BNL-104645-2014-TECH

AGS/AD/Tech Note No. 218;BNL-104645-2014-IR

CONTROLS UPGRADE FOR THE AGS MAIN MAGNET POWER SUPPLY

A. Feltman

July 1985

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

Accelerator Division
Alternating Gradient Synchrotron Department
BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
Upton, New York 11973

Accelerator Division Technical Note

No. 218

CONTROLS UPGRADE FOR THE AGS MAIN MAGNET POWER SUPPLY

A.V. Feltman and J.W. Glenn

July 23, 1985

ABSTRACT

Heavy Ion Acceleration and other new modes of operation require simple and precise Main Magnet Current Ramp adjustment as well as rapid restoration of previous proven Ramp setups. Instead of adding to the system more layers of piecemeal improvements to achieve these goals, it is proposed to purchase a highly reliable industrial process control computer to replace the various manually operated power supply controls that have grown over the years. A two phase project is outlined: first, a new ramp controller; then, as needed, further enhancements, including mixed cycle operation, improved stability, and remote control. Phase I of the project should cost about $420,000 in purchases plus three man years of technician and engineering labor, and Phase II about $90,000 plus another three man years of labor.

I. INTRODUCTION

The Alternating Gradient Synchrotron (AGS) accelerator is the major facility for high energy physics at Brookhaven National Laboratory. The power supply for the accelerator main magnet string is a motor generator set combined with eight three-phase full wave rectifier/inverter bridges that pulse the magnet to full current (~5,000 A) in 0.5 seconds, hold the current nearly constant (flattop), then inverts to remove the current from the magnets (see Figure 1 for typical wave forms). The total energy transferred (~10 MJ) is large as well as power swings (~±70 MW). This energy is stored in the rotating mass of the generator resulting in a speed change of about ±1%. The power supply voltage is controlled by the firing phase of the rectifiers allowing a voltage swing of ±3,000 V for each bridge resulting in a total swing of ±12 kV for the four bridges in series. The voltage required to hold the current constant for flattops is provided by four parallel lower voltage (~±500 V) bridges which are also phase controlled. Switching between these high and low voltage bridges is controlled by the relative firing phase of the rectifiers in these two supplies (see Figure 2 for power supply diagram).

The AGS is going through a series of upgrades and modernization stages. Future work on the AGS, including the polarized proton, higher intensity, and heavy ion acceleration effort require a more flexible and precisely controlled and regulated main magnet cycle. This will necessitate a re-design of the power supply's control system.

I.1 Description of Present System

The present system controls the phase of the firing of the rectifiers with ten pairs of delay units and a "master timer". The master timer switches control from one pair of delay units to the next. One delay unit controls two bridges and consists of 12 parallel analog delay modules.

Each module generates a voltage ramp initiated by a timing pulse from the generator. This voltage ramp is coupled to a voltage comparator which produces a delayed output pulse when the voltage ramp voltage passes through the comparator's reference input value. The comparator reference voltage which controls the delay is the sum of many inputs which may include a local reference to each delay to compensate for drift of bridge rectifier parameters, a voltage proportional to power supply current, time varying functions, and feedback signals. A pair of delay units are required to provide a specific voltage from the full power supply.

The master timer system switches these pair of delay units to the firing lines of the rectifiers, for individually preset periods of time. This sequential series of preplanned voltages produces the desired current waveform in the accelerator's main magnet string. This magnet cycle is reproduced by the timer at a self-generated fixed period. Auxiliary timing pulses are also generated ~0.1 second before the start of a cycle, at the start of the cycle and at the end of each voltage period.

Transition from voltage to voltage is smoothed by adding a voltage waveform to the comparator references to gently shift from one pair of delay units to the next, thus minimizing mechanical shock to the generator and electrical ringing of the filter on the power supply output and the magnet. To compensate for the increased commutation time at higher power supply currents a current proportional voltage is coupled to the comparators causing the rectifiers to fire earlier at higher currents. Also coupled to the comparators are output voltages of equipment that monitor power supply signals and accelerated beam parameters. Each comprises a feedback system designed to stabilize that specific parameter. Some feedback systems are operator closed; for example, the voltage ripple during flattop is analyzed and appropriate changes in the delays are made to reduce the harmonics of 60 cycles observed. Others are automatic, e.g., when the magnetic field reaches a preset value a voltage transition is initiated and as the field stabilizes another field mark changes the voltage to provide zero current change. There is also a real time voltage input to the system during beam extraction which modulates the power supply voltage to provide a uniform extraction rate (see Figure 3).

In total, there are about 250 knob-pots, hili-pots, and trim-pots plus a few dozen switches and computer settings that are adjusted to preprogram the supply to generate a magnet cycle and reference the various corrections and loops. Each new setup of the supply require a large fraction of these controls to be set to new values.

The motor for the motor generator set has a three-phase wound rotor with an active supply controlling power, while allowing it to operate above and below synchronous speed. The speed is controlled by a sample and hold unit that drives the motor power regulator. As the speed varies by ~±1% during the cycle, the speed is sampled at the same time (0.1 sec before each cycle) and the required motor power is updated with proportional and integral feedback. Changes in loading are not sensed until the next sampling time. Thus, many seconds are required to stabilize motor speed after a transient.

The generator output voltage is regulated with a fast excitor current supply that keeps the voltage at ~7500 volts (flux in the generator air gap is actually kept constant) while the generator current rises from zero to almost 5000 A in ~0.5 seconds, drops to ~1000 A during flattop, rises back to 5000 A at the end of flattop, and then falls to zero in ~0.5 seconds. To accomplish keeping the generator output constant, with ~±70 MW of power swing, the regulator must swing the excitor current between 500 Amps and 1200 Amps quickly.

I.2 Limitations of the Current System

The present system lacks in the following areas:

1. Flexibility. The polarized proton effort required many setups of "flattop" and "front porch" voltage profiles. The AGSII study calls for a more flexible voltage waveform tailored to rf and resonance crossing requirements. Heavy ion acceleration will require a precisely controlled but simply changed $\dot{B}$ program to balance the limits of the rf system and the vacuum system while minimizing ripple at different B's and $\dot{B}$'s.

2. Reproducibility. A detailed description of a magnet cycle cannot be stored due to the quantity of manual settings, the lack of readout on some, and long term drifts in much of the equipment. A system should be able to store and retrieve this information and reproduce the stored cycle at some future time. This would eliminate the extensive setup time presently required, including engineering staff time, to reproduce all but the simplest cycles.

3. Mixed cycles. During programmatic transitions, periodic mixed FEB and SEB (and possibly heavy ion or polarized proton) cycles may be useful. The present system cannot produce super cycles as CERN's system does within the power swing limits of BNL's power grid.

4. Increased stability. The changes in turnoff transients on the magnet and dwell period length affect the injection and capture of subsequent pulses. Temperature changes and other perturbations also affect the power supply's output and thus the beam. These should be measured and compensation made. Better reproducibility would increase beam stability and reduce the 5-20% lost time required for interpulse dwell. Drifts in the supply affect adjustments of other systems (e.g., the rf system in $\dot{B}$ sensitive).

5. Monitoring. A system should monitor its own performance, here: outputs, temperatures, firing delays, logic power supply voltages and vibration. This would reduce downtime as small but abnormal drifts can be annunciated and repaired on a scheduled basis instead of waiting for catastrophic failures of small devices that disable the entire system.

6. Better reliability. The reliability, including stability, of the current system is a testimony to a "tour de force" in 1950's and 1960's technology. The present equipment drifts and causes down time; replacement and repairs are becoming more difficult. As new features are added, the reliability becomes more critical, the next generation requirements would be excessive as some failures are subtle and difficult to find but significantly degrade performance. The present excitor regulator causes a large overshoot at the end of rectify and flattop. This overshoot increases the stress on the rotor and adds significantly to its heating.

7. Safety interlocks for the system are provided by a large (~500) relay logic system fifteen years of age. The relays are beginning to fail and Seimens does not manufacture replacements. Maintaining and testing of the system is time consuming and imperfect, and modifications are risky and difficult. The various interlocking

voltages, temperatures, and pressures are not monitored excepting the interlock trips, thus there are no "early warnings" of potential interlock shutdown. Interlock annunciation does not include sequence information, thus it is often impossible to determine which trip caused a shutdown and which were caused by the shutdown. It is not possible to remotely operate the supply with this system, thus there are two full time technicians on duty at all times to monitor and operate the supply (eight in total or ~30% of the on shift operating force). In a similar situation, removing the Pump Room technicians from shift coverage has improved the reliability of their equipment as more manpower is available for maintenance and improvements.

I.3 Piecemeal Solutions

The above deficiencies could be eliminated by piecemeal solutions. For example: 1) Replication, with some reengineering to improve stability, of the present peaker system, including its 200 knobs, would allow various cycles to be "stored" and "retrieved" quickly for rapid programmatic changes. 2) With the addition of more switching circuits in the Master Timer and modifications to the motor speed control that would trim the speed reference on a pulse-to-pulse basis, "Super Cycles" of mixed cycles would be possible.

The various other deficiencies could also be remedied one at a time, but the engineering effort would be excessive. The add on systems would increase operational complexities, maintenance, and the incidence of down time.

II. PROPOSED CONTROL SYSTEM

A more direct and simpler solution would be the replacement of the present system with a highly reliable industrial control computer that would provide the various basic inputs to the supply while appearing to be a standard "device controller" to our local computer network (RELWAY). This would provide central control of the power supply and archiving of the settings. Much of the old BNL built low level electronics would be replaced and commercial modules would be used where possible. This system would be much simpler, as the computer would handle inputs (replacing the hundreds of knobs), and monitor performance. The present open loop and slow controls would be replaced with real time closed loops. The references for these loops would be generated by the control computer which would also monitor performance and simplify control of the supply (see Figure 4).

The power supply voltage control (master timer and delay units) would be replaced either by voltage controlled rectifier firing units referenced by time varying voltage programs that are generated by the control computer, or computer controlled digital delay units. The programs would be separate for the high and low voltage bridges and thus control which set of bridges are operating at a particular time as well as roughly ($\pm 1\%$) controlling the output voltage of that bridge. The individual phases would be balanced by trim delays for each phase. The power supply output (probably $\dot{B}$ in the magnets) would be compared to a computer generated reference and the error applied to the delay units, thus closing a servo loop around the supply to achieve the required accuracy. These programs repeat every magnet cycle, or if a "super cycle" of various sequential magnet cycles is programmed, every "super cycle". The cycles would consist of a series of function segments reminiscent of standard AGS function generator segments which could be "Simple Logical Devices". Magnet field or time could be used to end each segment.

The motor speed would be controlled by a continuous, real time servo loop. The time varying reference program for this loop would be generated by the control computer and match the necessary speed changes both for normal repetitive cycles and for the varying cycle loads of a "super cycle". The large effects in the excitor caused by generator current swings would be corrected by computer generated "adaptive servo" corrections.

The relay logic startup and interlock system would be replaced by a "Ladder Logic" digital control system that would monitor temperature, pressure and voltage directly and provide both surveillance of these quantities as well as the present interlock functions. Trending software to predict future problems and a fast scan to indicate the primary cause of a trip would be included. This system would be engineered with the goal of no longer needing two experienced technicians, on duty at all times, to operate this power supply and stand by problems.

II.1 Implementation

For manpower and budget planning, this project can be divided into two major phases. The first and prime effort will be a new "ramp control". This job will include some ground work for the other phase of three jobs which will be ordered as priority dictates.

Phase I

The "ramp control" effort includes: new firing controls for the rectifiers, modifying the present "$\dot{B}$ loop" to operate during the entire cycle, the procurement of a highly reliable control computer, and applications software to simply control the magnet cycle waveform. This computer would be capable of doing the computations and control necessary for all jobs in Phase II excepting "Remote Control".

Phase II

A) Further improvement of stability, and thus intensity and Rep Rate, by elimination of magnet "ring off" at the end of a cycle; monitoring those temperatures that affect the magnet ramp and compensating for changes; and upgrade of the generator excitor system to eliminate drifts and transients.

B) "Super cycle" operation which requires: a real time motor speed servo referenced by a computer generated function, that anticipates changes in load; and a signal system, driven by the control computer, to synchronize other device controllers to the sequence of cycles within the "super cycle".

C) "Remote Control" of the power supply which requires: a highly reliable replacement of the relay system that starts and interlocks the supply with a major software effort to image the relay systems function; and fault anticipation through monitoring and trending of component vibration, temperature and voltages.

The following sections outline these efforts.

III. RAMP CONTROL (Phase I)

The following jobs are necessary for a new Ramp Control (Phase I). Completion of this work would alleviate some of the problems mentioned in Section I.2, i.e., Flexibility and Reproducibility, and also help with Stability and Reliability.

III.1 Low Level Grid Controls

After discussion with the CERN experts it was concluded that a completely real time system using analog delays would provide the versatility needed. The major concern here is the time and effort to extend their technology to our needs of $< 10^{-4}$ noise levels (< 0.2 volts in 2000 volts) within a power room environment. This is a major in-house job and the longest lead item. The control voltages for these delays would be provided by adding a precise time dependent ramp control voltage to trim voltages, that also are time dependent, for each phase. These trims remove subharmonics that are caused by phase to phase imbalance in the supply. The values of these voltages would be precalculated. The alternative of digital delays to provide ramp control would require real time digital addition of the ramp control delay numbers with phase dependent trim delay numbers. This time and phase dependent delay number would then be fed to digital delay units which would control the firing of each phase. This approach would be less of a burden on BNL's engineering staff as the amount of equipment with high noise susceptibility would be reduced. The resultant control computer may be more costly and this approach use more of the control computers time.

There are three different ways of accomplishing our final objective using analog delays.

They are:

1) Using a sinewave derived from the rectifier anode voltages coupled into a biased comparator and gate generator as at CERN. This scheme has the limitation that the maximum range you can get in phase of the output gate is 160°. Considering that we operate from prefired rectify to maximum invert, we need a full range of 180°.

2) Using the zero crossing of the rectifier anode voltage to initiate an analog delay. The range of these delays can be made in excess of 180° allowing us to operate our rectifier over their entire output voltage capability range.

3) Use a phase locked loop with a ripple through counter locked into the generator output voltage. The counters in turn would have small (0.5 msec) analog delays on their outputs for fine trimming. This system is attractive because all the critical timing functions are automatically set. Also, because most SCR power supply manufacturers are now using this system, packages should be commercially available.

An investigation has started as to how others do this job. Papers are being reviewed and manufacturer contacted. Because of the magnitude of this system, the engineering time required to determine which scheme to use and build a single unit prototype should take about six months. After a prototype has been built and tested, a decision will then have to be made to build it here or send it out for contract.

Alternatively, digital delay units for each firing phase would be purchased with the control computer. Instead of analog adders, these delays would calculate in real time by the repetitive addition of a precision delay to trim delays for each phase. As with voltage control, these two sets of delay information would be precalculated and stored in the computer.

The mode of grid control is a major decision point in this project and resolution of this issue is needed before work can continue. A small study group should be setup to resolve this issue and provide guidance to a design engineer.

III.2 Magnet Voltage Regulator

The CERN power supply has a voltage feedback loop around their main magnet power supply (MMPS), this is attractive in that it helps reproductivity from pulse to pulse.

We have a feedback loop around our power supply flattop bank, the "$\dot{B}$ servo". This proposal however calls for including the magnet in the loop, which means that the ripple filter is inside this loop (as at CERN) and would have to be taken into account for stability calculations. The feedback loop may have to be gated to eliminate transients as the power supply output steps from one voltage to another and goes to zero currents. It would feed analog delay units and use about 1 millisecond of range.

The design for this system should take about four engineering months. Equipment could probably be built by one technician in about a month. Installation should take about five days including two days for commissioning tests.

III.3 Computer Procurement Plan

It is planned to acquire the computer system to control the main magnet cycle by contracting for a six month project to provide:

1) A system design engineering effort to confirm, refine, or ammend, as appropriate, the specifications for the entire system to meet the objectives outlined. A BNL engineer would spend one to two months on this. This effort will include a critical design review of the system requirements and all equipment and software proposed to meet the system requirements.

2) Purchase of a system consisting of:

a) Computer equipment as described, subject to refinement as a result of the system engineering effort.

b) System software.

c) (Optional) application software.

The system, with custom equipment and all software, will be integrated and tested before shipping.

3) Installation, test and commissioning of the system at Brookhaven.

III.4 Computer Functionality

The functionality (excerpted from a preposed specification) include the aspects of the control computer for both phases of the project, excepting the replacement of the relay safety and startup system. The control computer system would accommodate these efforts as they are incorporated into the system. The relay logic replacement effort would require another unit dedicated to this job of interlock surveillance and response as well as controlling startup and shutdown of the motor generator. The two units would be coupled.

The computer system would generate a table of time varying rectifier control voltages or delays that are necessary to create a magnet cycle. These control values would be loaded into output devices which control their respective rectifier firing triggers by the required amount. Voltage waveforms simulating motor speed as a function of time and generator voltage as a function of time would be generated and used as time varying reference inputs for the motor speed regulator and the generator output voltage regulator. These voltage waveforms will be predetermined by calculations based on system equations and operating parameters of the power supply. Updating of these waveforms must be done in a real time synchronized fashion between machine pulses.

The system would have enough information about the performance of the power supply and load to set parameters to produce a current waveform of 0.1% accuracy. Updating this information by measuring the performance and recalculating settings would produce a waveform with less than 0.03% error. Interrupt response at critical times would produce currents with errors of less than 0.01% at these times. Controls would be compatible for future control to 0.001%.

The system would generate a marker pulse two to five microseconds wide at each magnet voltage transition and 0.1 sec before the start of a cycle. Each marker pulse will be on its own dedicated line. There would be ten such dedicated lines with provision for future expansion to a total of thirty.

Digital output information would be provided indicating the code number identifying the types of cycles for the next two cycles in the "super cycle".

During periods of shutdown and "save-a-watt" low power pulsing, a simulated $\dot{B}$ signal would be made available to the Gauss clock. With this signal, the Gauss clock can continue to provide timing signals to those devices requiring them (e.g., discharge power supplies). This signal would simulate the full cycle expected in normal operation including the different cycles of a "super cycle".

III.4.1 Setup

III.4.1.1 Initial Step

These calculations would be done before pulsing is started and may be updated while pushing is on with a required response of a few tens of seconds.

The desired cycle (or cycles for "super cycle" operation) is defined by the operators and/or recorded setups. The operator will work with a complete set of building blocks based on required magnet field and pulse duration to construct a cycle. This will include flat-top, rectify and invert voltage functions with transitions to provide smooth acceleration and gentle transfer of energy. These "blocks" may be operator modified as necessary.

The proposed magnet waveform would be displayed before commitment and illegal requests flagged. Each block could consist of three "simple logical devices" or possibly a "complex logical device" if deemed appropriate by the Controls Group or it is determined that a complex time function is needed requiring multiple entries. Storage for about fifty "blocks" would be needed.

The resultant desired time varying power supply output voltage function with the appropriate "milestones" would be permanently stored in a non-violable memory for future use. This data would be transferable to and from the AGS local network "Station" through an IEEE-488 link. The format is defined in Controls Section Reports.

III.4.1.2 Running

The required voltage waveforms (and possibly delay tables) are calculated, as a function of time into the cycle, for the magnet voltage reference, power supply controls, generator voltage, and motor speed. Also, a scenario of startup is defined that will minimize abrupt transients on the power supply.

The engineering model that produces these tables of voltages (and delays) shall include such factors as main magnet, generator and tank temperatures, line voltage and other parameters. The result shall be a current waveform accurate to 0.1%.

The required motor power and motor speed as a function of time will be tabulated and produce a time varying voltage function to provide a reference for the motor speed control loop. The result should be a speed stability of 0.1% pulse to pulse.

III.4.2 Slow Loops

Rectifier tank, load and other temperature sensitive devices in the system will be scanned a few times a minute. The rectifier control tables will be updated accordingly to compensate for these temperature variations. Auxiliary power supplies and equipment will be monitored. Drifts outside of predetermined limits will be annunciated, indicating that although an element is operational and within tolerance, it is outside design setting. This will allow scheduling of maintenance of borderline equipment before a catastrophic failure occurs.

III.4.3 Intermediate Speed Loops

These loops will work on a one second pulse-by-pulse basis and update the tables generated by the slow loop for the next pulse. This should improve reproducibility to 0.03% current versus time. It may not be possible to operate all these loops at once.

The magnet voltage and current, motor speed and current, generator voltage and excitor current are compared with the predicted values. Voltage ripple would be analyzed and corrections added to the commands. Voltage ripple must be held to less than 0.2 volts during flattop to insure smooth spill Delivery. During injection and early acceleration of heavy ions, voltage ripple must be held to less than one volt. If it is decided to use analog low level grid controls, the system would be susceptible to LILCO synched 60 Hz noise. The system should have provision to measure ripple synched to this frequency and compensate firing times synched to LILCO. Tables of commands versus time are updated for the next pulse.

MG set vibration would be recorded and the "soft" transitions updated to keep the vibration below an acceptable level.

The firing times and commutation angles of the rectifiers are checked to provide warning of time delay, firing circuit or rectifier problems as well as monitoring for the optimization of invert firings. A serious problem shall interlock the next pulse and generate an alarm message. (This feature is optional.)

Noncritical "annunciate only" faults (PL1) will be scanned each cycle, and active alarms will be displayed each cycle.

During pulsing turn on, the intermediate speed loops will monitor motor speed and increase pulse length and motor current in order to come to the final cycle quickly while keeping the motor power swing to less than 0.5 MW/sec.

III.4.4 Fast Loop

The start of the magnet current pulse must be synchronized with the power line phase to less than ±500 μsec. There will be a provision for moving this phase back and forth with respect to the power line.

Variation in flattop voltage caused by changes in beam extraction creates pulse-to-pulse jitter in the motor speed and magnet current at the end of the flattop. This makes the dwell time vary, causing changes in field at injection of the next pulse and motor power excursions. The fast loop will tailor motor current and magnet voltage at the end of the flattop and during the transition to, and start of invert. Perturbative solutions to the model will slightly increment or decrement the magnet voltage and motor speed tables appropriately. Required corrections must be made within 100 milliseconds.

Other "milestones" in the cycle may also require similar actions. These include end of the injection porch, end of ramp to full field and the end of intermediate front porches.

III.4.5 Ordered Interrupt Response

Spill abort in flattop is accomplished by increasing the power supply voltage to force the beam to sprial inward. Within three milliseconds of the interrupt, the flattop voltage must be increased to maximum. This condition will be maintained until all of the beam has been dumped into the "catcher". Then, within one hundred milliseconds of the interrupt, the power supply voltage is set to a valve so that the magnet current will match standard conditions at end of flattop.

The presence of a PL-2 interlock will cause within 3 milliseconds a change to invert to bring the pulse to a graceful end and then turn pulsing off. If the accelerator contains beams, it shall be dumped to the catcher first. A PL-4 will stop all firing of the flattop rectifiers and move the pulse rectifiers to invert voltage. Also, a PL-4 will start a fast scan of the alarms. A record of all alarms and sequence in which they occurred will be displayed.

A BNL pulse from the Gauss clock or current transformer shall cause an interrupt which will start the flattop or change the voltage in flattop. These changes must occur within 3 ms of the Gauss clock interrupt. This 3 ms delay must be reproducible to 0.5 ms.

The "ring off" of the current waveform at the end of the cycle is critical for producing identical field for the next pulse. It may be necessary to provide an interrupt driven change, as above, to produce identical turn offs pulse to pulse.

III.5 Commissioning

The various functions of this system would be brought on line in a "shadow" mode, where the present system would actually control the supply and the new system's timing and references compared to actual operation. When this is successful, the system would operate the supply at low power into the test resistor load. Then, finally, the main magnet would be pulsed using the new system. The existing system would not be removed until the new system is fully "on line". As the number of connections to this system are not large, switchover between new and old systems should take less than an hour.

IV. PHASE II

Phase II of this project assumes an adequate controller was installed in the first phase of this project to handle all but the remote control aspects of Phase II. This phase consists of four independent jobs that can be ordered by programmatic priorities as they develop next year.

IV.1 Improved Stabilization

These tasks should improve the pulse-to-pulse stability of the AGS magnet current waveform. This should allow a more precise optimization of the accelerator's operation and thus higher intensities at a faster repetition rate.

IV.1.1 Elimination of "Ring Off"

Obtaining a reprodicible current waveform at the end of the cycle is a continuing problem as the ripple filter and the Main Magnet rings when current stop flowing in the rectifier. When the Siemens Set was first commissioned it was not possible to accelerate beam as the large ringing changed field history, pulse to pulse. This problem was alleviated by programming a reduced voltage for the last $\sim$ 50 ms of the cycle, but keeping this program correct is a maintenance problem. At CERN the ripple filter is shorted at the end of every cycle, eliminating any ringing with the magnet.

Also, as part of an aborted effort to increase the rep-rate of injection into the SPS, the Power Supply Group at the CERN PS ran with ~ 200 A in the magnet between pulses. This effort has been abandoned there due to stability concerns and lack of the need for high rep-rate during $\bar{p}p$ collider running. This approach is very attractive for BNL for two reasons. It should be possible to increase our rep-rate, and the ripple filter on the Main Magnet Power Supply would not ring at the end of a cycle as it would be continuously connected to the low impedance of the power supply. Electrical tests have been made at BNL and do not indicate problems. A test of intensity vs. dwell did not show major changes even at essentially zero dwell after readjustment of the Injection "Peaker". An R&D absolute field marker to start the Injection "Peaker" gauss clocks has been built for further investigation. Adaptation of this method will require the building of an operational field marker. Tests on beam acceleration with nonzero dwell current and with various turnoff conditions must be made to determine if this approach is viable or if a "shorting switch" need be purchased and what its specs would be.

IV.1.2 Monitoring Perturbation

Various phenomena have small but significant effects on the magnet cycle (e.g., magnet and rectifier temperature). Others need to be searched out and continuously monitored. These effects will be compensated for in the main magnet ramp program.

IV.1.3 Excitor Modifications

During the transition when the power supply goes from full positive output to full negative output there is an extreme transient of excitor output voltage.

A study of the excitor regulator has disclosed that during the transition from rectify to invert, the rectifier commutation notches occur at the peak of the generator output voltage waveform. The excitor regulator which compares the peak value of the generator voltage against the reference input thus gets an erroneous signal and goes through gyrations trying to correct for it.

It should be straightforward to correct this signal by inserting an appropriate filter network in the excitor regulator feedback loop. The engineering time required would be primarily to make a stability study of the modified feedback loop. This should take about one man week. One man week of technician time, and eight hours of machine time in two hour periods two days apart would be needed for building and then commissioning. A computer generated "adaptive correction" would eliminate the remaining error.

IV.2 "Super Cycle" Operation

A "Super Cycle" consists of a repeated series of different AGS cycles. Fast Beam operation does not require a flattop while Slow Beam operation does. When starting up a Slow Beam run the experiments typically only require an occasional beam bust to check their equipment. Then a Fast Beam user could continue using most of the AGS cycles with only an occasional cycle diverted to Slow Beam for testing. Here a "Super Cycle" may consist of five Fast Beam cycles and one Slow Beam one. When RHIC comes on line switching between injection to RHIC and other Heavy Ion (or polarized protons) users would allow utilization of the time the AGS is "on line" between injection periods.

IV.2.1 Motor Speed Control

The original motor speed control was required to maintain average motor speed stable to 0.01% and keep motor input power transient variations to less than 500 Kw/sec. The tight speed spec was necessary as all power supply timing functions were taken from the generator shaft. This is no longer done, all critical timing functions are derived from a separate clock. Thus, there is no longer any need to maintain a precisely stable motor speed. The only limitation being due to the generator/motor which can vary ±2% with respect to synchronous speed.

With mixed cycles, the average power into the motor would not be constant. For example, one would expect average power variations to 5 megawatts when removing the 1.5 second flattop from a pulse. This variation on the BNL power grid would not be be acceptable.

The magnitude of the power swing could be alleviated by running the motor up near its upper speed limit during the normal 7 mw or operation. Then several cycles before a lower power cycle run the speed down to the lower limit by gradually reducing the motor power input. The timing of this operation should be that the lower speed limit is reached just as the low power cycle starts. Motor speed would then increase due to this cycle's low power usage. Then after this cycle, the power can gradually be brought back up to the steady state value (see Figure 5 for waveform of a typical "super cycle").

The motor speed control loop will be changed from a sample data system to a continuous real time loop. A computer generated reference would be supplied that is calculated from an energy flow model of the motor speed and provide the correct speed (and rate of change of speed) versus time to achieve the desired "super cycle" scenario. BNL power grid limits, presently 0.5 mw/sec, limit the variety of cycles in a "super cycle".

The motor speed control should be built in-house. There should be about four engineering months devoted to system analysis and equipment design. Once the design is solidified, it should take one technician about four weeks to construct and install the equipment. Machine down time will be required to swing over from the old system to the new system.

IV.2.2 "Super Cycle" Synchronization

When operating with different cycles in a "super cycle" many device controllers will need real time information as to what types of cycle is in process and what types will follow. This information will be made available from the control computer and transmitted via an as yet identified transmission system to those device controllers needing this information.

IV.3 Remote Operation

Remote operation of the main magnet supply is planned at CERN. (The one operator presently on shift there divides his time between the supply and other duties.) Remote operation here will require higher confidence in the well being of the various subsystems and complete assurance that the safety system will act properly.

IV.3.1 Fault Anticipation

There is a large multiplicity of systems that have to work to keep this power supply on line (e.g., ~100 low level supplies). Also there are over a hundred possible trips (80 under/over voltages, ~40 flow or pressure switches and ~30 temperature) and vibration monitoring should be added. Monitoring these levels and trending them would provide early warning of potential failure that could be handled during normal maintenance periods, avoiding downtime. At present a "two bit" low level power supply monitoring card is in production to monitor the logic supplies. Other inputs will be added and monitored as available.

IV.3.2 Relay Replacement

Modern high reliability computer systems have lower failure rates, more exact documentation of logic, and more continuous self checking than relay logic safety systems. This coupled with the age and failure rate of the relay control system require its replacement.

The relay logic startup-safety system is in the process of being documented with lists of inputs, outputs and functions. Currently the input (~400 elements), output (~100 elements) documentation is compliant for the safety system. The safety logic and startup system still needs to be documented. This documentation will allow a more intelligent computer "Ladder Logic" system to be developed. A possible redundant logic check can be made if the actual relay drawings are blindly inserted into a "ladder logic" array and its operation is compared to the analyzed input. (Also of support to this effort will be the computer documentation, monitoring, and control of the Security System.) Savings may result from adding this job to the computer purchase then and implementing it as manpower permits.

V. BUDGET AND SCHEDULE ESTIMATE

The following budget (Table I) is the sum of estimates for the various jobs. Only Phase I was done in detail. Our purchase estimates, excluding the computer, are probably high. For the computer, procurement, and labor estimates are from discussions with August Systems. They depend on a vendor that knows what we need and can provide it without trauma to his company. Programming estimates are very crude. A more precise estimate depend greatly on the operating system of the computer purchased.

The schedule outlined (Figure 6) is based on our labor estimates and August Systems' estimate. Availability of BNL engineering support will greatly affect the schedule.

VI. STATUS

An agreement of the senior electrical engineers as to whether to proceed with digital or analog delays is the next step in this project. This decision affects the amount of local engineering needed as well as the kinds of computer interface hardware purchased. A review by the Controls Section, at this time, is also appropriate to provide estimates of the computer size needed and also to provide their expertise as necessary. Specifications for the computer system were written for both analog as well as digital grid control approaches, but release requires the above reviews.

Table I

Budget Phase I

Using Analog Grid Controllers

	Purchases (x $1000)	BNL Labor (x 1 man week) E.E.	Cont. E.	Pgmr.	Tech.
Grid Control	10	> 35	--	--	35
Voltage Regulator	3	15	--	--	15
Computer	400	15	20	30	25
	413	> 65	20	30	75

(about 4 man years)

Using Digital Grid Controllers

	Purchases (x $1000)	BNL Labor (x 1 man week) E.E.	Cont. E.	Pgmr.	Tech.
Trim Grid C.	3	10	--	--	15
Voltage Regulator	3	15	--	--	15
Computer	420	15	20	30	20
	426	40	20	30	50

(about 3 man years)

Budget Phase II

	Purchases (x $1000)	BNL Labor (x 1 man week) E.E.	Cont. E.	Pgmr.	Tech.
Stabilization	8	15	--	15	15
Super Cycle	7	25	--	5	25
Remote Control	75	20	10	20	25
	90	60	10	40	65
			(about 3 man years)		

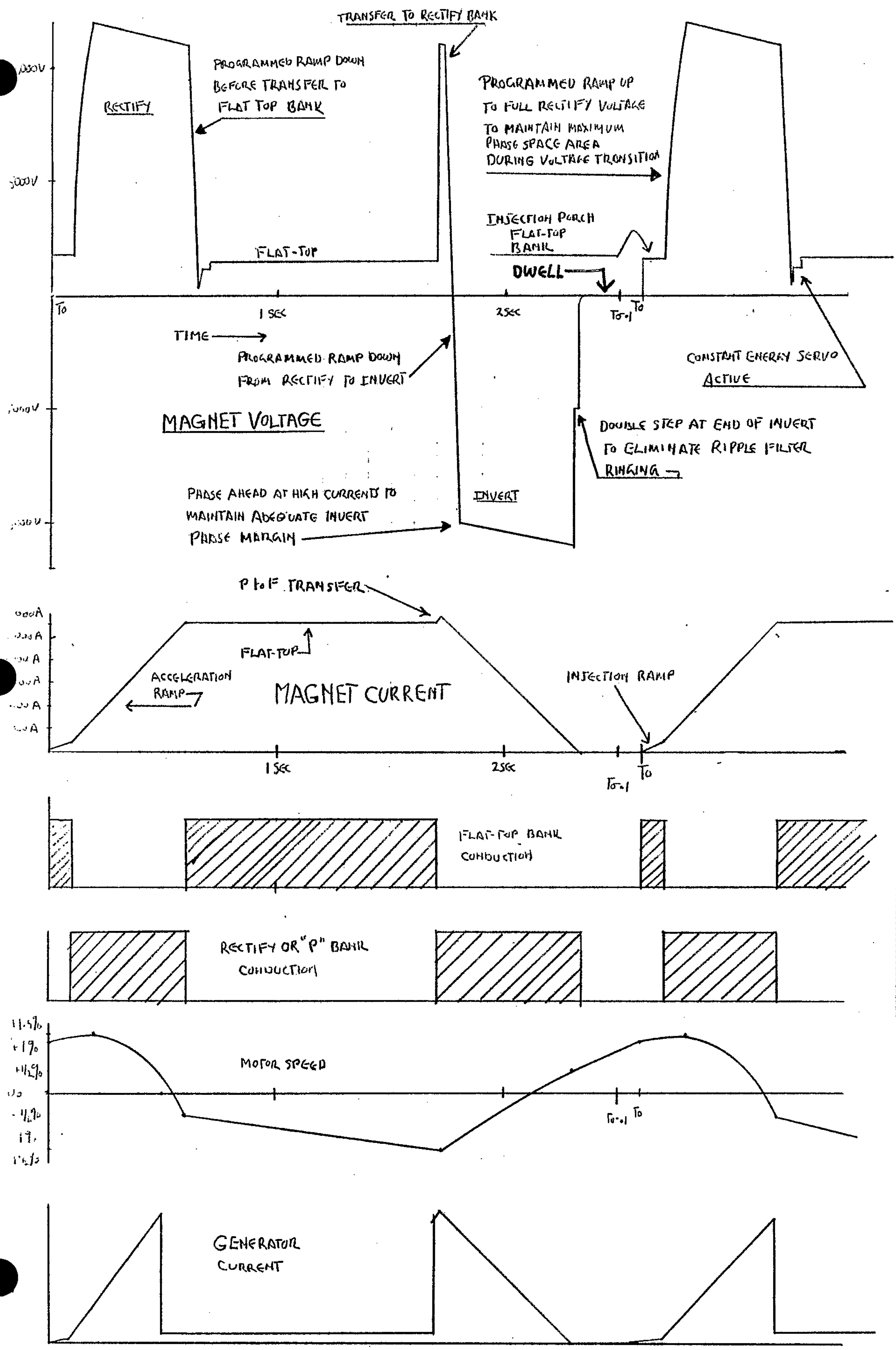


FIGURE 1
TYPICAL WAVEFORMS

AF 10/31/84

BROOKHAVEN NATIONAL LABORATORY
BY........ DATE........ SUBJECT........ SHEET NO.....OF.....
CHKD. BY........ DATE........ DEPT. OR PROJECT........ JOB NO........

BROOKHAVEN NATIONAL LABORATORY

BY______ DATE______ SUBJECT______ SHEET No.______ OF______
CHKD. BY______ DATE______ JOB No.______
DEPT. OR PROJECT______

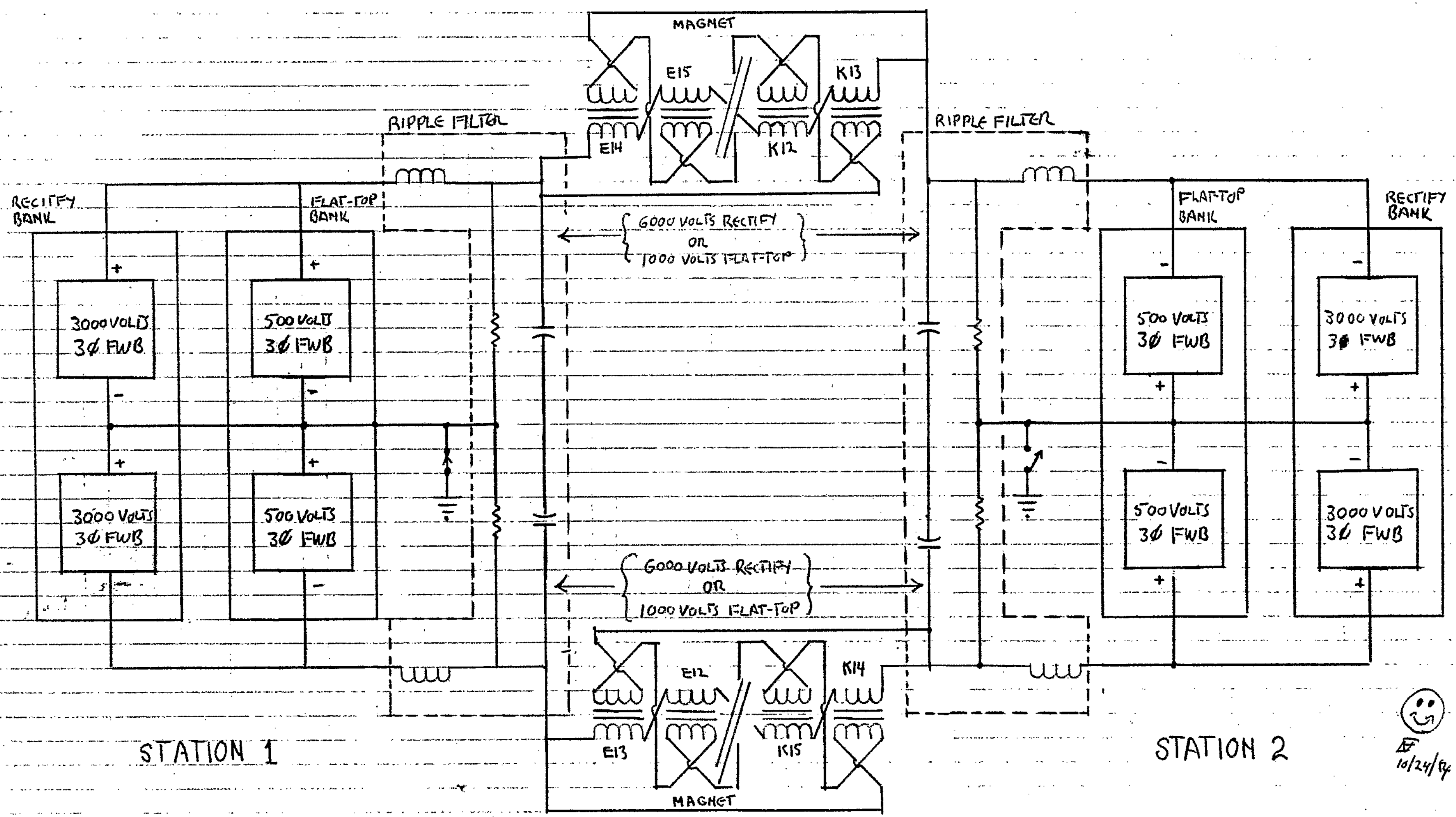


FIGURE 2
A.G.S. MAIN MAGNET POWER SUPPLY CONNECTIONS TO MAGNET

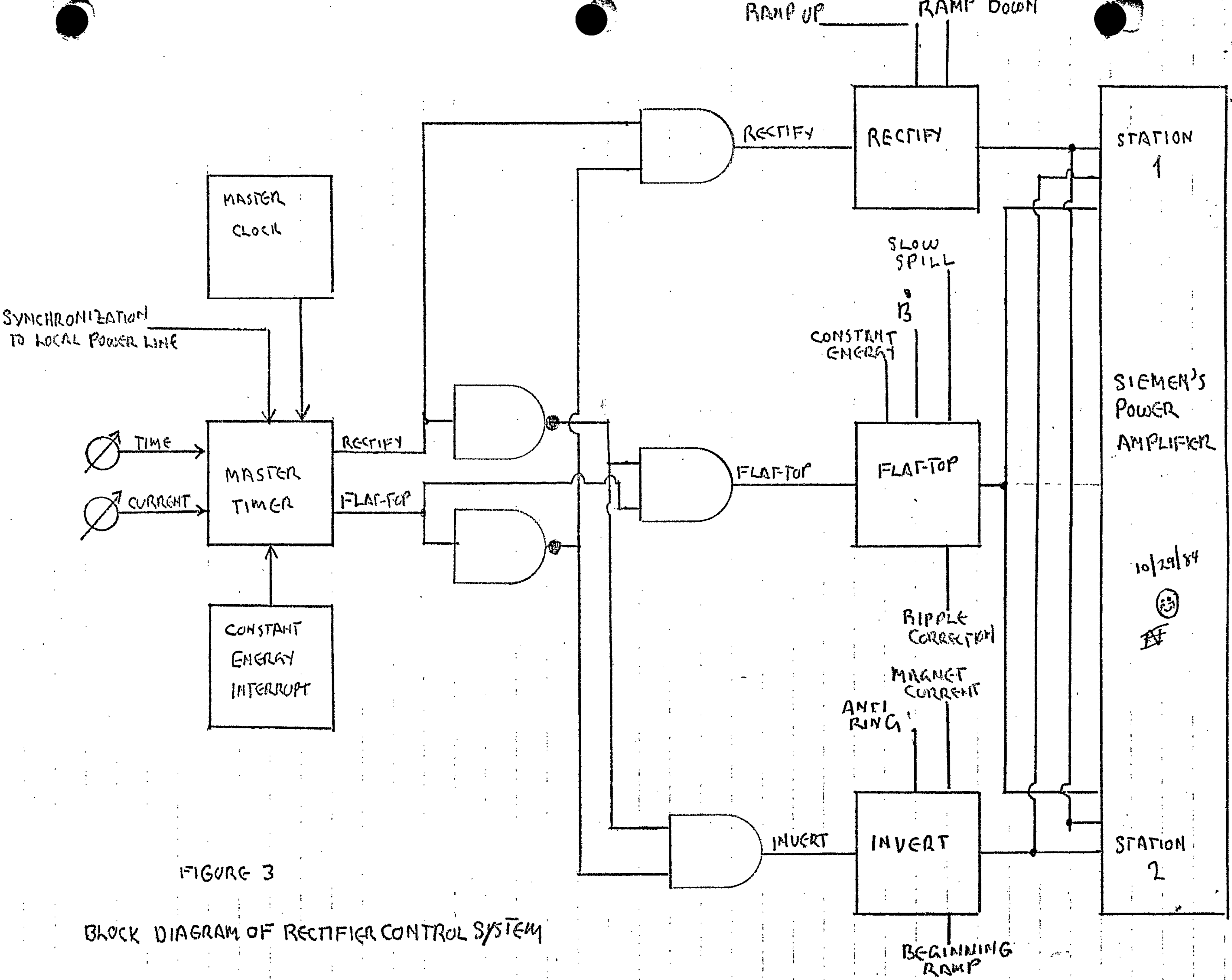
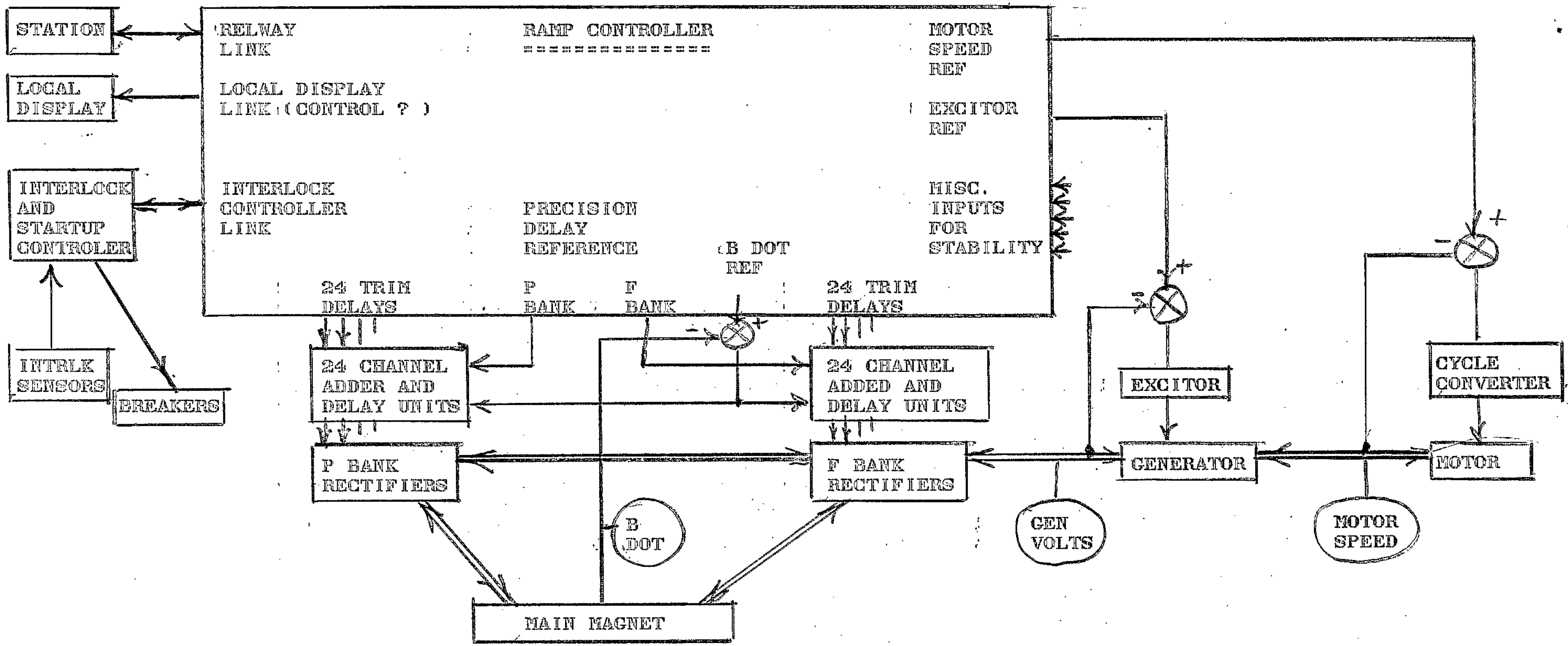
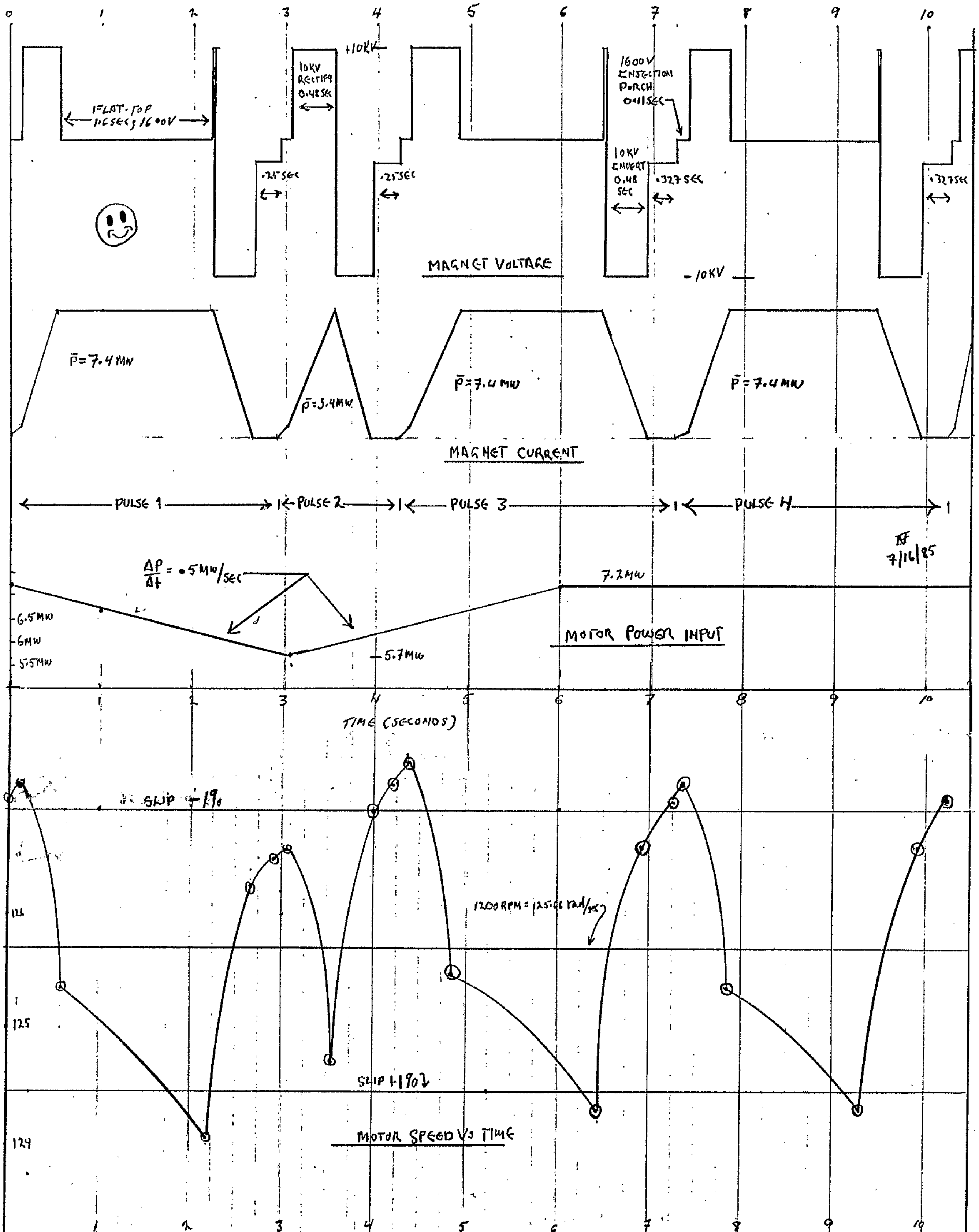


FIGURE 3

BLOCK DIAGRAM OF RECTIFIER CONTROL SYSTEM

FIG. 4 CONTROL COMPUTER (PHASE I & II)





PULSE TO PULSE MODULATION AT 28.25 GEV/C TYPICAL WAVEFORMS

FIGURE 5

FIG. 6 PHASE I - RAMP CONTROL WITH ANALOG GRID CONTROL

```
              START                                          6 MO                                          1 YEAR
                +       +       +       +       +       +       +       +       +       +       +
GRID            :      PROTOTYPE                            :       BUILD          :  INSTL8TST  :
CONTROL   EE1   X-------------------------------------------X -- -- -- -- -- -- --X-----------X
(CRITI-   TECH                  X-- -- -- -- -- -- -- -- ---------------------------X--   -- -- -X
 CAL      TECH                                              X---------------------------X
 PATH)

VOLTAGE                                 : DESIGN 8 TEST : BUILD :                  : INSTL8TST :
REGULA-   EE2                           X---------------X-- -- --X                  X-- -X -- -- -X
TOR       TECH                                  X-----------------X                  X---X -- -- -X

                : SPEC  : PRPSL : DESGN : VENDOR ASSEMBLY        : FCTRY :  : INSTL      :
COMPUTER        : REVW  : REVW  : REVW  : (15 WEEKS)             : TESTS :  : 8 TEST     :
          EE2   X-------X       --X-----X                        X-- -- --X  X-- -- -- -- -X
          CE    X-------X       --X-----X                        X-- -- --X  X-------- -- -X
                                          APPLICATIONS SFTWR
          PGMR  X-- -- --X        X-----X------------------------X-- -- -X----------- -- -X
                                                                  PREPAR
                                                                  LOCATN
         TECH                                                    X----------X------------X
         TECH                                                    X-----------------X
                +       +       +       +       +       +       +       +       +       +       +
```

PHASE II - RAMP CONTROL WITH DIGITAL GRID CONTROL

```
              START                                          6 MO                                          1 YEAR
                +       +       +       +       +       +       +       +       +       +       +
TRIM                                    + DSGN  +   + BUILD      + INSTL8TST +
GRID      EE                            X-------X   X-- -- -- -- -X -- -- -- X
CONTRL    TECH                                      X-------------X--- -- -- X

VOLTAGE                 + DESGN +               + TEST + BULD +   + INSTL8TST +
REGULA-   EE            X-------X               X------X-- -- X   X-- -- -- -X
TOR       TECH                                  X-------------X   X--  -- -- X

                + SPEC  + PRPSL + DESGN + VENDOR ASMBLY    + FCTRY + INSTL      +
COMPUTER        + REVW  + REVW  + REVW  + (12 WEEKS)       + TESTS +   8 TEST   +
( CRITI-  EE    X-------X       --X-----X                  X-- -- --X-- -- -- -X
CAL       CE    X-------X       --X-----X                  X-- -- --X------ -- -X
PATH )                                   APLICTIONS SFTWR
          PCMR  X-- -- --X        X-----X------------------X--------X----------X
                                                            PREPAR
                                                            LOCATN
         TECH                                              X--------X----------X
         TECH                                              X---------------X
                +       +       +       +       +       +       +       +       +       +       +

                +       +  ( 5 WEEKS )

                X-------X  FULL TIME
                X-- -- --X PART TIME
```