RESONANT RAMPING SCHEME FOR CLS BOOSTER DIPOLE MAGNETS

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Abstract

The booster for the proposed Canadian Light Source is being designed to ramp the electron beam from 250 MeV to 2.9 GeV in approximately 180 mS, with a repetition frequency of 2.5 Hz. The booster dipole magnets will be connected in series with a capacitor bank and operated as a series resonant circuit. This approach reduces the peak power drawn from the supply and consequent load fluctuations on the incoming AC lines. The series connection ensures that the current through each magnet is identical. The circuit is simple and easy to control, especially when compared to other ramping power supply approaches. An SCR bank, configured as an H-Bridge, controls the orientation of the capacitor bank in the circuit. To initiate a ramp cycle two opposing legs of the bridge are switched on, thereby applying power to the magnets. The magnet current is a half sinusoid; when it drops to zero the SCRs turn off with the capacitors charged to the opposite polarity, ready for the next cycle. The system will apply a peak voltage of approximately 3500 Volts and a peak current of 1550 Amps to the magnet string.

1 CLS BOOSTER

The Canadian Light Source (CLS) [1] will consist of the Saskatchewan Accelerator Laboratory's electron linac operating at 250 MeV, a booster synchrotron to increase the energy to 2.9 GeV, and a 2.9 GeV storage ring. The booster has been designed for an injection frequency of 2.5 Hz. The booster magnet parameters are summarized in Table 1.

Table 1: Booster Dipole Magnet Parameters

Magnet	H-type
Number of Magnets	20 + 1 reference
Core length	2.56 m
Gap	44 mm
Maximum flux density	1.33 T
Peak current	1550 A
Turns per coil	16
Turns per magnet	32
Resistance per magnet	13.2 mΩ
Inductance per magnet	11.4 mH
Interconnection resistance	6.6 mΩ
Dipole string resistance	284 mΩ
Dipole string inductance	239 mH

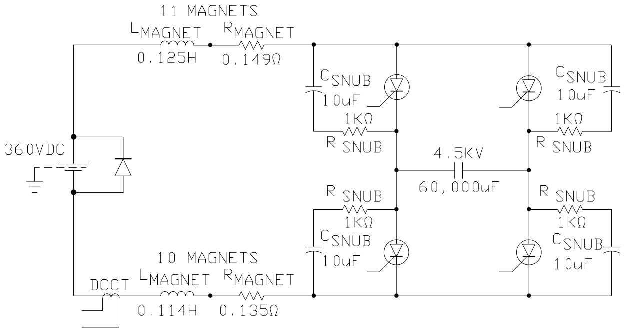

Figure 1: Resonant Ramping Supply Schematic

For very long ramp periods the inductance of the magnets has little effect on the power supply requirements. Varying the current through the magnet coils requires that the power supply voltage be increased to overcome the inductive component of the load. Inductive effects begin to dominate the CLS booster dipole magnet power supply requirements around 1 Hz, which was the initially proposed rate. With an injection rate of 1 Hz, and assuming an equal ramp up/ramp down time, the magnet current must increase 1420 A in 0.5 seconds.

Three power supply designs have been considered: linear ramping; exponential ramping; and series resonant ramping. Comparisons of the designs were made assuming a minimum injection frequency of 1 Hz and equal times for increasing and decreasing the current. The technique referred to as a White circuit seemed overly complicated for this injection frequency, and has not been analyzed.

A linear ramping approach increases the dipole flux at a constant rate, so the waveform of the power supply output voltage is approximately a sawtooth. The proposed CLS booster dipole network has a total resistance of 0.284 ohms, a total inductance of 0.239 Henry, and requires a current of 1550 A at 2.9 GeV (see Table 1). This requires a power supply output voltage of 1120 V just before maximum current is reached, for a peak output of 1.7 MW. The time constant of the circuit is 0.84 seconds so the current will not decay to the level required for 250 MeV injection unless a bipolar supply is used.

A second approach was considered in which the supply would be operated with a stepped output voltage, with the magnet current following exponential curves according to the L/R time constant of the system. The required supply voltage would be 980 V, with a peak output power of 1.5 MW. This supply would also have to be bipolar.

A third approach, and the one chosen for use at the CLS, is to reduce peak power requirements by connecting a capacitor bank in series with the magnets to create a resonant RLC circuit. At resonance the reactive components of the

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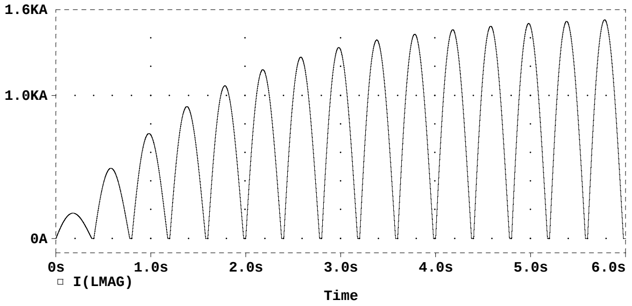

Figure 2: Dipole current as supply switched on

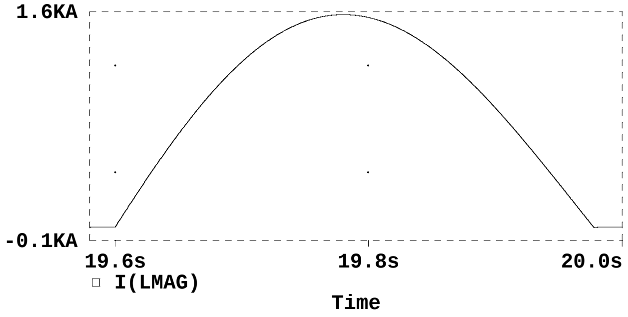

Figure 3: Expanded view of operating state dipole current

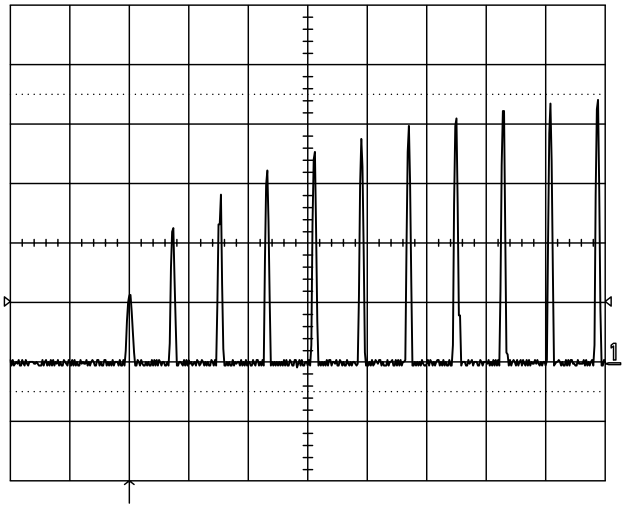

Figure 4: Magnet current in prototype supply as it is switched on. Horizontal scale: 0.5 S/division, Vertical scale 30A/division

capacitance and inductance cancel. This system, and accompanying thyristor switches as shown in Figure 1, can be used with a unipolar, constant output voltage supply. The CLS constant voltage power supply needs to provide only 360 V at 1550 A, for a peak output of 0.56 kW.

The ramp period can be chosen by adjusting the number of turns in the magnet windings to vary the magnet inductance as described below. This has a minimal effect on power consumption. If the overall cross sectional area of the copper is constant there will be no change in the peak power dissipation. The resistance of the winding is proportional to the square of the number of turns. For example doubling the number of turns results in half the conductor area and twice the length, quadrupling the resistance. Since the required field remains the same, the peak current varies inversely with the number of windings so only half the current would be required. Power, which is proportional to I^2R, remains constant. In practice the total cross sectional area of the windings is fixed, so as the number of windings is increased proportionally more area will be occupied by insulation, and resistive losses will increase somewhat.

The magnet load will be split into two sections as shown in Figure 1. This configuration reduces the magnitude of the voltage between the windings and ground since one section is pulsed with a positive voltage while the other is pulsed with a negative voltage. During normal operation the magnets adjacent to the SCR/capacitor section will have to withstand 2 kV between their coils and ground. A fault in either of these locations would impose the full capacitor voltage on the windings of the first coil in the other half of the string of dipoles, so the coil winding insulation must be able to withstand momentary peak voltages of 4 kV. Ground fault detection will be incorporated in the supply to detect these faults and provide protection to the supply and magnets.

A PSpice model of the schematic in Figure 1 was developed by replacing the SCRs with switches in series with diodes. Figure 2 shows the simulation of magnet current I(LMAG) as the power supply ramps up to the operating state. Figure 3 shows an expanded view of the dipole current after it has reached this state.

A low power prototype was designed and tested. The capacitor bank was implemented with twelve 10000 μF electrolytic capacitors. The capacitors were arranged as two sets of 6 capacitors connected back to back. Each set included a bypass diode to protect the capacitors from being charged with the wrong polarity. The magnet string was simulated with an air core coil having a resistance of 110 mΩ and an inductance of 8.1 mH. The capacitors each have an equivalent series resistance of 18 mΩ, resulting in a total resistance of 113 mΩ. A 300 A DCCT, which provides a full scale output of 200 mA, connected to the 50 Ω input of an oscilloscope corresponds to 30 A/V. Figures 4 and 5 show the operation of the prototype as it is switched on and after the current has reached its operating point.

The energy stored in the magnets must be transferred between the magnet flux and the capacitor's electric field. The peak voltage across the capacitors will be inversely proportional to the square root of the capacitance. This voltage will be limited by the voltage rating of available SCRs. The Powerex TC20 SCR which has a rating of 4.5 kV and 2.8 kA$_{av}$, or the International Rectifier ST1900C52R0 rated at 5.2 kV and 1.6 kA$_{av}$, are suitable for this design.

Although the resonant supply imposes a smaller tran-

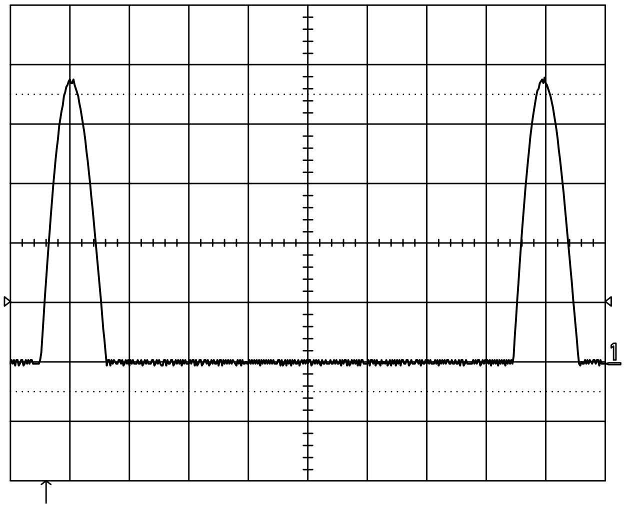

Figure 5: Expanded view of operating state dipole current Horizontal scale: 50 mS/division, Vertical scale 30A/division

sient load on the AC supply lines than do supplies which reverse the power load on the supply lines, the load fluctuation from ramping the booster magnets will induce voltage fluctuations on the 60 Hz voltage distribution throughout the lab. Feeding the ramped supplies from a separate transformer will minimize the effects on other power supplies. This transformer can also function as the transformer in the 360 V DC supply. In this case the transformer would be ordered with both Delta and Wye secondaries, and operated with a twelve phase rectifier. The leakage inductance of this transformer will have a negligible effect on the circuit operation. Assuming a 250 V RMS secondary voltage and a 750 kVA 6 phase transformer with a 10% leakage inductance, each leg would have approximately 70 μH inductance. Two legs would be conducting at a time, so the total inductance seen by the circuit would be 140 μH, which is less than 0.1% of the circuit inductance.

To avoid a large fluctuating dipole effect, the return current path will retrace the outgoing path in close proximity to the outgoing conductors. The booster circumference is 102 m. Allowing 2 m for each dipole connection, the conductor will have a total length of 246 m. Losses in the magnet interconnections should be kept low. Initially the booster was specified for operation at 1 Hz, with the magnets connected in series using water cooled conductors having a copper cross sectional area at least that of a 3” copper pipe with a wall thickness of 0.054”. Since the booster’s resonant frequency is controlled by varying the number of turns of the booster dipoles, the peak dipole current increases proportionally with this frequency. The current at a ramp rate of 2.5 Hz would result in a peak power dissipation of 90 kW in these conductors. Three 500 MCM conductors will be used instead of the water cooled conductors, reducing the conductor resistance to 6.6 mΩ, the peak power dissipation to 16 kW, and the peak output of the power supply by 74 kW.

With the resonant design the booster ramp period can be reduced with little effect on the dipole power supply’s peak output power. Non-resonant supplies, which can be adjusted to match the booster dipole current, will be used for the booster quadrupoles. Shorter periods make the inductive component of the quadrupole magnet load more significant. With the present CLS design the reactive component of the quadrupole load equals the resistive component at 3 Hz. Shorter periods would rapidly increase the quadrupole supply requirements, so 3 Hz was chosen as the maximum booster frequency.

The booster quadrupole supplies and RF have to be regulated to match the dipole current. Either a DCCT or Hall probe could be used as a basis for the control. At the maximum current levels the magnet cores will be somewhat saturated, so flux cannot be assumed to be directly proportional to current. Feedback using a DCCT would require accurate modeling of these saturation effects, based on a complete mapping of the dipole. The Hall probe measures flux directly, so provides a simple feedback system but requires an extra reference dipole. A Hall probe is planned to be used as the main feedback to the magnet control system. A DCCT will be installed for diagnostic purposes.

With the proper number of turns the quadrupole magnets could be connected in series with the dipole magnets and form part of the resonant system. Trim windings on the quadrupoles would allow control over the tune of the booster. This approach was considered, but concerns about the risk of an untested system and limited ability to adjust the tune of the beam resulted in its rejection.

The simplicity of the circuit should result in good reliability for the system. The most common failure will be a shorted capacitor in the 60 mF capacitor bank. The capacitors will be individually fused to limit the energy dissipation during a such a fault. The capacitor bank will be constructed with spare units in place, making it possible to resume operation with a very short down time. A high voltage relay could be used to connect the spare capacitor, reducing down time further. Alternatively, a self healing capacitor construction could be used. These capacitors use a dielectric film with a thin metal coating. The metal in the vicinity of a dielectric fault is unable to carry the fault current, and is blown away, clearing the fault at the expense of reduced capacitance. Banks of electrolytic capacitors could be used to provide a compact design. The reliability of these capacitors would likely be worse than oil filled capacitors, especially since a combination series/parallel bank would be required. Self healing capacitors with manually switchable spares will be used for the CLS.

2 REFERENCES

[1] CANADIAN LIGHT SOURCE, The Proposal for Construction of a National Synchrotron Light Source for Canada, January, 1999.