HIGH POWER FAST RAMPING POWER SUPPLIES

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Abstract

Hundred megawatt level fast ramping power converters to drive proton and heavy ion machines are under research and development at accelerator facilities in the world. This is a leading edge technology. There are several topologies to achieve this power level. Their advantages and related issues will be discussed.

INDRODUCTION

The Brookhaven Alternating Gradient Synchrotron (AGS) is a strong focusing accelerator which is used to accelerate protons and various heavy ion species to an equivalent proton energy of 29 GeV. At this energy, the maximum intensity achieved is 7 x 10^{13} protons per magnet cycle. This corresponds to an average beam power of about 0.2 MW. Future programs in high-energy and neutron physics may require an upgrade of the AGS accelerator to an average beam power of around 4 MW, with proton beams at the energy of 24 GeV. This can be achieved with an increase of the beam intensity to 2 x 10^{14} protons per magnet cycle that requires a 1.5-GeV super-conducting linac, as a new injector and by upgrading the AGS main magnet power supply system to allow cycling at 5 beam pulses per second. This paper examines the present mode of operation of the AGS main magnet power supply and the requirements for future operation at 5 Hz. Proposed solutions and modifications required to upgrade the AGS main magnet power supply to operate at 5 HZ, are examples of potential solutions for fast ramping power converters to drive proton and heavy ion machines in the future.

PRESENT MODE OF OPERATION

The AGS Main Magnet Power Supply (MMPS) is a 6000 Amp, ±9000 Volt Silicon Controlled Rectifier (SCR) power supply**.** A 9-MW Motor Generator, made by Siemens, is a part of the main magnet power supply of the accelerator, which allows, pulsing the main magnets up to 50 MW electric peak power, while the input power of the motor generator remains constant. The maximum average power into the motor ever utilized is 7 MW and the maximum average power dissipated in the AGS magnets never exceeds 5 MW. The AGS ring consists of 240 magnets hooked up in series. The total resistance R is 0.28 ohms and the total inductance L, is 0.8 H. There are 12 super-periods, A through L, of 20 magnets each, divided in two identical sets of 10 magnets per super-period. There are two stations of power supplies each capable of delivering up to +/-4500 Volt and 6000 Amp. The two stations are connected in series as shown in Figure 1**,** where the two magnet loads have a total resistance R/2 and a total inductance of L/2. The grounding of the power supply is done only in one place, in the middle of station 1 or 2 through a resistive network. With this grounding configuration, the maximum voltage to ground in the magnets will not exceed 2500 Volt. The magnets are hi-potted to 3000 Volt to ground, prior to each starting of the AGS MMPS after long maintenance periods. Each of the two stations is composed of the F-bank and the P-bank power supplies in parallel. The F-bank power supply, consists of a 24 pulse thyristor control rectifier (fundamental frequency 1440 Hz), operating at ±1900 Volt maximum, and 6000 Amp, and it is used during the flat tops of the AGS cycles. The P-bank power supply, consists of a 24 pulse thyristor control rectifier also (fundamental frequency 1440 Hz), operating at ±9000 Volt maximum, and 6000 Amp, and it is used during ramping up or down of the AGS magnet cycles. This ensures minimum ripple during the flat tops, an essential condition for slowly extracted beam. However, there were still frequency components multiples of 60 Hz that needed to be reduced. There are also, two 300-Hz 60-dB/decade passive filters, to minimize voltage ripple of the AGS MMPS. SCR's and a set of fast and slow 95 switches are used to short stations 1 and 2 in case of a failure of the AGS MMPS, so that the energy stored in the AGS magnets decays with the L/R = 2.8 sec time constant. A typical magnet current with proton beams at the energy of 24 GeV, has a cycle period of 3.6 seconds long, including a 1.6-second flat-top and a 0.8-second front-porch. The acceleration or deceleration ramp lasts 0.6 seconds. The flat top current is close to 4200 amps. The peak power during acceleration is close to 30 MWatts. The average power dissipated in the AGS magnets for this pulse was estimated to be 2.8 MW.

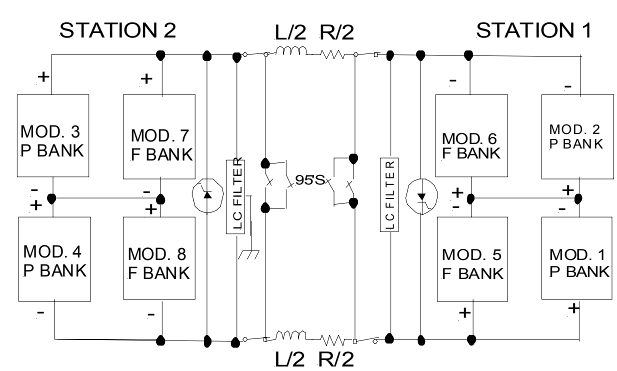

Figure 1: Present AGS Magnet Power Supply.

FIVE-HZ MODE OF OPERATION

To cycle the AGS for the 24-GeV proton mode of operation at 5 pulses per second, the magnet peak current is 4200 Amp. The cycle does not include a front-porch and a flat-top. Only single-turn extraction has been assumed. The magnet ramp up, or down, would take 0.1 second. The total average power dissipated in the AGS magnets is estimated to be 1.7 MW. It was calculated that one needs +/-37 kVolt across the whole magnet system to accomplish this pulse**.** The peak power requirement for such a cycle is approximately 160 MW. It was mentioned above that currently the maximum magnet voltage to ground, is 2500 Volt maximum. Assuming that we are not going to redesign the AGS magnets, this constraint has to be followed in the new design of the AGS MMPS to run at 5 Hz.

THE AGS MAGNET CONNECTIONS FOR 5 HZ OPERATION

It is assumed that the existing ripple specifications are to be preserved, to run present flat top cycles and PPM modes as well as to be able to run 5 Hz mode, in the future. To do this, and to limit the AGS coil voltage to ground to 2.5 KV, the AGS magnets will need to be divided into eight identical sections, each powered similarly to the present half AGS power system, except that now the magnet load is 1/8 of the total resistance and inductance per supply. In this manner we will have eight identical P type stations of power supplies as one existing station and two F type stations, all hooked up in series as shown in Figure 2. Note that every P type station will be rated at +/-5000 volts 6000 Amps, the same as the present rating of the P type units. Bypass SCRs will be used across the 6 P type stations, to bypass these units during the flattops, for flat top modes of operation and ensure minimum ripple requirements. Note that only station 1 will be grounded as is done presently. Using the configuration of Figure 2, ensures that the maximum voltage to ground of every section of magnets will not exceed 2500 volts.

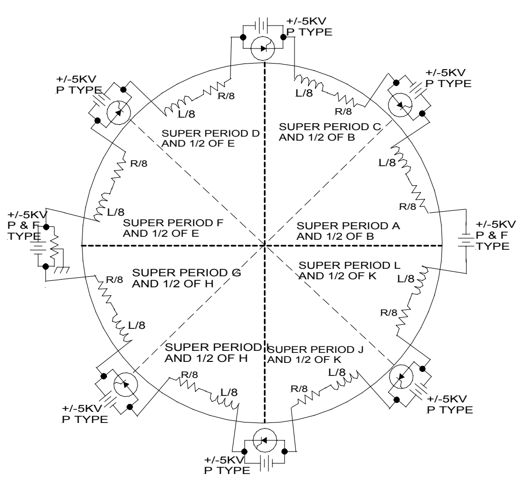

Figure 2: Modified AGS Power Supply Configuration for the 5-Hz mode of operation.

MOTOR GENERATOR SOLUTION

As one can calculate from Figure 2, the peak power required for a 5 HZ mode of operation is approximately 160 MW. The existing motor generator cannot provide such a power swing, since it is rated at only 50 MW continuous 95 MW pulsed for 1 sec. One needs to investigate, if the upgrade can be done with a 200-MW generator or perhaps two 100-MW generators. It is convenient and maybe more economical that the motor generator(s) is of 6 or 12 phase to limit or even eliminate phase-shifting transformers so that every power supply system generates 24 pulses. For the case of a single generator if the generator is 6 phase the generator voltage would have to be around 15 kVolt line-to-line, so that the generator current is approximately equal to the magnet current during the time that the P-banks are turned on, as is presently done. This needs to be evaluated if it is technologically possible. If however two 100-MW generators are used, the output voltage would have to be 15 kVolt line-to-line for a 3 phase generator, or 7500 volts line-to-line, for a 6 phase one, to keep the generator and the magnet current approximately equal. Another specification of the motor generator is the 5 Hz frequency. That is, the motor load is to be rated to be pulsed at 5 Hz. One should investigate what is technologically possible, regarding these specifications and costs involved. Another approach is to use the existing motor generator and the rest of the power system for one quarter of the AGS ring, provided that it can indeed run at 5 HZ, and use another motor generator rated at 150 MW with a voltage 12 kV line-to-line, 6 phase, for the other three quarters of the AGS ring. All power supplies in this mode will be thyristor control supplies.

The Motor Generator Issues

Certainly one can think of using one or two motor generators as referenced above, to store energy. However there are issues that should be considered. It is not clear if companies will be manufacturing similar machines in the future to such a high power level. These machines are very expensive and require a great degree of maintenance. They require Cycloconverters, to regulate the motor power and exciter power supplies to excite the generators. They need to run at 5 Hz, which must be investigated if it is technologically possible. For these reasons it seems such an application may not be the best solution.

THE INDUCTOR ENERGY STORAGE SOLUTION

The assumption is that we replace the existing supplies with new ones. As a result all 8 power supplies shown in Figure 2 should be identical. The basic building block of one of these power supplies is shown in Figure 3. All formulas and calculations referenced below are for the basic building system. There are two thyristor controlled supplies; one is connected to 1/8 of the magnet load and the other to a storage inductor. There is also a reactive power compensator interfaced at the incoming ac line, to compensate for reactive power. The idea is that we store energy in the storage inductor and during pulsing the magnet, the energy comes from the storage inductor. Thus the average incoming power is constant. The total energy stored in all 8 storage inductors is equal approximately to 22 MJ. It was calculated that in order to maintain the average incoming power constant, we must pulse the current of the storage inductor using the following formula. Note this formula does not take into account storage inductor losses. It is representative for a superconductor.

$$Ic(t) := \sqrt{\frac{1}{4 \cdot L1} \cdot \left[\left(\int_0^t Pam\, dt \right) + \frac{8 \cdot L1 \cdot I0^2}{2} - \frac{L \cdot I(t)^2}{2} + \frac{L \cdot I(0)^2}{2} - \int_0^t I(t)^2 \cdot R\, dt \right]}$$

Ic(t) is the storage inductor current in amps. L1 is the inductance of the storage inductor equal to 0.153 H. Pam is the average incoming power in watts. L is 1/8th of the total magnet inductance equal to 0.1 H. I(t) is the magnet current in amps. R is 1/8th of the magnet resistance equal to 0.035 Ohms. I(0) is the magnet current in amps at t=0 sec. Vc(t) is the storage inductor voltage in volts. V(t)/8 is the magnet voltage for 1/8th of the magnets. Figure 4 displays the waveforms for a 5 Hz magnet current pulse. Figure 5 displays the waveforms for a slow magnet current pulse used during the present operations of the AGS. The bottom wave forms of Figures 4 and 5 display the peak magnet power for 1/8th of the magnets and the peak storage inductor L1 power, for 5 Hz and present operation, in MW. Note if the two peak power levels are added, they are equal to the average incoming power. This solution indicates that we could pulse the magnets using the present mode of operation, as well as pulsing them at 5 Hz for future operations. It should be stated that the power supplies shown in Figure 3 could also be two quadrant dc to dc converters.

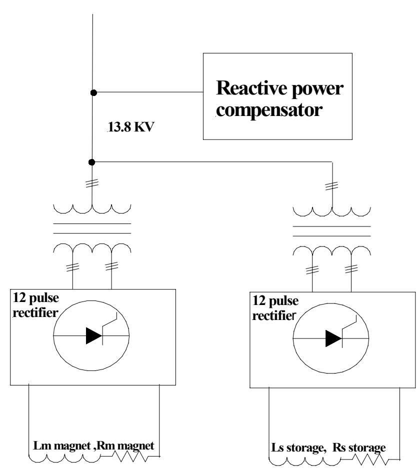

Figure 3: Two thyristor control supplies interfaced with a magnet and a storage inductor.

The inductor solution issues

Conventional inductors are large in size. The losses are high. If they are superconductors, additional amount of power is needed to cool them. This could be as high as the losses of a conventional inductor. We need a reactive power compensator to compensate for reactive power. This will increase the cost. If however thyristor control supplies are used, it should be noted that they are more reliable than dc to dc converters.

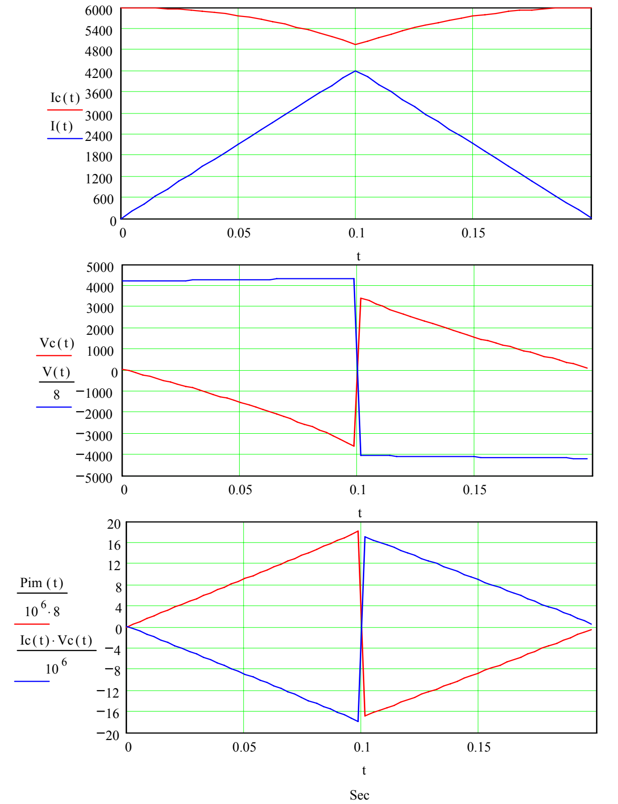

Figure 4: Inductor storage wave forms, for 5 Hz operation.

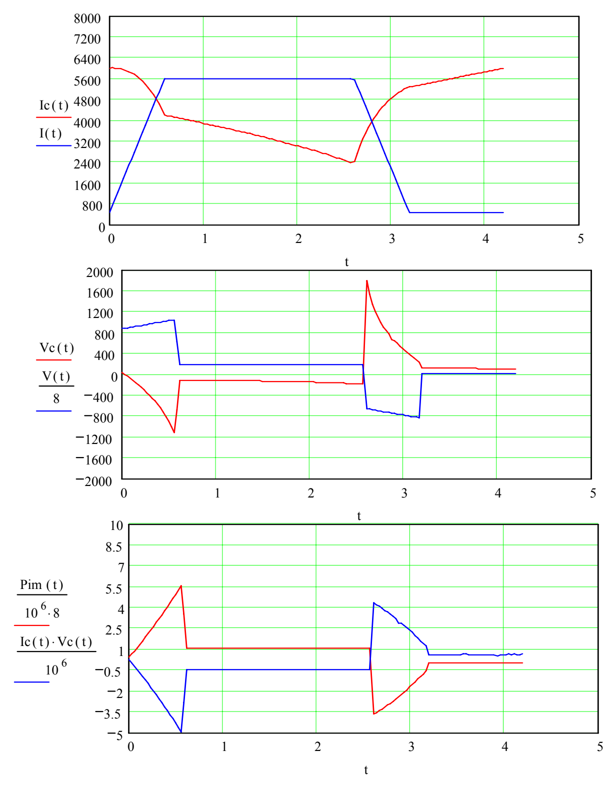

Figure 5: Inductor storage wave forms, for present operation.

THE CAPACITOR ENERGY STORAGE SOLUTION

Power Supply Topology

The technique mentioned above could also be used using a capacitor bank instead of a storage inductor. However the thyristor supply or the dc to dc converter interfaced with the capacitor bank, should be bipolar in current.

Another topology is to use two dc to dc converters interfaced with a capacitor bank as shown in Figure 7. The assumption again, is that we replace the existing AGS supplies with new ones. As a result all 8 power supplies shown in Figure 2 should be identical. The basic building block of one of these power supplies is shown in Figure 6. The switching elements could be IGCT's, made by ABB or IGBT's. The total energy stored in all 8 storage capacitor banks is equal approximately to 22 MJ for this simulation.

The Power System

The proposed power supply is composed of 8 stations connected as shown in Figure 2. Every station is composed of a 12 pulse full-wave bridge rectifier, charging a capacitor bank, through a one quadrant buck converter. In addition, a two quadrant dc to dc converter is used to convert the capacitor bank voltage into pulsed dc voltage across the magnets, see Figure 6. The other stations are identical. Note the grounding is done in the middle of one of the power supply as shown in Figure 2.

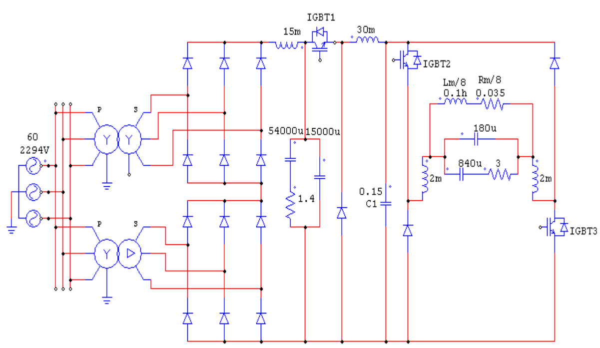

Figure 6: Simulation power supply topology.

The energy of the capacitor bank C1 is 2.7 MJ. The maximum voltage is 6000 volts and the capacitance is 0.15 F. The frequency used to run the power electronics of both dc to dc converters for this simulation was 500 Hz. The reason is that ABB manufactures IGCT's with ratings similar to the ratings of our power electronics and they are being pulsed at around 500 Hz to 1 KHz. Another station could be pulsed at 500 Hz, but delayed from station I by 180 degrees resulting in minimizing the magnet voltage ripple, thus creating a pair. In the end we could have 4 identical pairs of supplies. This however was not taken into account for this simulation. The LC filter of the 12 pulse full wave bridge rectifier has a 3 db point at 8 Hz. The LC filter of the 2 quadrant dc to dc converter has a 3 db point at 100 Hz. Both filters have not fully been optimized at this time.

The Control System

There are two control systems used in the simulation. One which controls the buck converter power electronics IGCT1, and another used to control the magnet current, using the power electronics of the two quadrant dc to dc converter IGCT2, IGCT3. The block diagram of the first control system is shown in Figure 7. There are two loops being used, the inner loop and the outer loop. The inner loop has a reference called Vcapref_noactive(t). This represents the capacitor bank C1 voltage reference when power is drawn prom the capacitor only during ramping the magnet, not taking into account magnet losses. This was calculated to be.

$$Vcapref\_noactive(t) \approx \sqrt{V_0^{\,2} - \frac{L}{C1}[\mathrm{Im}(t)^2 - I_0^{\,2}]}$$

V0, is the original capacitor bank voltage the capacitor is charged to, and in this case is 6000 volts. L is the magnet inductance, and is equal to 1/8th of the AGS inductance, which is 0.1 H. C1 is the capacitor bank value equal to 0.15 F. Im(t) is the magnet current as a function of time and I0 is the magnet current at the front porch, equal to around 200 A. Vcap_actual(t) in Figure 7, represents the actual voltage across the capacitor bank C1 during a magnet cycle. Pref is the average power loss, referenced to $1/8^{th}$ of the AGS ring, for a given cycle of the magnet current. Pdraw is the average active power being drawn from the ac line for the same magnet cycle for one of the 8 supplies. Note that this loop, is the outer loop and it is slower than the inner loop. The objective of these two loops is to keep the average active power coming from the ac line constant, while the magnet current is being pulsed and to keep the capacitor bank C1 charged to a voltage grater than the maximum magnet voltage for a given cycle.

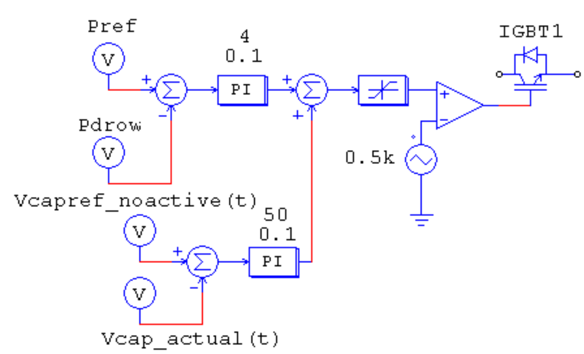

Figure 7: Buck converter control system.

It was calculated that, for a given magnet cycle, in order to keep the average active incoming power constant, which includes all losses in the magnets, the capacitor bank voltage should follow the waveform of the following formula.

$$Vcap(t) := \sqrt{\frac{1}{4 \cdot C1} \cdot \left[\left(\int_0^t Pam\,dt \right) + \frac{8 \cdot C1 \cdot V0^2}{2} - \frac{L \cdot I(t)^2}{2} + \frac{L \cdot I(0)^2}{2} - \int_0^t I(t)^2 \cdot R\,dt \right]}$$

It is possible in the actual system of Figure 7, instead of the Vcapref_noactive(t) to have Vcap(t) as a reference. The system should perform as well or better since we are dealing with the magnet losses in the control loop.

The second control system is used to control the magnet voltage and it is shown in Figure 8. In actuality a current loop should also be used as the outer loop, however for this simulation only the voltage loop was used. Vref represents the magnet voltage reference for one of the 8 supplies, for a given magnet current. Vmagnet represents the actual magnet voltage corresponding to 1/8th of the magnet load.

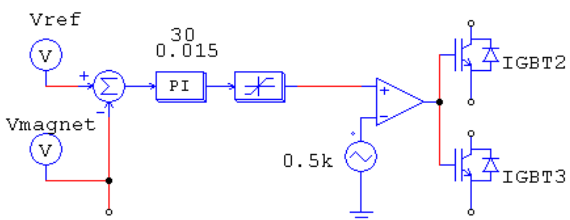

Figure 8: Two quadrant converter control system.

Simulation Results

The following results were observed after simulating the circuit of Figure 6. The magnet current, the magnet voltage, the capacitor bank voltage and current for 5 Hz and present operation are displayed in Figure 9 and 11. The capacitor and magnet peak power levels for 5 Hz operation are displayed in Figure 10. Note that the active power draw fluctuations were simulated to be not more than 150 KW. Since we have 8 power supplies the maximum incoming power fluctuations will be 1.2 MW. This however is not optimized at the present time. Also the reactive power was simulated to be not more than 0.1 MVAR per supply.

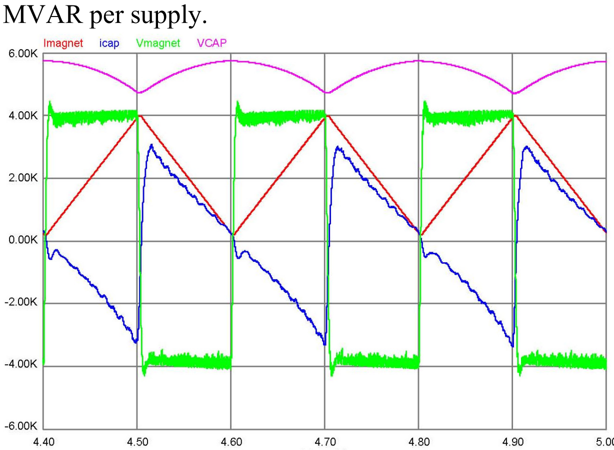

Figure 9: Magnet current and voltage, capacitor current and voltage for 5 Hz operation.

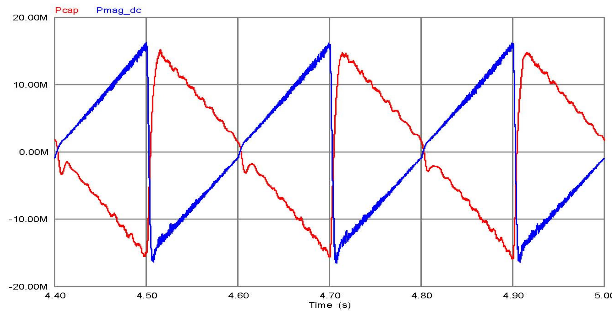

Figure 10: Capacitor and magnet peak power waveforms For 5 Hz operation.

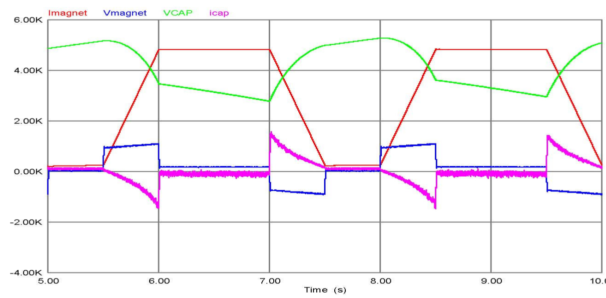

Figure 11: Magnet current and voltage, capacitor current and voltage for present operation.

CONCLUSION

Based on the above the best topology may be the capacitor bank with the two dc to dc converters. The simulation shows that such a system may be possible. However details of the capacitor bank and associated safety issues should be looked at. A further evaluation of the power devices IGCT's or IGBT's, is also needed. It also seems this solution may be the most economical; however, a detailed, cost estimate of such a system is a must.

ACKNOWLEDGMENTS

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