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Simulation Results of Running the AGS MMPS, by Storing Energy in Capacitor Banks

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Introduction.

The Brookhaven AGS is a strong focusing accelerator which is used to accelerate protons and various heavy ion species to equivalent maximum proton energy of 29 GeV. The AGS Main Magnet Power Supply (MMPS) is a thyristor control supply rated at 5500 Amps, +/-9000 Volts. The peak magnet power is 49.5 Mwatts. The power supply is fed from a motor/generator manufactured by Siemens. The motor is rated at 9 MW, input voltage 3 phase 13.8 KV 60 Hz. The generator is rated at 50 MVA its output voltage is 3 phase 7500 Volts. Thus the peak power requirements come from the stored energy in the rotor of the motor/generator. The rotor changes speed by about +/-2.5% of its nominal speed of 1200 Revolutions per Minute. The reason the power supply is powered by the Generator is that the local power company (LIPA) can not sustain power swings of +/- 50 MW in 0.5 sec if the power supply were to be interfaced directly with the AC lines. The Motor Generator is about 45 years old and Siemens is not manufacturing similar machines in the future. As a result we are looking at different ways of storing energy and being able to utilize it for our application. This paper will present simulations of a power supply where energy is stored in capacitor banks. The simulation program used is called PSIM Version 6.1. The control system of the power supply will also be presented. The average power from LIPA into the power supply will be kept constant during the pulsing of the magnets at +/-50 MW. The reactive power will also be kept constant below 1.5 MVAR. Waveforms will be presented.

The power system.

The power supply is composed of two stations. Station I is composed of a 12 pulse full-wave bridge rectifier charging a capacitor bank through a, one quadrant buck converter. A two quadrant DC to DC converter is used to convert the capacitor bank voltage into pulsed DC voltage across the magnets. See Figure 2. Station II is identical to station I. Note station I is connected to half of the AGS magnets which are also connected in series with station II power supply. This power supply is also connected in series with the other half of the AGS magnets which are also connected in series with station I power supply see Figure 1.

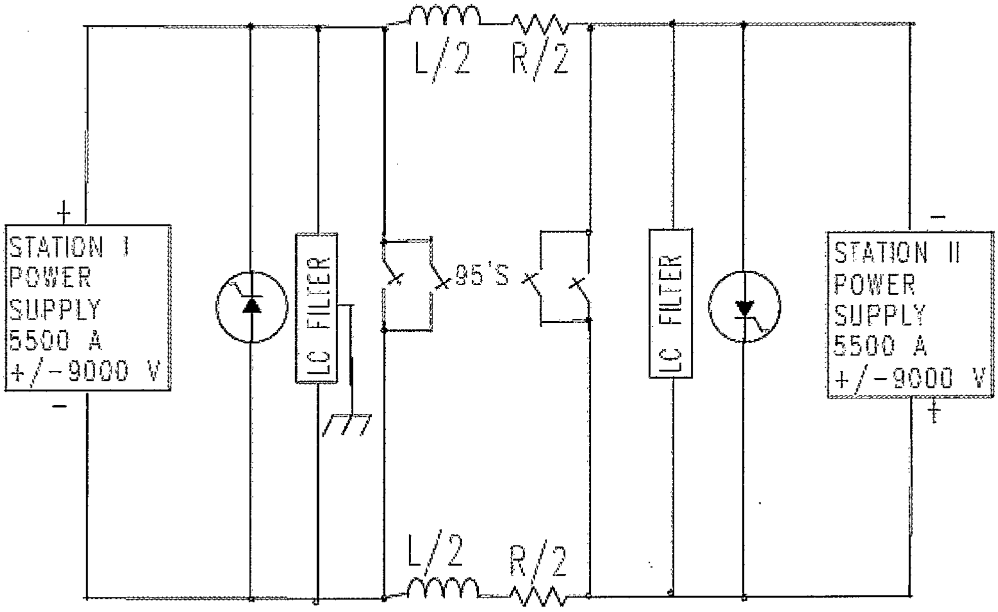

Figure 1

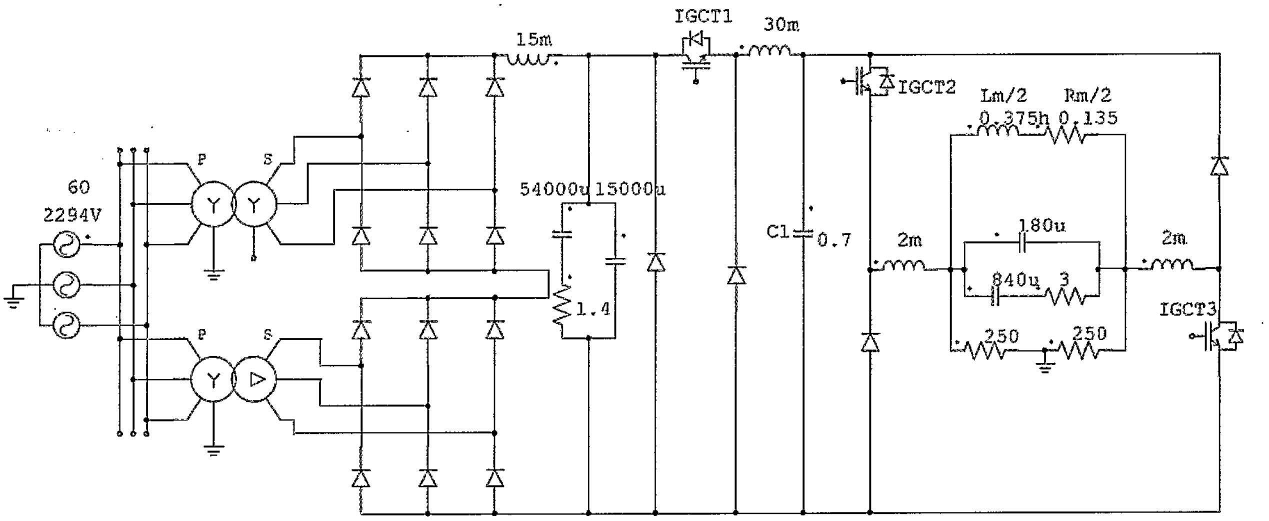

Figure 2

The energy of the capacitor bank C1 is a 12.6 MJ. The maximum voltage is 6000 volts and the capacitance is 0.7 F. The frequency used to run the power electronics of both DC to DC converters for this simulation was 500 Hz. The reason was 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. If at the end IGCT's are used and they are pulsed at 500 Hz, station II could be pulsed again at 500 Hz but delayed from station I by 180 degrees resulting in minimizing the magnet voltage ripple. Of course these details need to be looked at in more detail. 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 yet.

The control systems

There are two control systems used in the simulation. One that 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 3. There are two loops being used, the inner loop and the outer loop. The inner loop has a reference called Pcapref_noactive. This represents the reactive power draw from the capacitor bank C1 for a given magnet current cycle. This was calculated to be P(t).

$$P(t) = \sqrt{V0^2 - \frac{L}{C}\cdot\left(Im(t)^2 - I0^2\right)}$$

V0 is the original capacitor bank Voltage the capacitor is charged to in this case is 6000 volts. L is the magnet inductance in this case and is equal in value to half of the AGS inductance equal to 0.375 H. C is the capacitor bank value in this case is equal to 0.7 F. Im(t) is the magnet current as a function of time and I0 is the magnet current at T0 and during the time of the front porch which is equal to around 300 A. VCap_actual represents the actual voltage across the capacitor bank C1. Pref is the average power losses for a given super cycle of the magnet current. Pdraw is the average active power being drawn from the AC line for a given super magnet cycle. Note that this loop is the outer loop and it is slower than the inner loop. The time delay of this loop is 0.9 sec and the time delay of the inner loop is 0.1 sec. The objective of these two loops is to keep the average active power coming from the line constant, while the magnet current is being pulsed to about 25 MW peak power and of course to keep the capacitor bank charged to a voltage grater than the maximum magnet voltage for a given cycle.

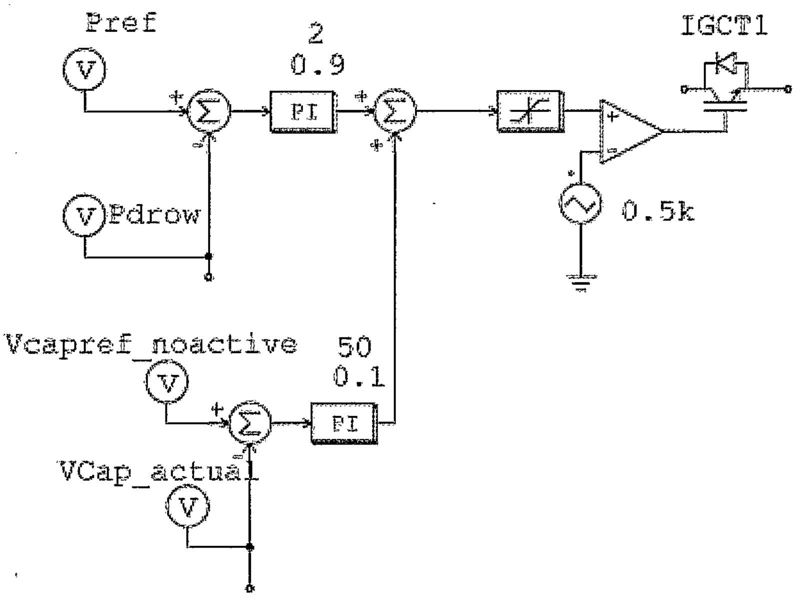

Figure.3

The second control system is used to control the magnet voltage and it is shown in figure 4. In actuality a current loop should also be used as the outer loop, however for this simulation only the voltage loop was used. Verf represents the magnet voltage reference of station I for a given magnet current. Vmagnet represents the actual magnet voltage.

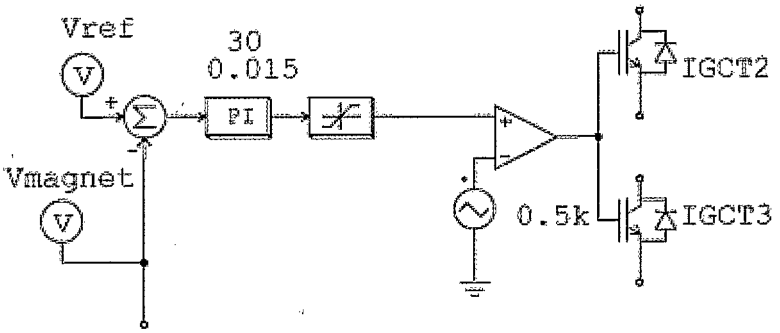

Figure 4.

It was calculated that for a given magnet cycle in order to keep the average power coming in constant, the capacitor bank voltage should follow the wave form of the following formula.

$$\mathrm{Vcap1}(t) := \sqrt{\frac{2}{C}\cdot\left[\mathrm{Pam}\cdot t + \frac{C\cdot V0^{2} - L\cdot\left(I(t)^{2} - I(0)^{2}\right)}{2} - \int_{0}^{t} I(t)^{2}\cdot R\,dt\right]}$$

C is the capacitor bank capacitance, Pam is the average input power V0 is the cap bank peak voltage (6000 volts), L is the load inductance 0.375 H, R is the load resistance (0.135 Ohms), I(t) is the magnet current, I(0) is the front porch current, around 300 Amps. This means that one could setup an independent loop to control the IGCT1 of the buck converter with a voltage reference the above formula and voltage output the cap bank voltage. Doing this the average incoming power should remain constant. This loop however was not simulated due to difficulties of the simulator program.

Simulation results.

Figure 5 displays the magnet current the magnet voltage and the capacitor bank voltage for a typical AGS cycle.
Figure 6 displays the capacitor bank C1 voltage (Vcap), the reactive power reference P(t) referenced above for the capacitor bank C1 for a given magnet current cycle (Pcapref_noactive) and the 12 pulse full wave bridge rectifier output voltage after the filter (Vps).
Figure 7 displays the capacitor bank voltage and current.
Figure 8 displays the calculated power reference (Pref) the active power draw from the line (WATTS-AC) and the reactive power draw from the line (VAR). Note that the active power draw fluctuations are not more than 100 KW. Also the reactive power is not more than 0.6 MVAR.
Figure 9 displays the current provided by the 12 pulse rectifier in to the cap bank for the same magnet cycle.
Figure 10 displays the peak magnet power and the average magnet power drawn from the AC line. Note that the peak magnet power is 20 MW while the average input power remains constant around 2 MW.

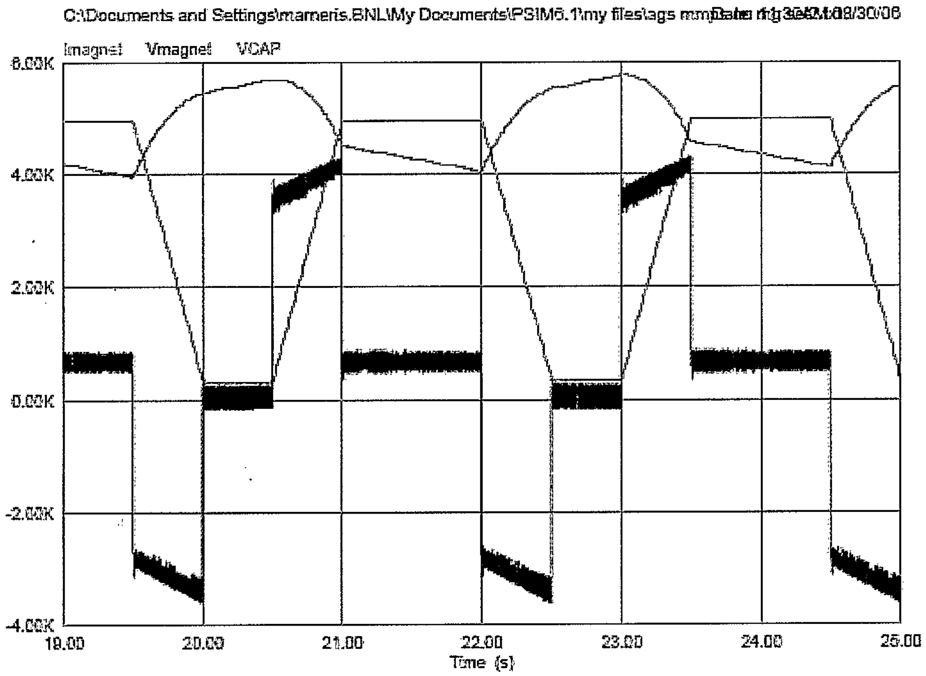

Figure 5.

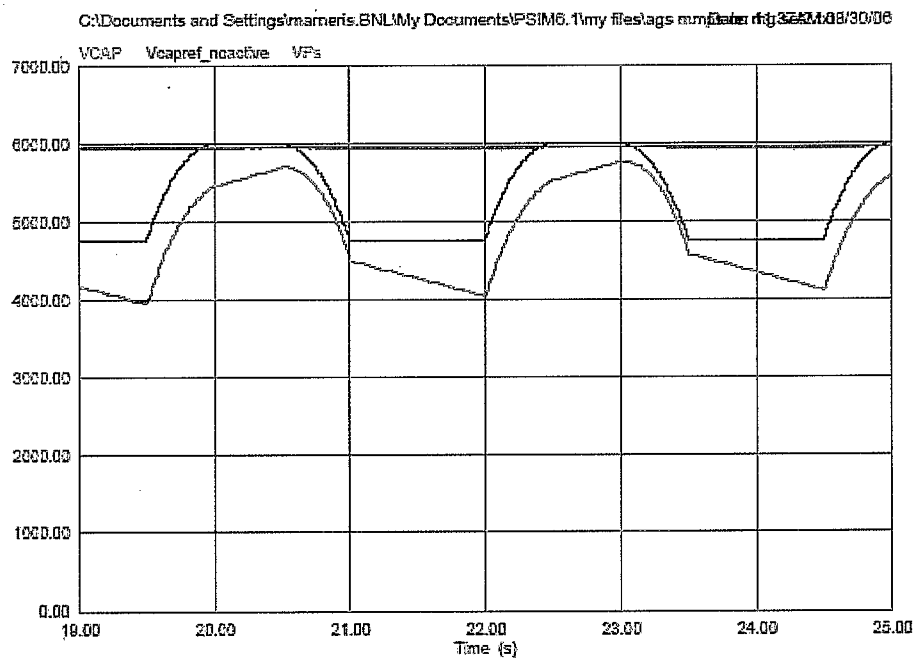

Figure 6.

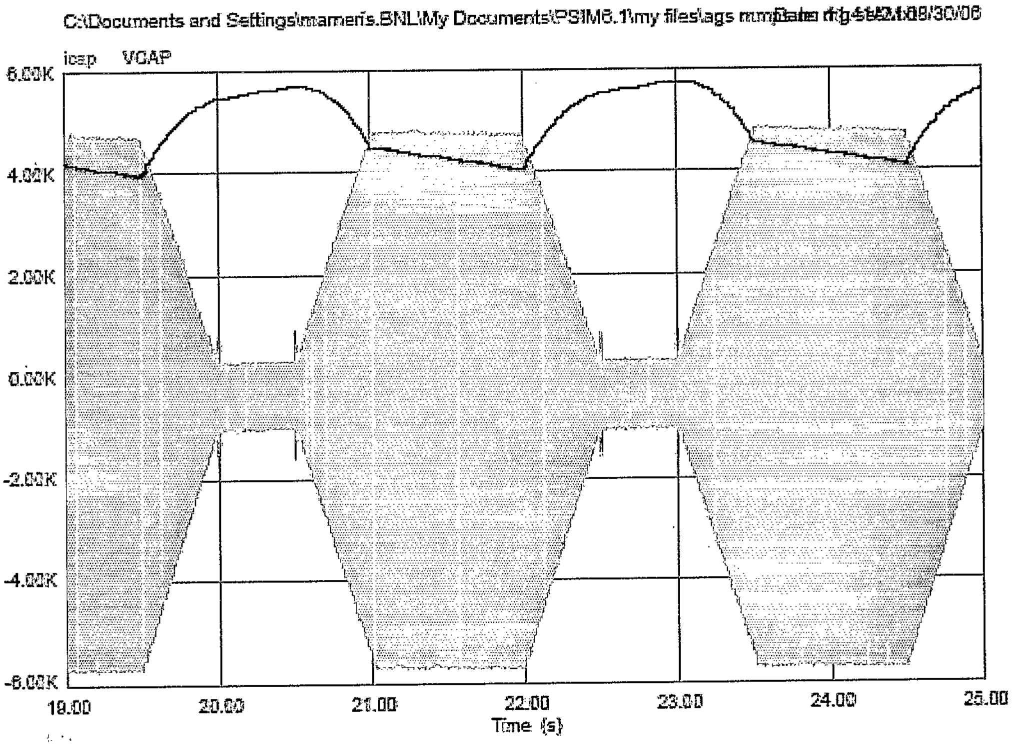

Figure 7.

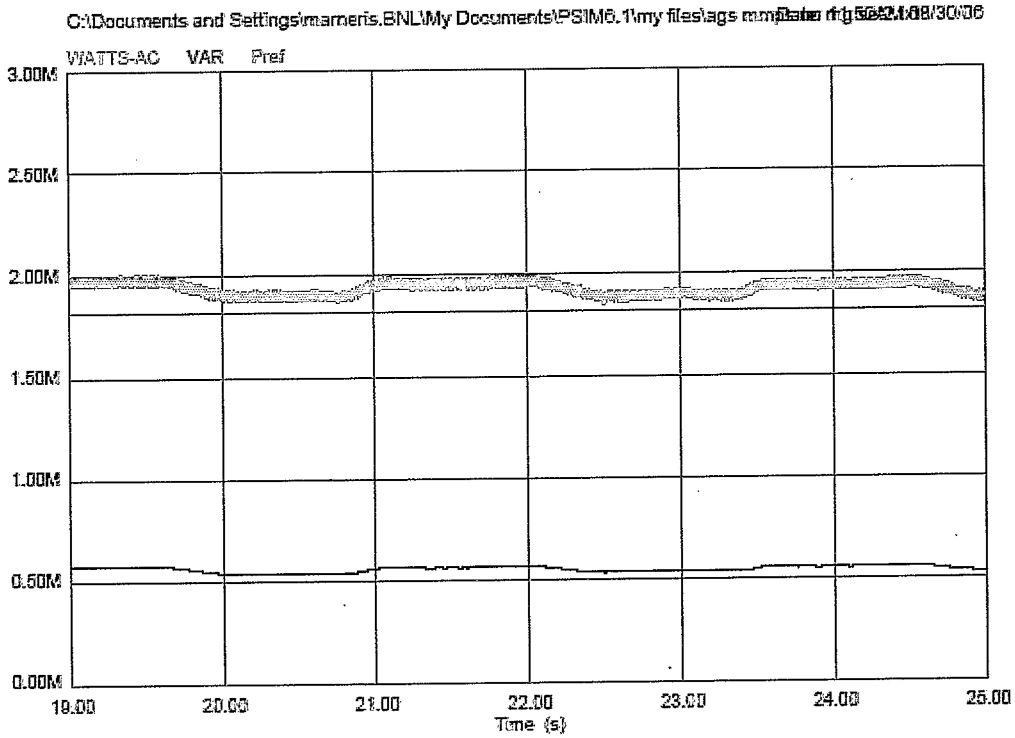

Figure 8.

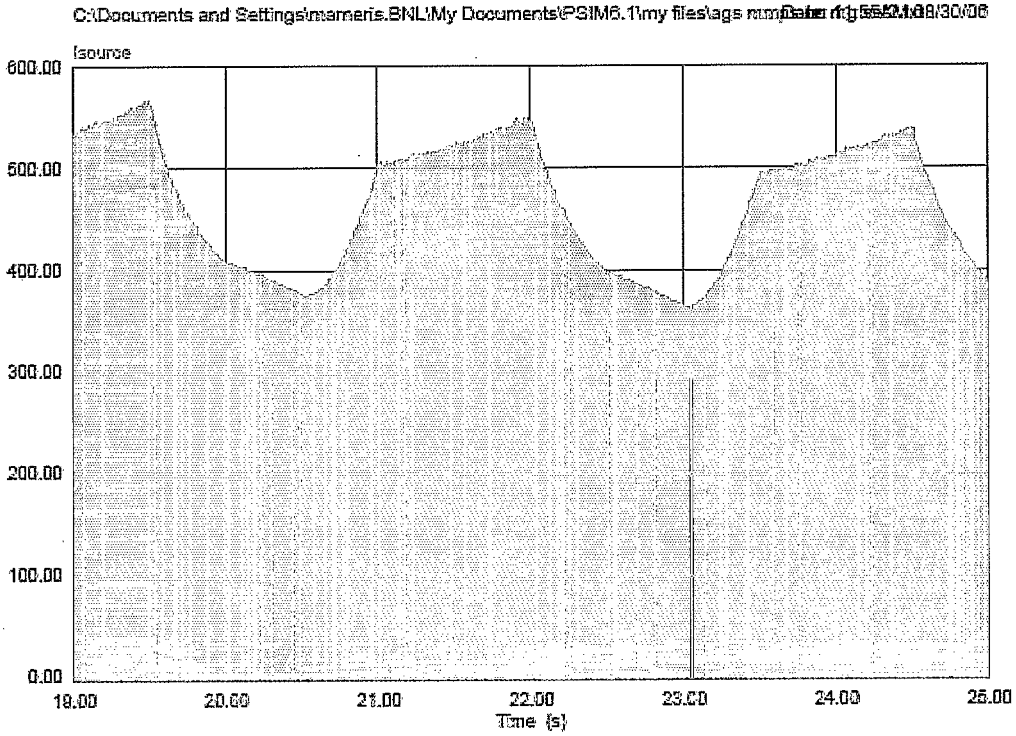

Figure 9.

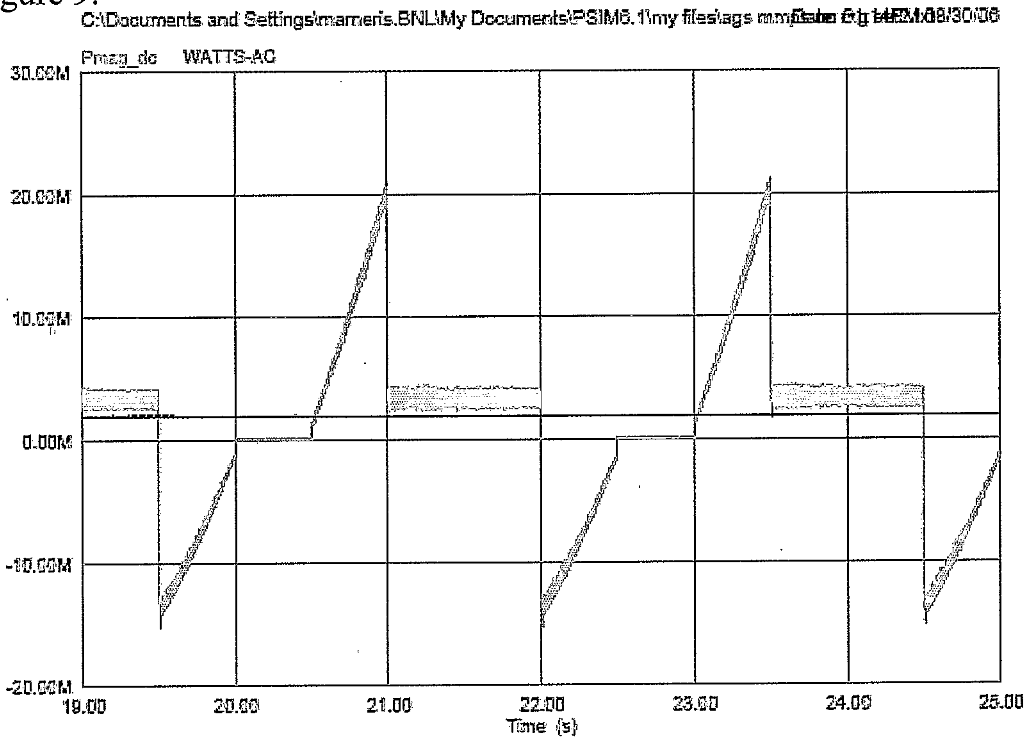

Figure 10.

Conclusion.

It seems that based on the above simulation such a system may be possible, however one needs to address the following issues.
Is a 0.7 F, 12.6 MJ, 6000 V, 5000 A capacitor bank realizable? What are the safety issues with such a cap bank?
What power devices must one use IGCT's or IGBT's currently available from the industry? What frequency should they run at and what will be the magnet voltage ripple? How does it compare with the current values? The 12 pulse rectifier should not be a problem. One needs a 6000 V, 800 A DC rectifier.
It seems that we need to do a study with companies such as Siemens or ABB and understand better the complexity of the issues. If this solution is feasible how much does it cost?
Are there other potential solutions and how do they compare price wise? It is my understanding that we should be looking at these issues to be able to eventually have some answers if need be.

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