High Power Fast Ramping Power Supplies

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BROOKHAVEN NATIONAL LABORATORY
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U.S. DEPARTMENT OF ENERGY

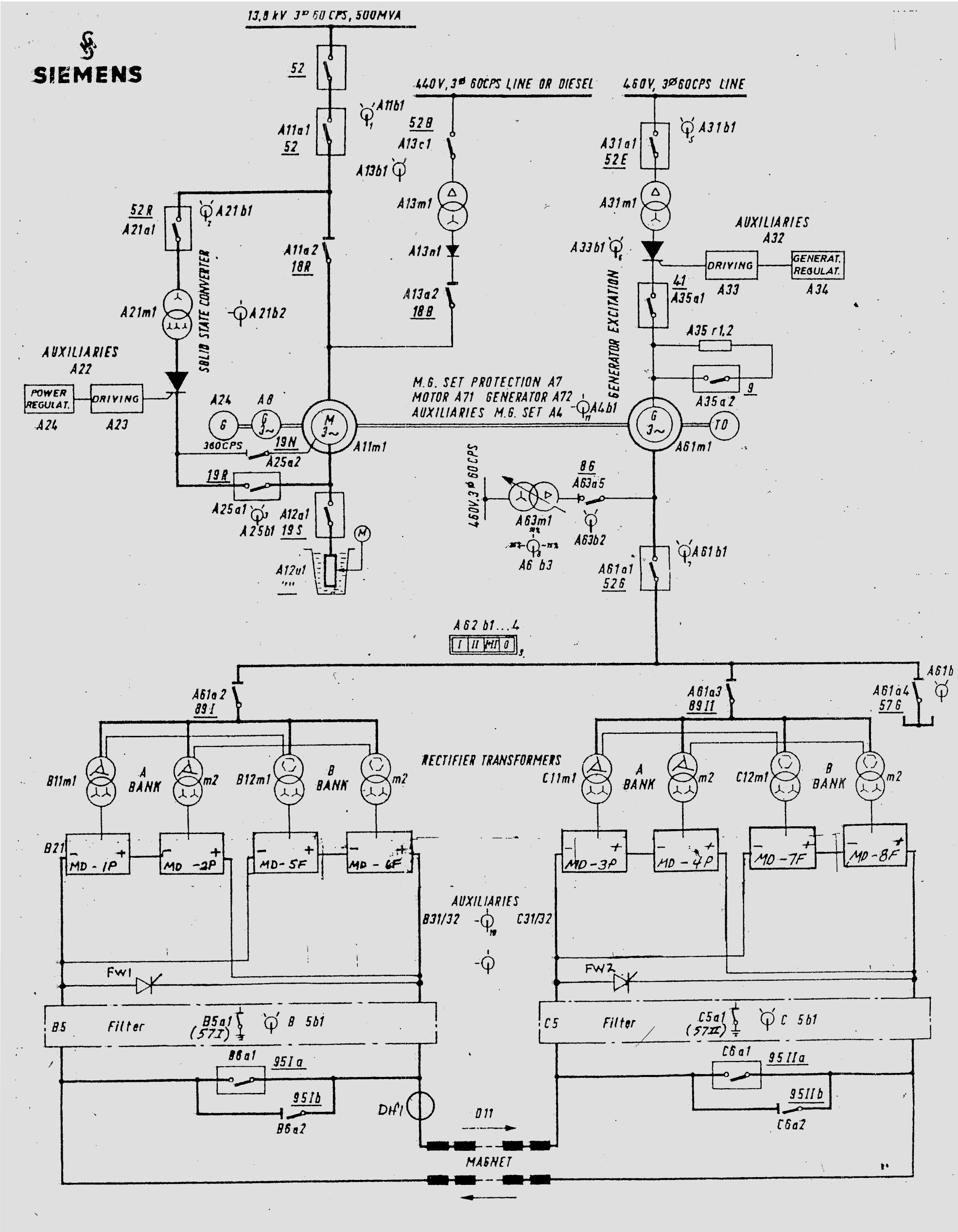
Introduction

- 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 33 GeV, with an average beam power of about 0.22 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.

Introduction

- One of the upgrades for this requirement was to run the AGS main magnet power supply at 5 Hz.
- The fastest current mode of operation of the AGS MMPS is approximately 1 Hz.
- This paper is part of a conceptual study to determine the best topology for this upgraded mode of operation.
- We will examine the present mode of operation of the AGS main magnet power supply and the requirements for potential future operation at 5 Hz.
- The proposed solutions, are examples of fast ramping power converters to drive proton and heavy ion machines in the future.

AGS MMPS BLOCK DIAGRAM PRESENT MODE



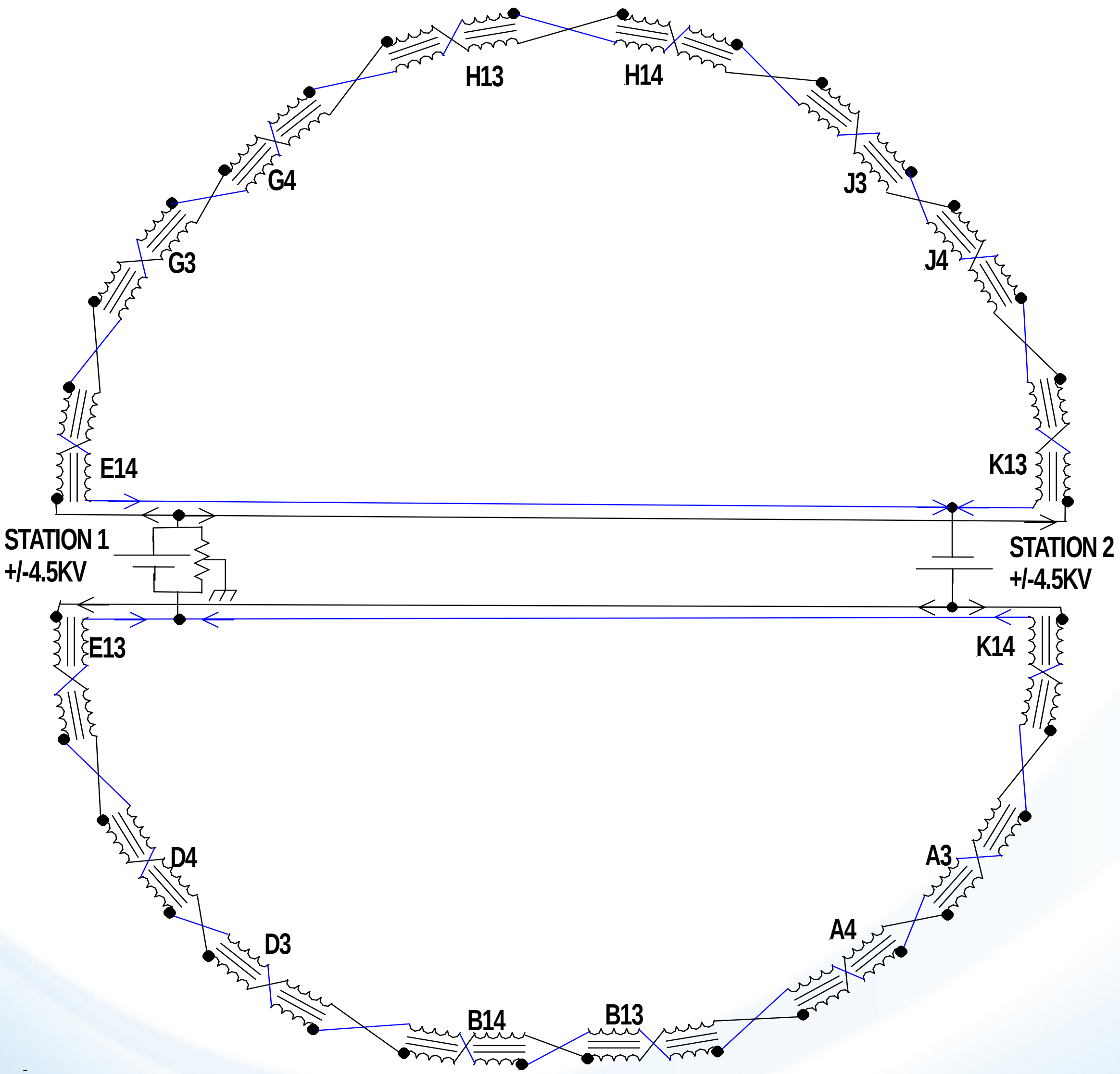
- AGS MMPS 6000 Amps, ±9000 Volts (SCR) power supply.
- Maximum AGS magnets average power 5 MW.
- Two stations of power supplies +/-4500 Volts and 6000 Amps each.
- The grounding of the power supply is done in the middle of station 1 or 2 through a resistive network.
- With this grounding configuration, the maximum magnet voltage to ground will not exceed 2500 Volts.

SIEMENS MOTOR/GENERATOR PARAMETERS

- MOTOR PARAMETERS
- 12000 HP, 9 MW MADE BY SIEMENS
- INPUT VOLTAGE 13.8KV 3 PHASE 60 HZ
- SYNCHRONOUS SPEED 1200 RPM
- SPEED CONTROL, CYCLOCONVERTER (CC) THYRISTOR CONTROL
- SLIP FREQUENCY +/-3%

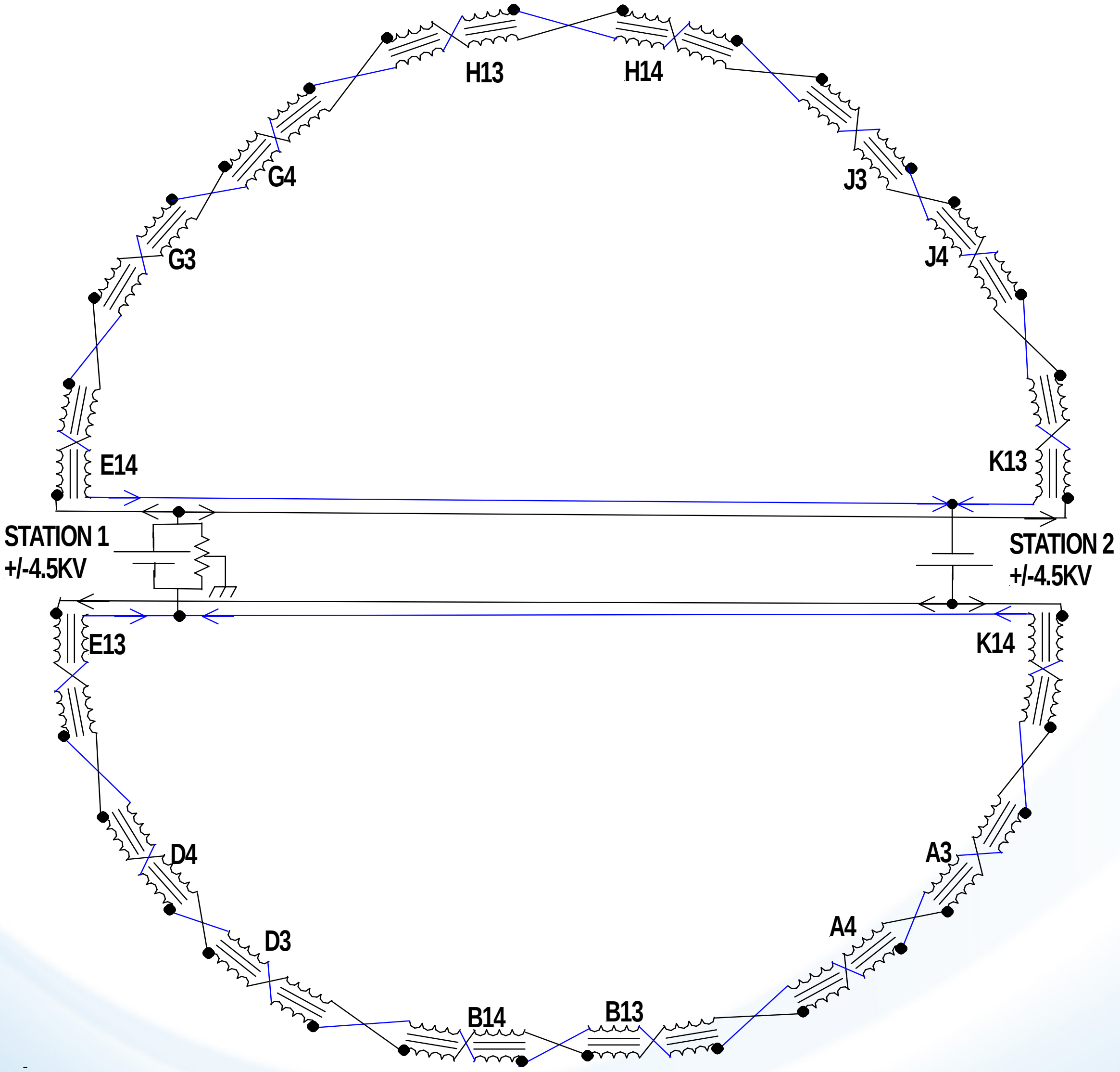
- GENERATOR PARAMETERS
- THREE PHASE SYNCHRONOUS SALIENT POLE TYPE- 6 POLES
- 50 MVA CONTINUOUS
- 7500 VOLTS 3 PHASE

Present AGS Magnet Power Supply Configuration.



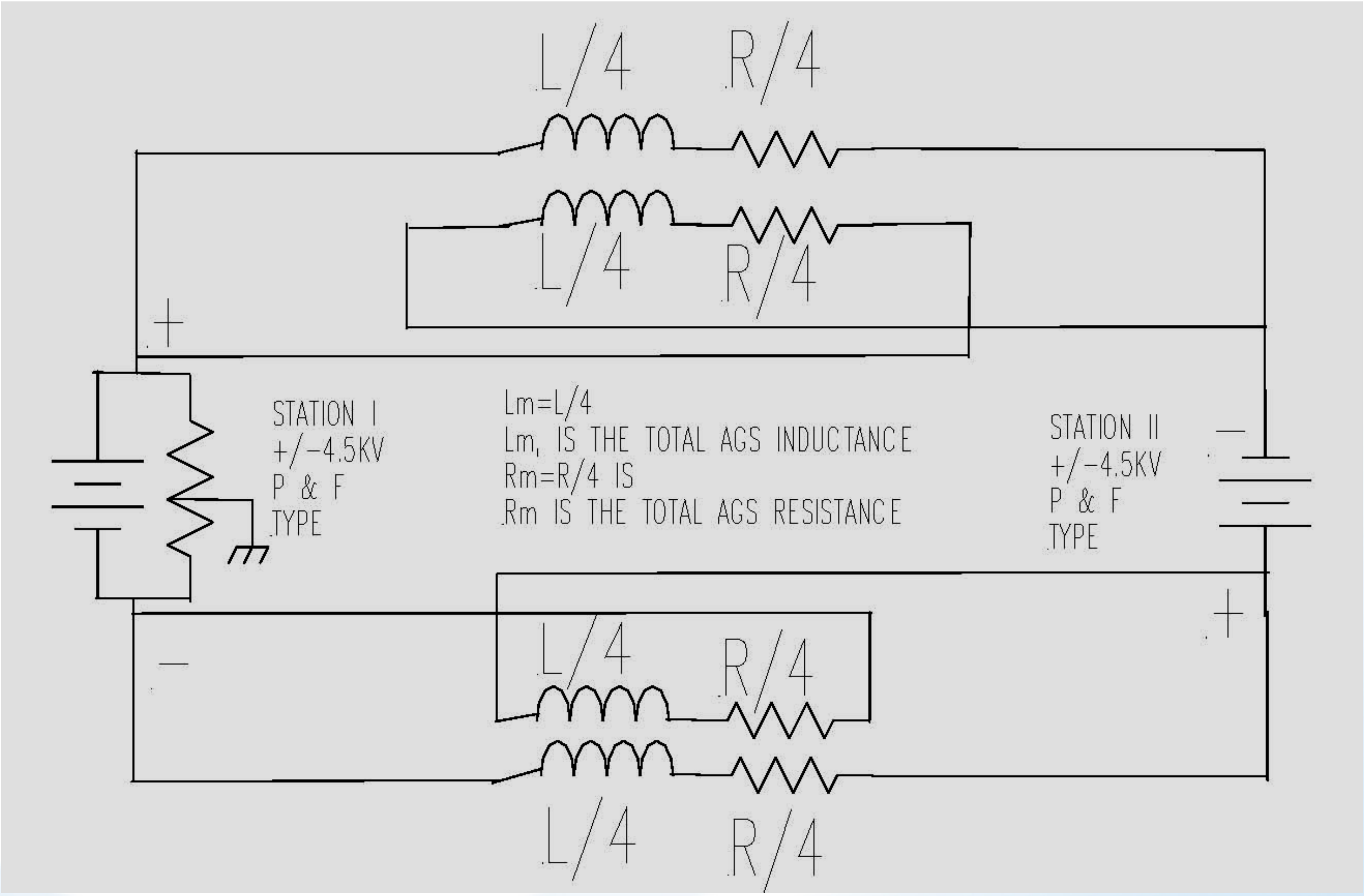
- The AGS ring consists of 240 magnets hooked up in series.
- The total resistance R is 0.28 ohms and the total inductance L, is 0.8 henries.
- There are 12 super-periods, A through L, of 20 magnets each.

Present AGS Magnet Power Supply Configuration.

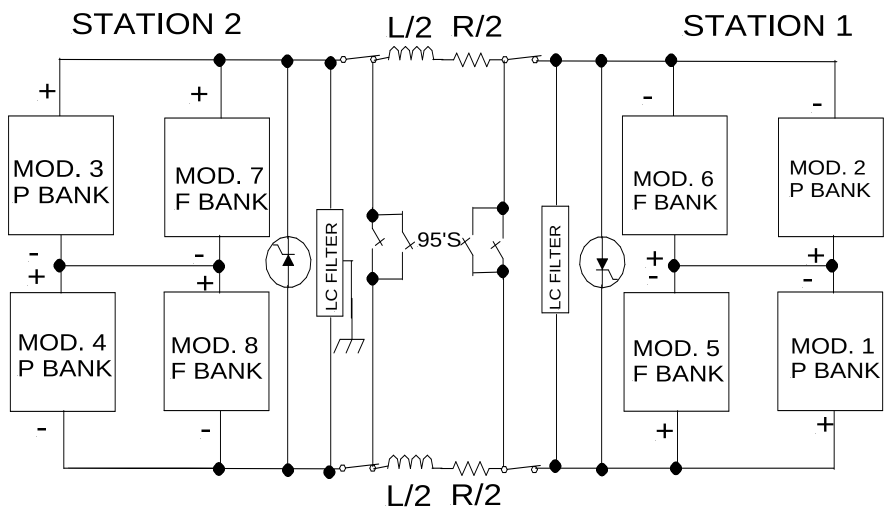


- Resistance to ground of every magnet is the same since they are water cooled.
- Capacitance to ground is the same for every magnet to avoid resonances.

Present AGS Magnet Power Supply Configuration.



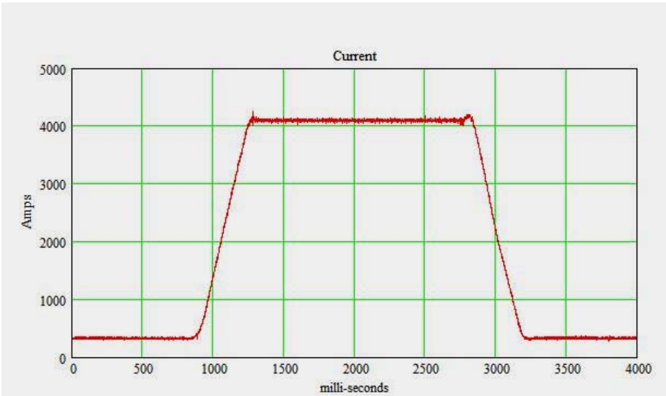
Present AGS Magnet Power Supply Configuration.

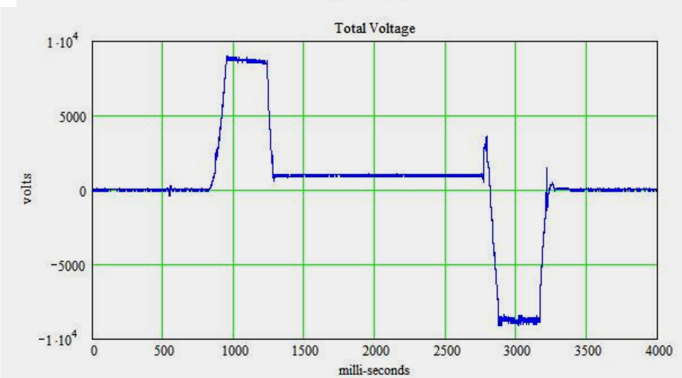


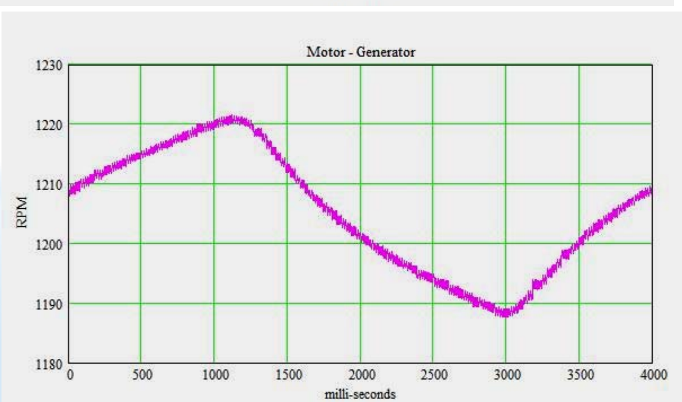
- Each station is composed of an F-bank and a P-bank power supplies in parallel.
- Each F-bank power supply, consists of a 24 pulse thyristor control rectifier operating at ±1900 Volt maximum, and 6000 Amp, and it is used during the flat-tops of the AGS cycles.

- The P-bank power supply, consists of a 24 pulse thyristor control rectifier 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 a slowly extracted beam.

Present AGS Magnet Power Supply polarized proton cycle.

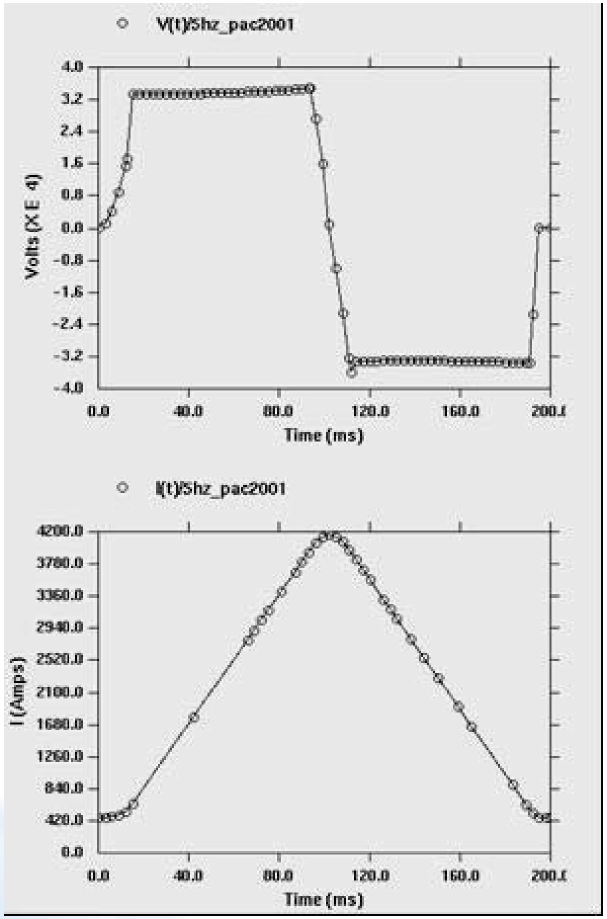






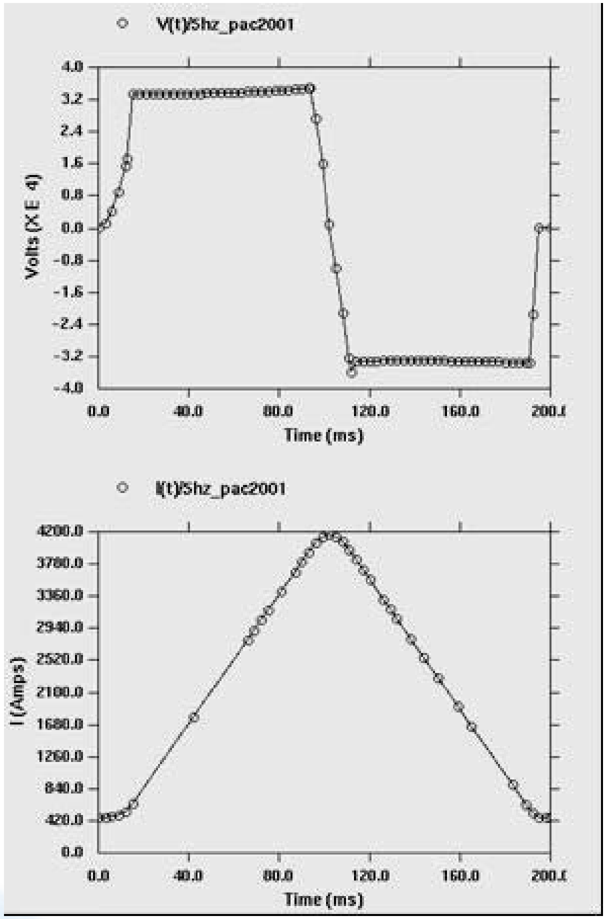
- A typical polarized proton magnet current cycle, has a period of 4.0 seconds long, including a 1.6-second flat-top and a 0.8-second front-porch.
- The acceleration or deceleration ramp lasts 0.4 seconds. The flat-top current is close to 4200 amps.
- The peak power during acceleration is close to 38 MW. The average power dissipated in the AGS magnets for this pulse was calculated to be 3.0 MW.
- The motor speed changes from 1220 to 1190 RPM equal to about 2.5%
- The average motor power is 4.1 MW.

POSSIBLE AGS MAGNET FIVE-HZ MODE OF OPERATION



- For 5 Hz operation, the magnet peak current would be 4200 Amps.
- 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, takes 0.1 seconds.
- The total average power dissipated in the AGS magnets was calculated to be 1.7 MW.

POSSIBLE AGS MAGNET FIVE-HZ MODE OF OPERATION



- The peak to peak voltage across the entire magnet string would be +/-37 kVolt.
- The peak power requirement for such a cycle is approximately 160 MW.
- Due to the existing magnet constraints, the peak voltage to ground must be limited to 2500 volts.

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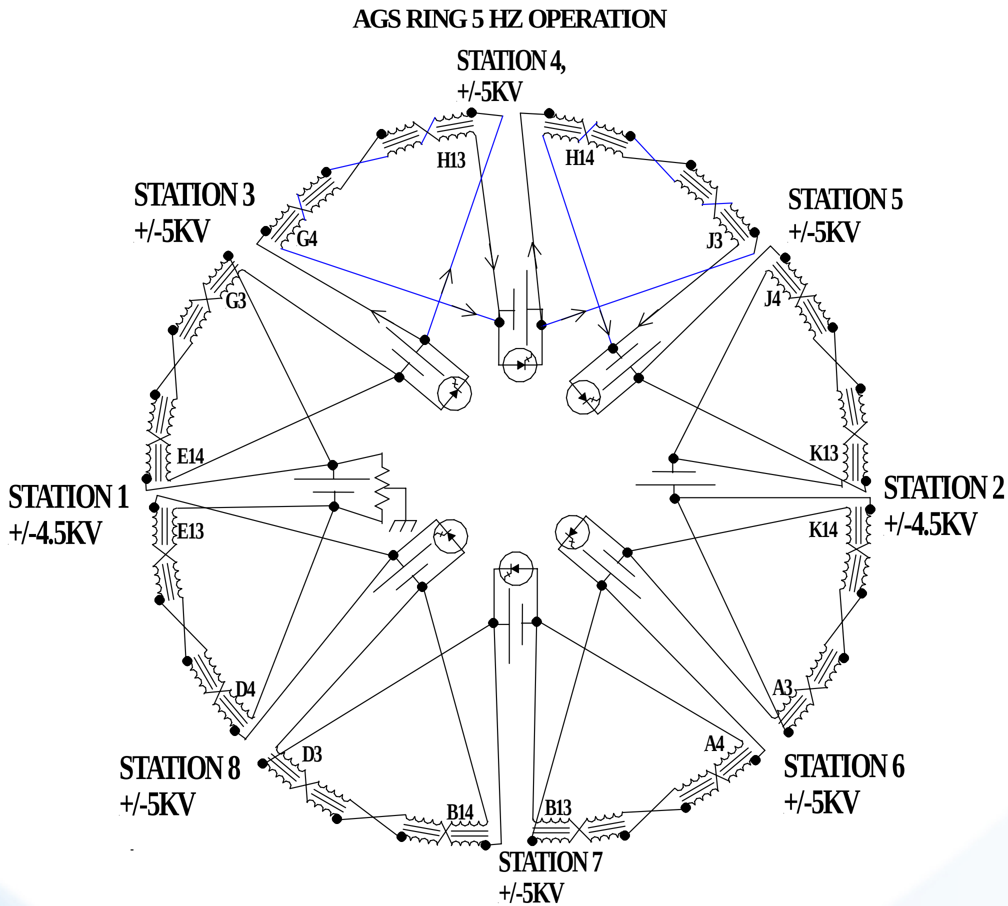
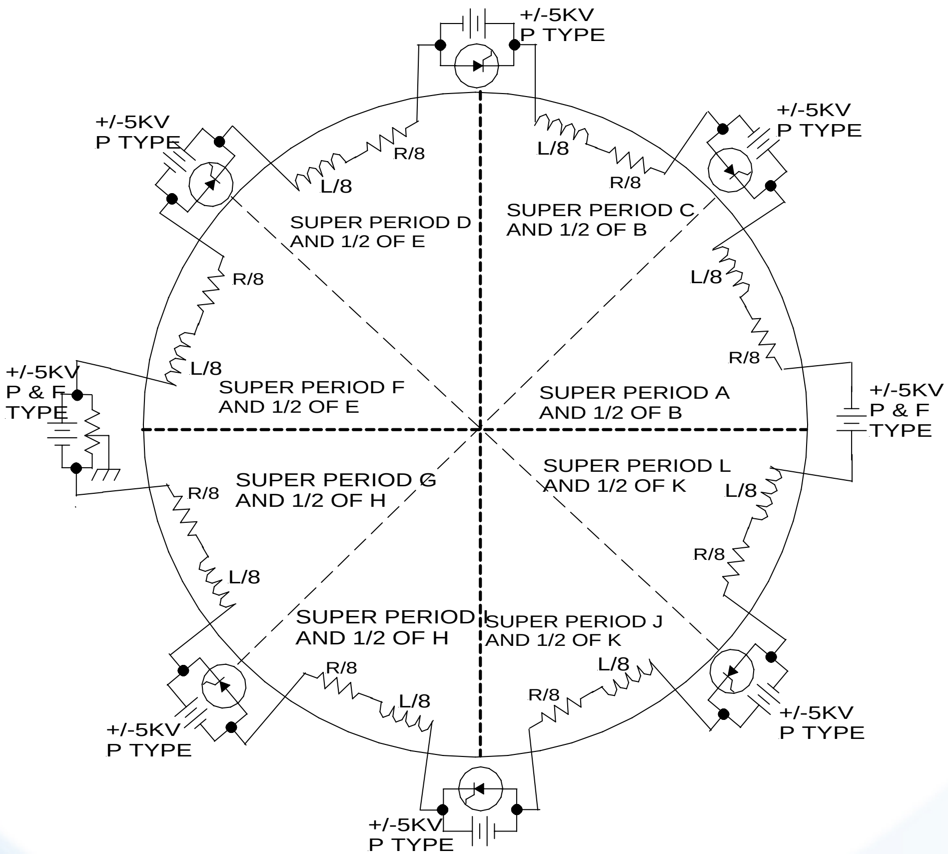
THE AGS MAGNET CONNECTIONS FOR 5 HZ OPERATION



- To do this, the AGS magnets will need to be divided into eight identical sections, each powered similarly to one present AGS Station.
- There will be 8 P type stations similar to one of the existing stations and two F type stations.
- With this configuration we could run at 1 Hz, present mode and 5 Hz.

THE AGS MAGNET CONNECTIONS FOR 5 HZ OPERATION



- Every P type station will be rated at +/-5000 volts 6000 Amps.
- Bypass SCRs will be used across the six P bank stations that are not associated with an F type station.
- Station 1 will be grounded in the middle, ensuring a maximum voltage to ground of less than 2500 volts.

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POTENTIAL ENERGY STORAGE SOLUTIONS

- Reason for energy storage, is to pulse the magnets at 160 MW while maintaining an almost constant input power from the Utility, thus greatly reducing the voltage flicker on the mains.
- Will examine the following energy storage solutions.
- 1. The Motor Generator solution.
- 2. The Capacitor Bank energy storage using DC/DC converters.
- 3. The inductor/capacitor energy storage.

1. MOTOR GENERATOR SOLUTION

- All power supplies will be thyristor control supplies.
- 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.
- One needs to investigate, if the upgrade can be done with a 200-MW generator or perhaps two 100-MW generators.

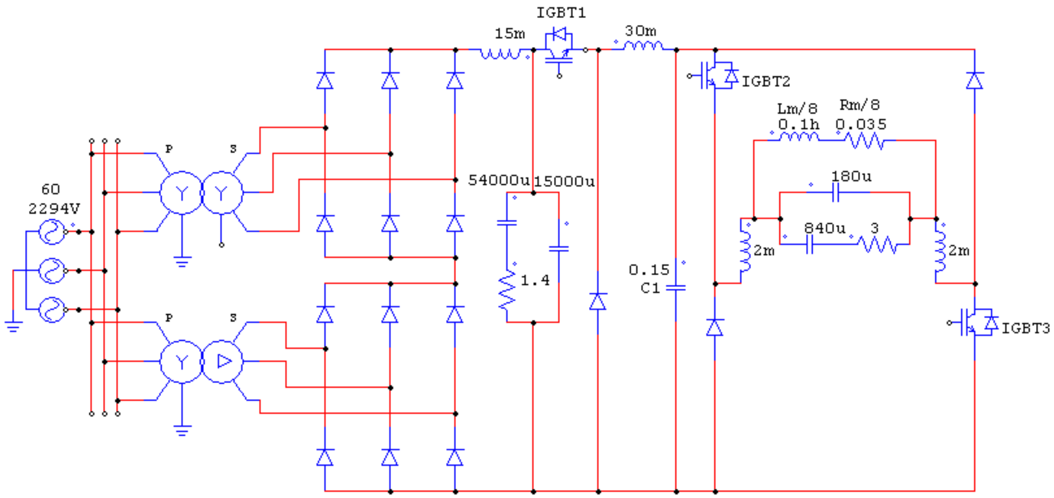
1. MOTOR GENERATOR SOLUTION

- Another specification is that 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 for the other three quarters of the AGS ring.
- If more than one MG sets are used since they may not be able to be line synchronized the ripple will be a problem.

The motor generator issues

- It is not clear if companies will be willing to manufacture 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.
- Such an application may not be the best solution.

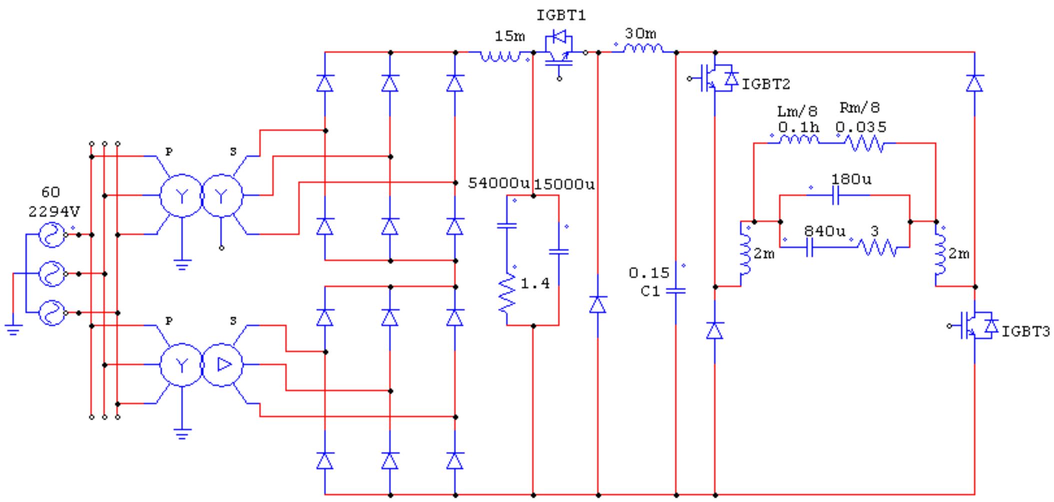
2. THE CAPACITOR ENERGY STORAGE SOLUTION



- Another topology is to use two dc to dc converters interfaced with a capacitor bank as shown.
- The assumption, is that we replace the existing AGS supplies with new ones.

- As a result all 8 power supplies should be identical.
- The basic building block of one of these power supplies is shown.
- The switching elements could be IGCT's, or IGBT's.
- The total energy stored in all 8 storage capacitor banks is equal to approximately 22 MJ for this simulation.

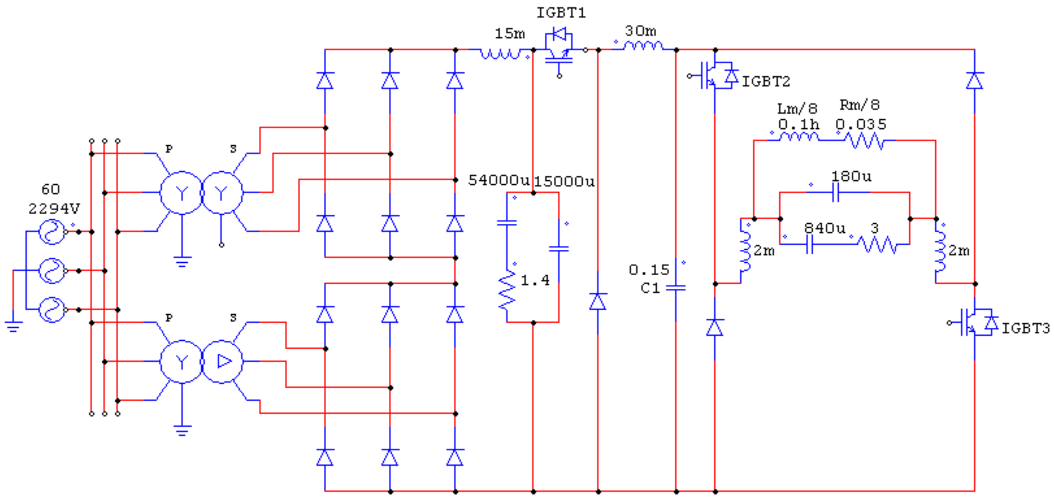
The power system



- 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.
- The other stations are identical.
- Note that the grounding is done in the middle of one of the power supplies as mentioned earlier.
- The energy of the capacitor bank C1 is 2.7 MJ.
- The maximum voltage is 6000 volts and the capacitance is 0.15 F.

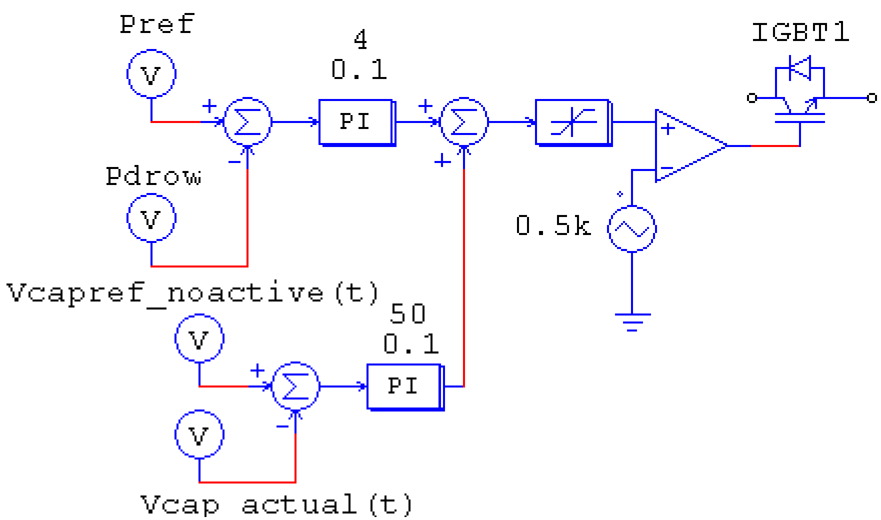
The power system

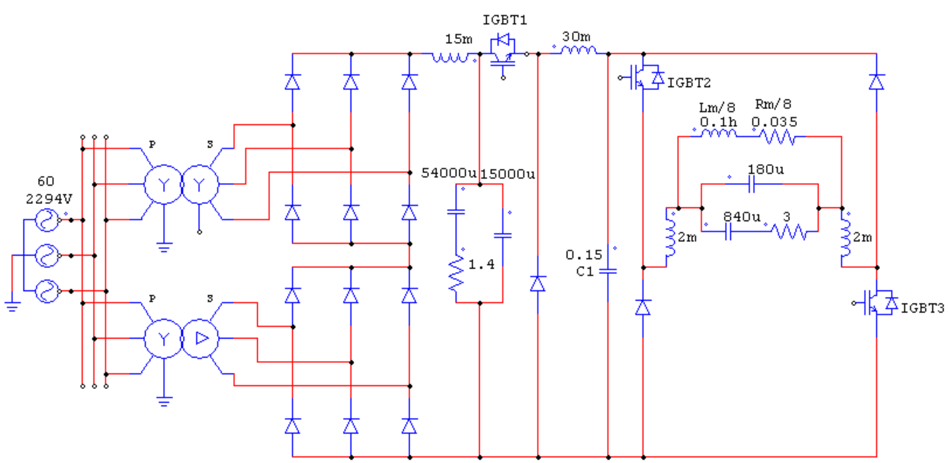


- The frequency used to run the power electronics of both dc to dc converters for this simulation, was 500 Hz.
- IGCT's with ratings similar to the ratings of our power electronics are being pulsed at around 500 Hz to 1 KHz.

- 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



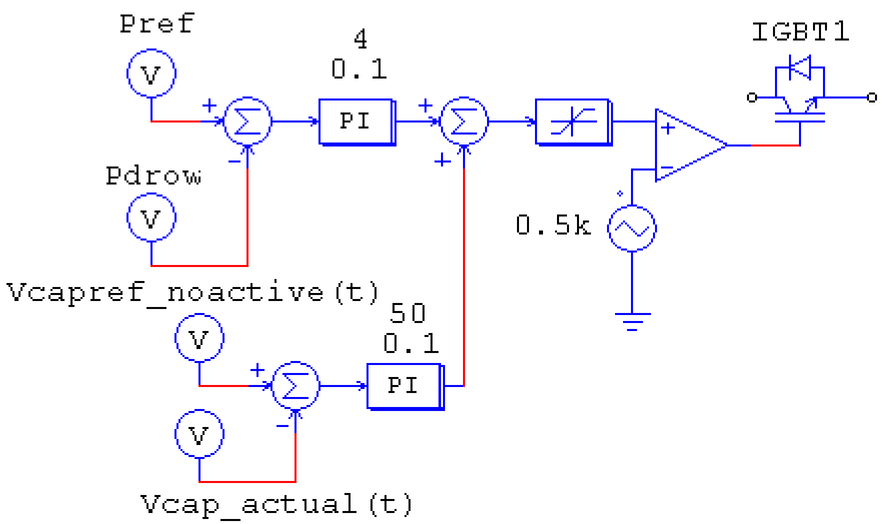


- There are two control systems used in the simulation. The first, controls the buck converter power electronics IGBT1, and the second is used to control the magnet voltage, using the power electronics of the two quadrant dc to dc converter IGBT2, IGBT3.
- The block diagram of the first control system is shown.
- 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 from the capacitor only during ramping up the magnet, not taking into account magnet losses. This was calculated to be.

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

The control system

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

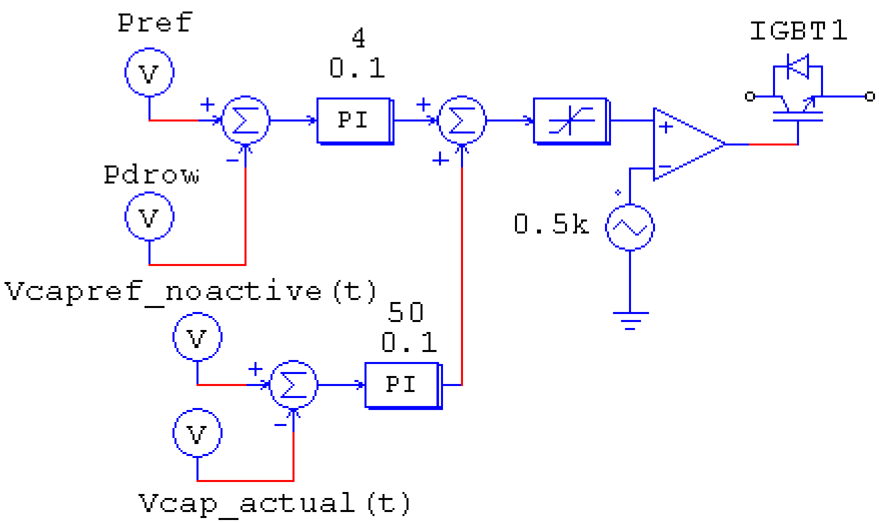


- V0, is the original capacitor bank voltage the capacitor is charged to, and in this case is 6000 volts.
- L is the magnet inductance, and is equal to 1/8th of the AGS inductance, which is 0.1 H.
- C1 is the capacitor bank value equal to 0.15 F.
- Im(t) is the magnet current as a function of time. I0 is the magnet current at the front porch, equal to around 200 A.
- Vcap_actual(t) represents the actual voltage across the capacitor bank C1 during a magnet cycle.

- Pref is the average power losses ,reference of 1/8th 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.
- **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 greater than the maximum magnet voltage for a given cycle.**

The control system

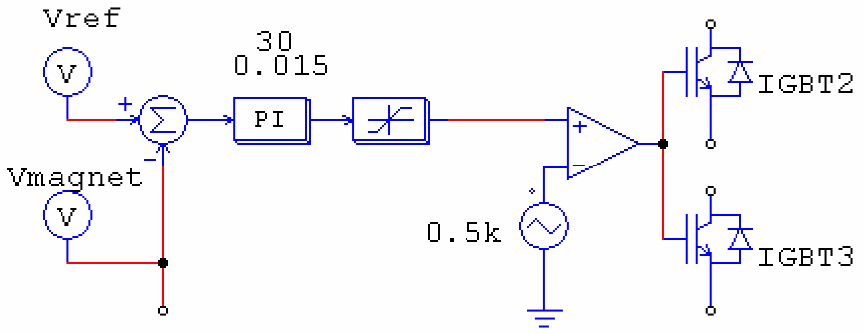
$$Vcap(t) := \sqrt{\frac{1}{4\cdot C1}\cdot\left[\left(\int_0^t Pam\,dt\right) + \frac{8\cdot C1\cdot V0^2}{2} - \frac{L\cdot I(t)^2}{2} + \frac{L\cdot I(0)^2}{2} - \int_0^t I(t)^2\cdot R\,dt\right]}$$



- It was also calculated that, for a given magnet cycle, in order to keep the average incoming power constant, including all losses in the magnets, the capacitor bank voltage should follow the waveform of the formula to the left.

- It is possible in the actual system, 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.

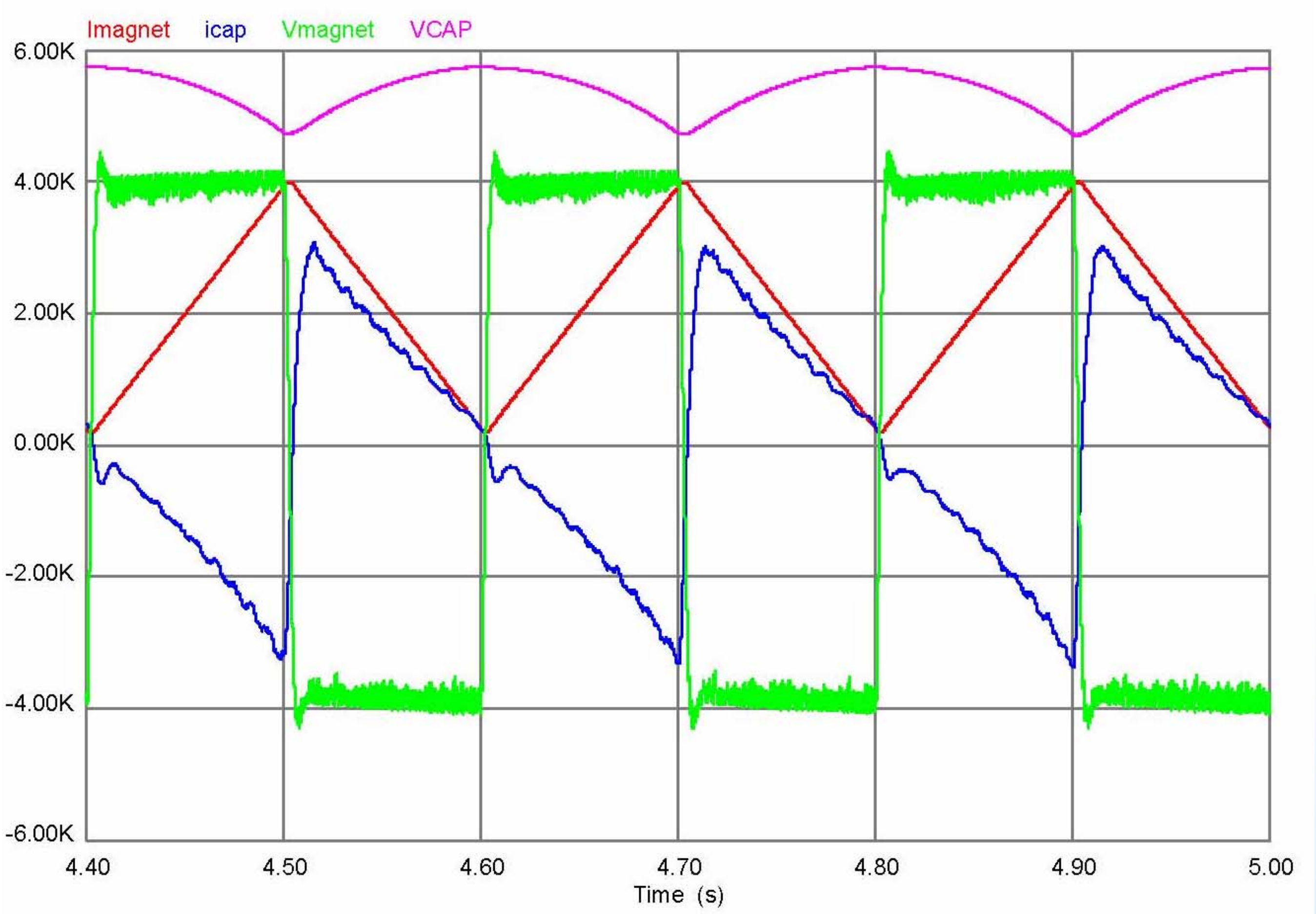
The control system



- The second control system, is used to control the magnet voltage. Every supply out of the 8 supplies will have one.
- A current loop will also be used as the outer loop, for one out of the 8 supplies.
- For this simulation only the voltage loop was used.

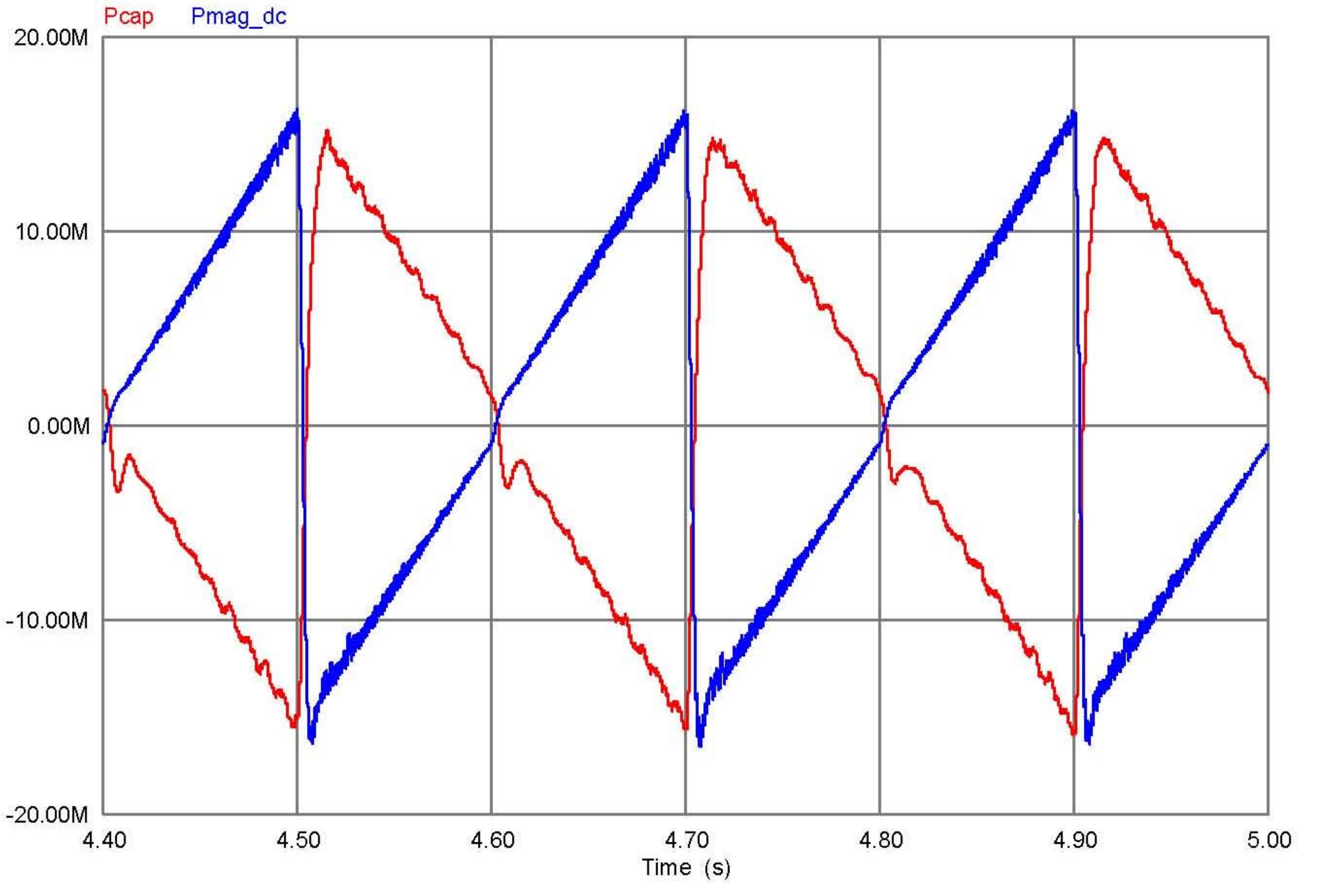
- Vref represents the magnet voltage reference for one of the 8 supplies, for a given magnet current.
- Vmagnet represents the actual magnet voltage corresponding to 1/8th of the magnet load.

Simulation results



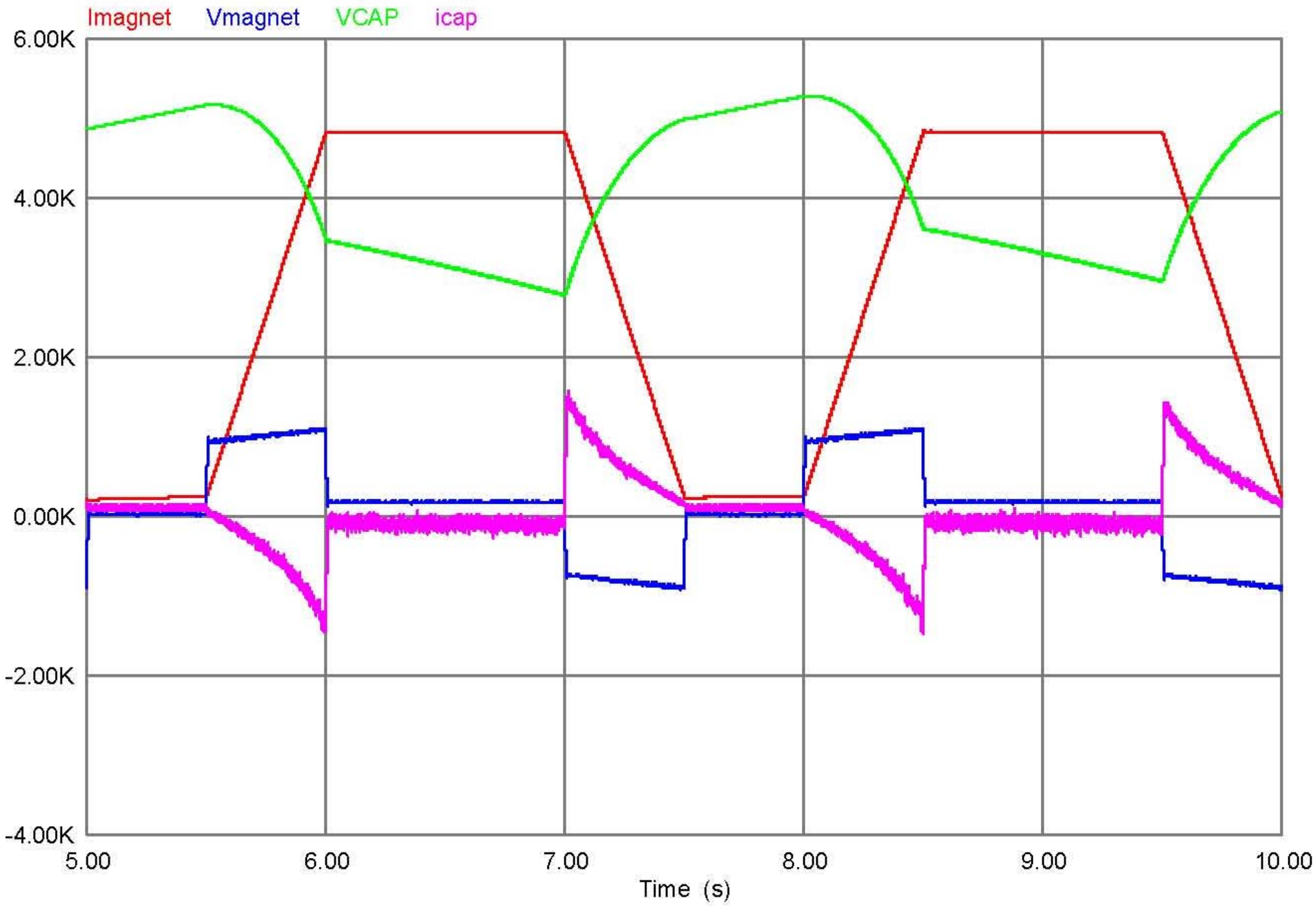
- Magnet current and voltage; capacitor current and voltage for 5 Hz operation

Simulation results



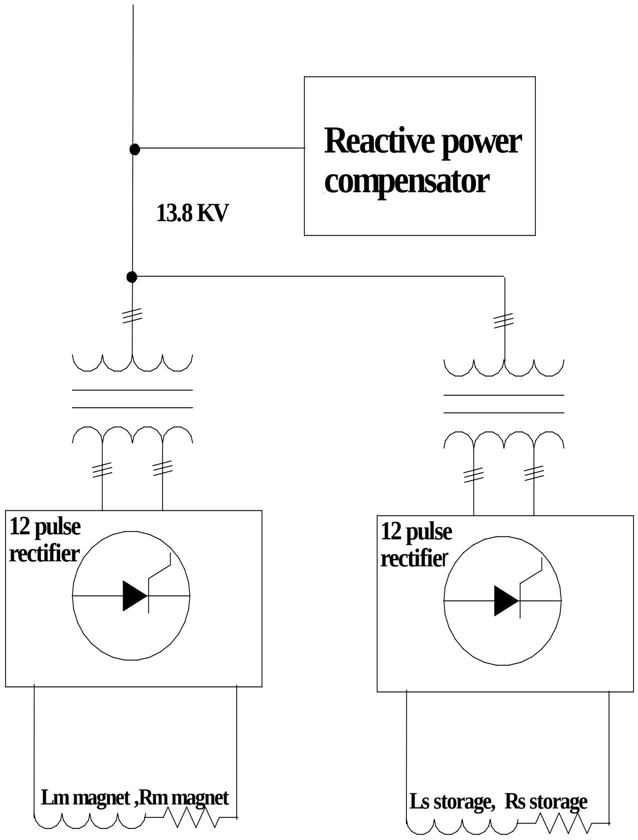
- Capacitor bank and magnet, peak power waveforms for 5 Hz operation

Simulation results



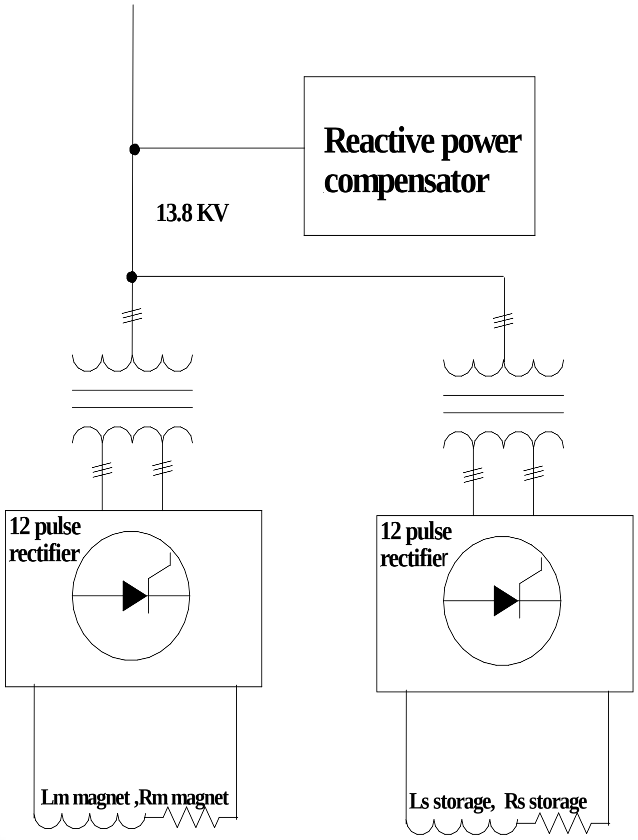
- Magnet current and voltage; capacitor current and voltage for present operation.

THE INDUCTOR ENERGY STORAGE SOLUTION



- The assumption is that we replace the existing supplies with new ones. As a result all 8 power supplies should be identical.
- The basic building block of one of these power supplies is shown.
- All formulas and calculations referenced below are for the basic building block supply.
- There are two thyristor control supplies; one is connected to 1/8 of the magnet load and the other to a storage inductor.

THE INDUCTOR ENERGY STORAGE SOLUTION



- There is also a reactive power compensator interfaced at the incoming ac line, to compensate for reactive power.
- We store energy in the storage inductor and during pulsing the magnet up, the energy comes from the storage inductor.
- During ramping the magnet down the magnet stored energy goes back to the storage inductor.
- The total energy stored in all 8 storage inductors is equal to approximately 22 MJ.

THE INDUCTOR ENERGY STORAGE SOLUTION

- 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.

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

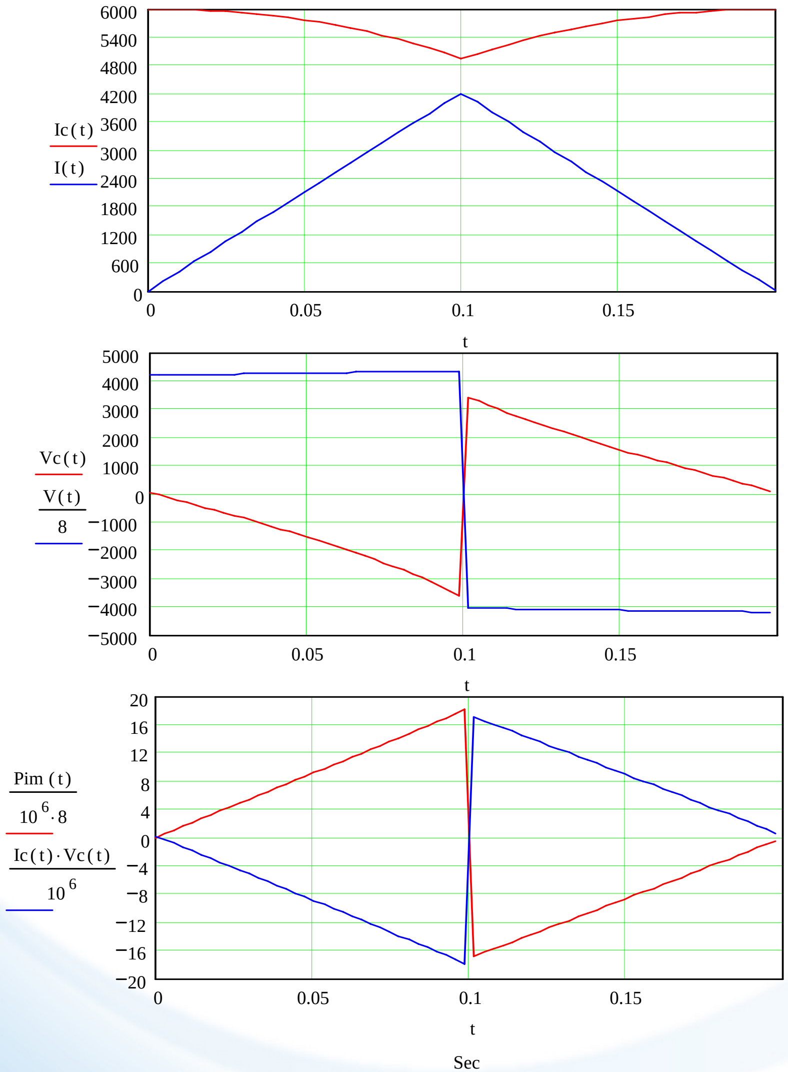
- Note, this formula does not take into account storage inductor losses.
- It is applicable for a superconductor only.

THE INDUCTOR ENERGY STORAGE SOLUTION

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

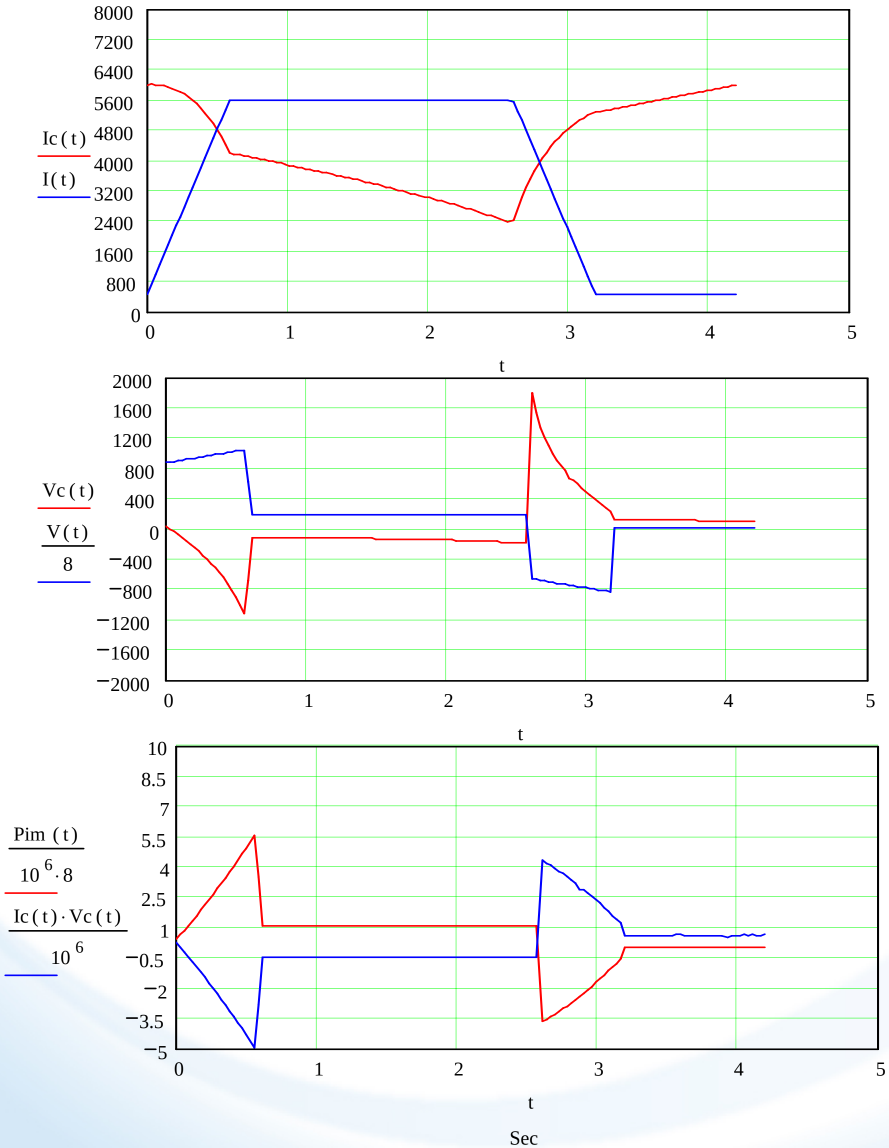
- Ic(t) is the storage inductor current in amps.
- L1 is the inductance of the storage inductor equal to 0.153 henries.
- Pam is the average incoming power in watts.
- L is 1/8th of the total magnet inductance equal to 0.1 henries.
- I(t) is the magnet current in amps.
- R is 1/8th of the magnet resistance equal to 0.035 Ohms.
- I(0) is the magnet current in amps at t=0 sec.

Inductor storage wave forms, for 5 Hz operation



- Ic(t) is the storage inductor current in amps.
- I(t) is the magnet current in amps.
- Vc(t) is the storage inductor voltage in volts.
- V(t)/8 is the magnet voltage for 1/8th of the magnets.
- The bottom wave forms display the peak magnet power for 1/8th of the magnets and the peak storage inductor L1 power in MW.

Inductor storage wave forms, for present operation.



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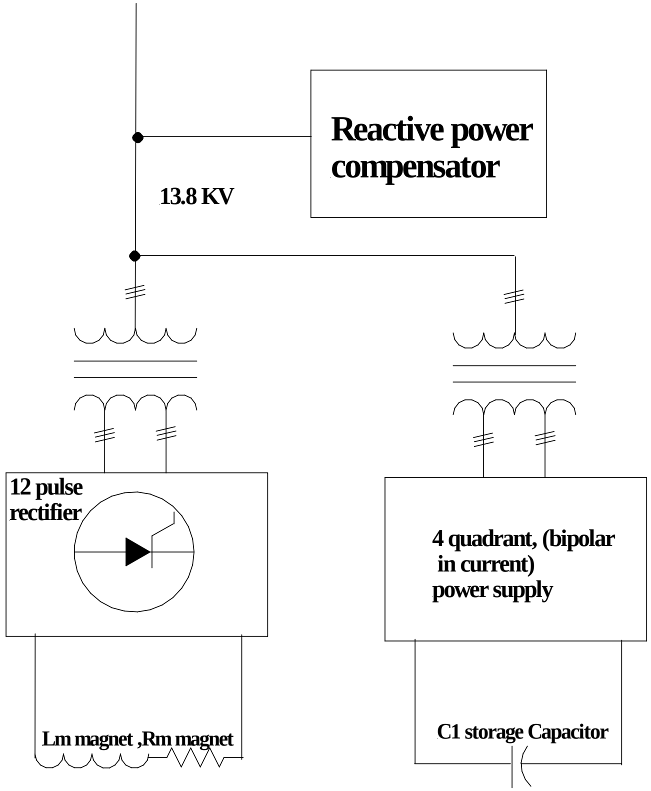
- The bottom wave forms display the peak magnet power for 1/8th of the magnets and the peak storage inductor L1 power in MW.

USING A CAPACITOR BANK INSTEAD OF INDUCTOR FOR ENERGY STORAGE



- It was calculated that in order to maintain the average incoming power constant, we must pulse the voltage of the storage capacitor using the following formula.
- Note this formula does not take into account storage capacitor losses.

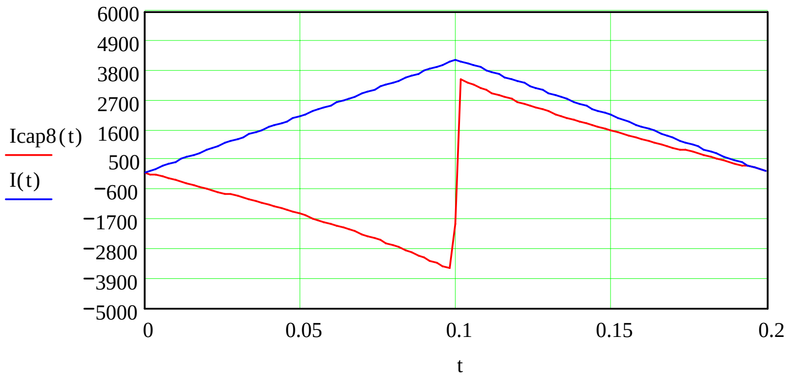
$$\mathrm{Vcap}(t) := \sqrt{\frac{1}{4\cdot C1}\cdot\left[\left(\int_0^t \mathrm{Pam}\,dt\right) + \frac{8\cdot C1\cdot V0^2}{2} - \frac{L\cdot I(t)^2}{2} + \frac{L\cdot I(0)^2}{2} - \int_0^t I(t)^2\cdot R\,dt\right]}$$

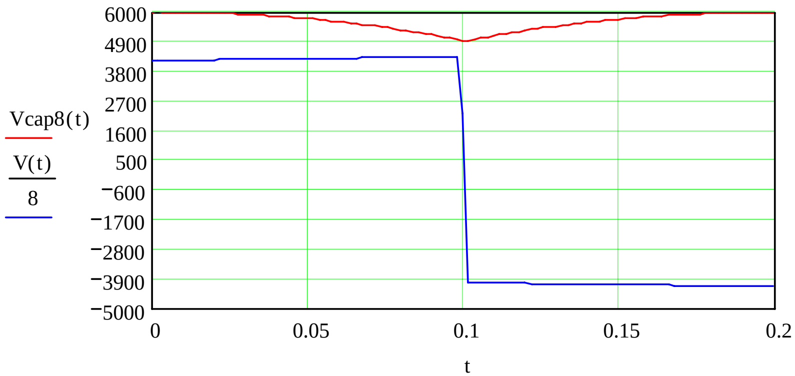
THE INDUCTOR ENERGY STORAGE SOLUTION

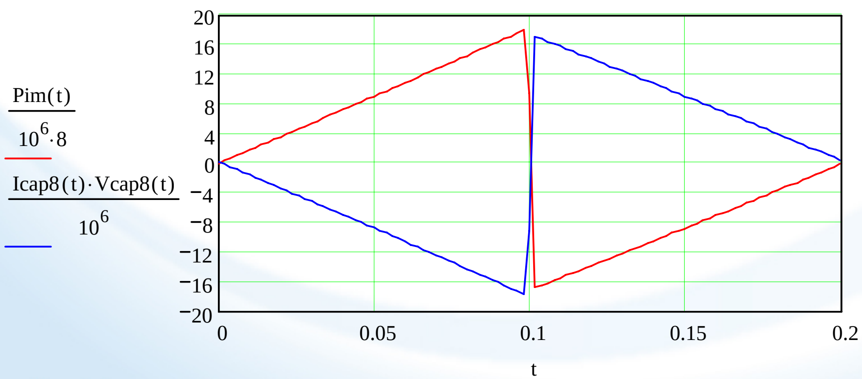
$$\mathrm{Vcap}(t) := \sqrt{\frac{1}{4 \cdot C1} \cdot \left[\left(\int_0^t \mathrm{Pam}\, dt\right) + \frac{8 \cdot C1 \cdot V0^2}{2} - \frac{L \cdot I(t)^2}{2} + \frac{L \cdot I(0)^2}{2} - \int_0^t I(t)^2 \cdot R\, dt\right]}$$

- Vcap(t) is the storage capacitor voltage in volts.
- C1 is the capacitance of the storage capacitor equal to 0.15 Farads.
- Pam is the average incoming power in watts.
- L is 1/8th of the total magnet inductance equal to 0.1 henries.
- 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.

Capacitor storage wave forms, for 5 Hz operation

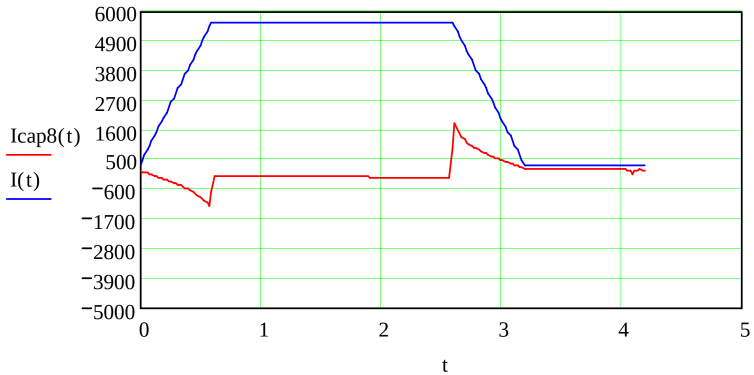


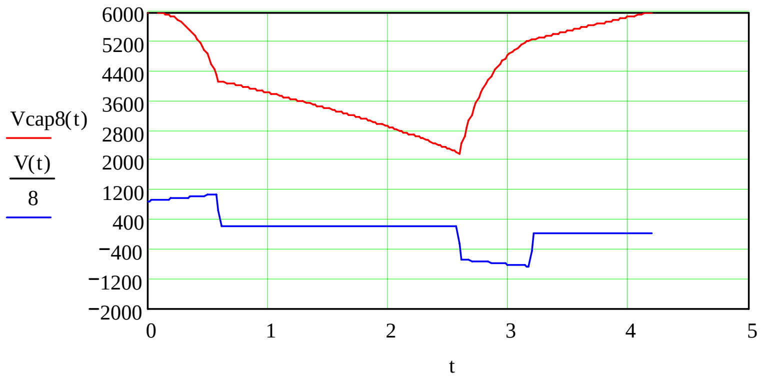


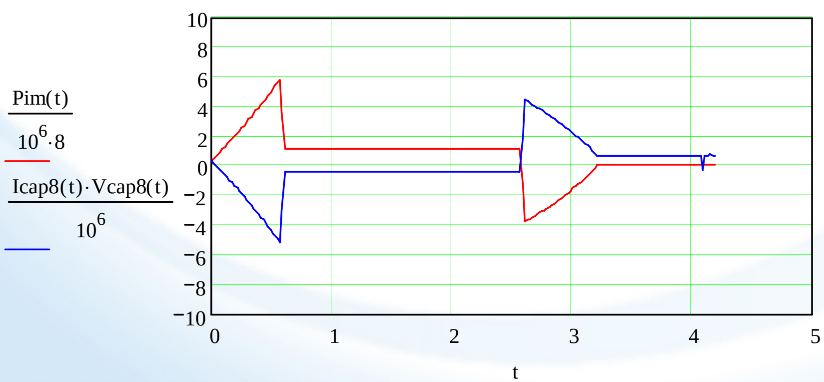


- Icap8(t) is the storage capacitor current in amps.
- I(t) is the magnet current in amps.
- Vcap8(t) is the storage capacitor voltage in volts.
- V(t)/8 is the magnet voltage for 1/8th of the magnets.
- The bottom wave forms display the peak magnet power for 1/8th of the magnets and the peak storage capacitor power in MW.

Capacitor storage wave forms, for present operation.







- Icap8(t) is the storage capacitor current in amps.
- I(t) is the magnet current in amps.
- Vcap8(t) is the storage capacitor voltage in volts.
- V(t)/8 is the magnet voltage for 1/8th of the magnets.
- The bottom wave forms display the peak magnet power for 1/8th of the magnets and the peak storage capacitor power in MW.

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.
- If capacitor banks are used instead of inductors, the power supplies interfaced with the capacitors should be bipolar in current.

EDDY CURRENTS

- Calculated Eddy-current losses on the vacuum chamber and concluded there is no problem.
- Calculated Eddy-current losses on the magnet current conductors and they are 5% of the dc losses.
- We are pulsing the Booster MMPS at 7.5 Hz and there is no problem.
- It was calculated that the magnetic multipoles at the region of the circulated beam, created due to Eddy-currents on the vacuum chambers will not affect the quality of the magnetic field of the magnets during acceleration.

CONCLUSION

- The most attractive topology appears to be the capacitor bank with two dc to dc converters.
- The simulation shows that such a system may be possible.
- Cern is replacing the PS motor generator and power supply with capacitor banks and dc to dc converters, a system with some similarities to the one described.
- 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.
- A detailed, cost estimate of such a system is a must.

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