse i_p on the primary winding of the choke.[5] This pulse is usually applied during the descending portion of the magnet current. When the current pulse occurs symmetrically around the peak of the capacitor voltage, $e_C = -e_M$, there is no phase disturbance.[5] Therefore, it is possible to make up circuit losses more economically during acceleration with a current pulse i_p^1 arranged symmetrically around time t_1 in place of pulse i_p. During acceleration, there is more time for the pulse and the capacitor voltage is smaller. For initial start-up switch S_{II} is closed until the magnet current i_M and the choke current i_{CH} have risen to the values shown for time t_0.

Long Injection and Extraction Times with Different Frequencies for Acceleration and Reset

The waveshapes of Fig. 4 can be generated by the circuit of Fig. 5 which is shown in its start-up condition. With switches S_{II} and S_{III} closed, the dc power supplies $E_{CH} + E_{CH}^{FB}$ drive the choke current to its flat-top value; power supply E_M^{FB} drives the magnet current to its flat-bottom value. This condition is the one shown at time t_0. Beam is injected between times t_0 and t_1. At time t_1 switch S_I closes and switches S_{II} and S_{III} open. The energy stored in the choke is transferred to the magnet via capacitors C_1 and C_2 between times t_1 and t_3 when the beam is being accelerated. At time t_3 slow beam extraction begins when switches S_{II} and S_{IV} close and switch S_I opens. The magnet current is held constant at its flat-top

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level by the series connected power supplies $E_M + E_M^{FB}$, the choke current is held at its lowest level by power supply E_{CH}^{FB}. At time t_4 beam extraction is terminated by opening of switches S_{II} and S_{IV}. The energy stored in the magnets is transferred to the choke via capacitor C_1 at a frequency f_2 between times t_4 and t_6. At time t_6, switches S_{II} and S_{III} are closed again and the above cycle is repeated.

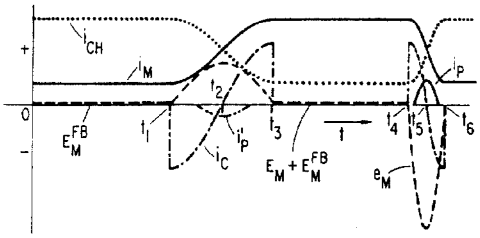

Fig. 4 Long injection and extraction.

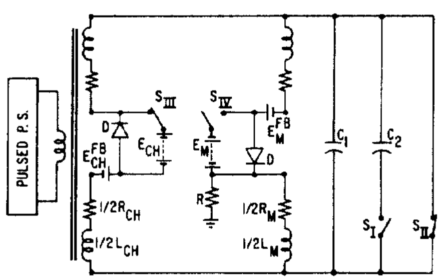

Fig. 5 Circuit to generate the waves of Fig. 4.

Different Combinations of Injection and Extraction Times

The circuit of Fig. 5 can provide any combination of injection and extraction times by operating switches S_I through S_{IV} appropriately. For example, for the proposed TRIUMF II "Kaon Factory", Fig. 6 illustrates the facility operation.[6] Protons from

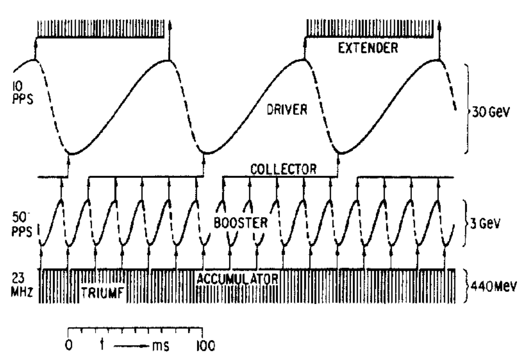

Fig. 6 TRIUMF II facility operation.

the 23 MHz cw TRIUMF cyclotron are stored in an ACCUMULATOR before they are injected at 440 MeV into a 50 pps BOOSTER-RCS which accelerates them to 3 GeV. During acceleration the BOOSTER resonates at $f_1 = 33\ 1/3$ Hz and when the magnets are reset it resonates at $f_2 = 100$ Hz. Five BOOSTER pulses are extracted into a COLLECTOR before they are injected into a 10 pps DRIVER-RCS which accelerates them to 30 GeV. The dual frequency driver resonates at 6 2/3 Hz and 20 Hz; its beam may be extracted fast or into an EXTENDER ring for slow extraction. The TRIUMF group is also considering a staged construction which initially would not have the COLLECTOR and EXTENDER rings. The same beams could be provided at a lower repetition rate by operating the BOOSTER and DRIVER synchrotrons as illustrated in Fig. 7. The BOOSTER could use a RMPS as described in reference 7, and the DRIVER could use the one illustrated in Fig. 5.

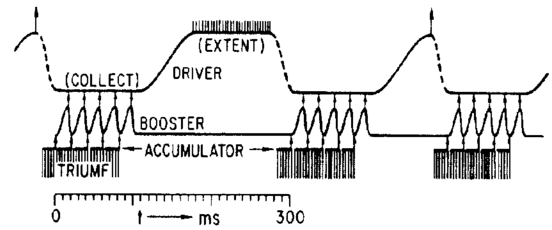

Fig. 7 TRIUMF II initial stage without COLLECTOR and EXTENDER.

Solid-State Switching Circuits

The switches shown in the above circuits must be capable of carrying currents of ≤ 5 kA and of holding off forward and reverse voltages ≤ 20 kV. In the low voltage proof-of-concept circuits of Figs. 8 and 10 SCRs and/or GTOs were used to make up switches S_I and S_{II}. For practical applications, each of the SCRs or GTOs shown in Figs. 8 and 10 for S_I and S_{II} would represent a column of these components connected in series to achieve the required voltage rating. This is being done routinely with SCRs and their hard turn-off circuits (comprising C_X, S_3, S_4, L_X, and R_X in Fig. 8) are relatively inexpensive. Only recently have GTOs become commercially available with ratings approaching those of SCRs. Devices with heavy metal doping possess symmetrical blocking characteristics which makes them suitable for our applications. However, at this time, it is not clear whether a column of series connected GTOs with their more complicated gate and snubber circuits will be as economical and reliable as SCR-columns. In the near future, experience will be gained in this respect; as will be shown below, either component can be used. For very large currents, thyristor columns must be connected in parallel with forced current sharing.

Proof-of-Concept SCR Circuit

In the circuit of Fig. 8, a constant dc current circulates through the magnet, L_M, and choke L_{CH}; ac-excitation is provided by a current pulse when the magnet voltage is at its peak. The circuit was operated in three modes as shown in Figs. 9a through 9c. This circuit was arranged to test the SCR-switching, no effort was made to hold the bottoms and tops very flat. Therefore, when the magnet was crow barred at its lowest current, Fig. 9a, the fixed voltage E_{dc} drove the current up at a rate of $di_M/dt = E_{dc}/L_M$. During flat top, Figs. 9b and 9c, the voltage E_{dc} was not quite large enough to maintain the current constant.

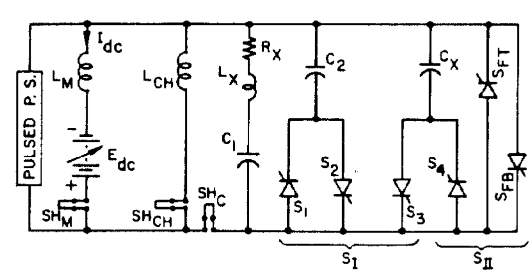

Fig. 8 Proof-of-concept SCR circuit.

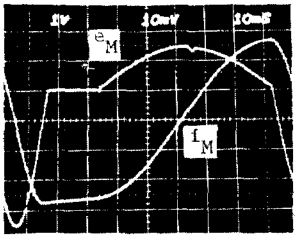

Fig. 9a Flat-bottom.

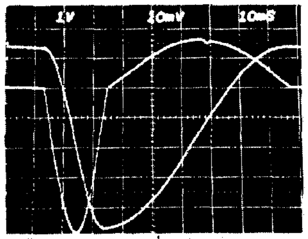

Fig. 9b Flat-top.

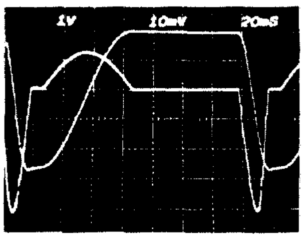

Fig. 9c
Flat-bottom and very long flat-top.

Proof-of-Concept GTO Circuit

Figure 10 shows the test circuit which simulates the circuit of Fig. 5. Three modes were successfully tested as shown in Figs. 11a to 11c.

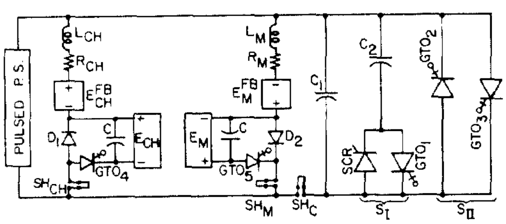

Fig. 10 Proof-of-Concept SCR and GTO circuit.

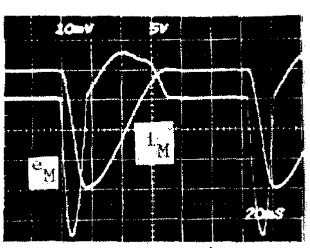

Fig. 11a Long flat-tops separated by dual frequency cosine wave.

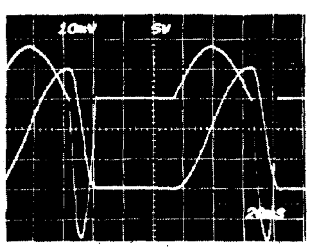

Fig. 11b Long flat-bottoms separated by dual frequency cosine wave.

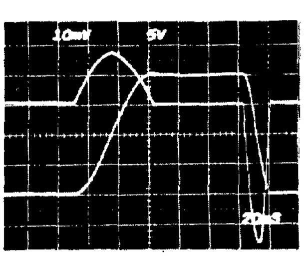

Fig. 11c
Long flat-bottom, "slow" current rise, long flat-top and "fast" current decay.

An Application for LAMPF II BOOSTER

The 6 GeV Booster-RCS proposed for LAMPF II has a repetition rate of 60 pps. Its injection current of 1.05 kA is maintained for 1 ms, the current rises to 5 kA at a frequency f_1 = 41.55 Hz during acceleration and returns to 1.05 kA at a frequency f_2 = 127.7 Hz.[8] A block diagram of the Booster-RMPS is shown in Fig. 12; its estimated cost is $4.4 x 10^6.

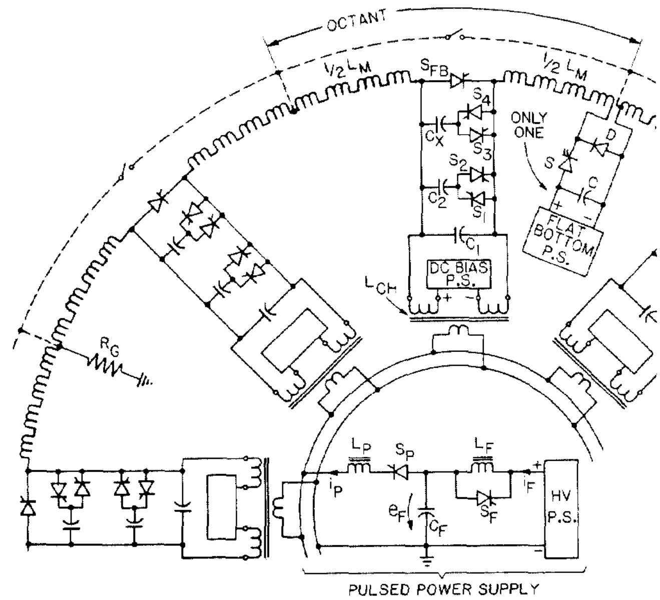

Fig. 12 RMPS for LAMPF II 6 GeV 60 pps Booster.

Acknowledgment

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