The AGS Main Magnet Power Supply Upgrade*

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I. INTRODUCTION

The AGS is a strong focusing, combined function magnet, particle accelerator. The main parameters of the accelerator are a peak operating energy of 29.4 Gev, a peak magnetic field of 11.5 kG, a typical injection field of 0.9 kg, an injection energy of 1.5 Gev, and a maximum pulse repetition rate of 0.6 Hz. The injection is from a rapid cycling Booster synchrotron, which receives either a proton beam from a 200 Mev Linac, or a Heavy Ion beam from a 15MV Tandem Van de Graaf Accelerator. Flattops of up to 2 seconds can be added to the AGS cycle for slow extracted beam applications. Particles accelerated include protons (mass=1), both polarized and non-polarized, and fully striped ions up to gold (mass=197). The maximum proton intensity attained thus far is 60x10^13 particles per pulse. Modes of operation for the AGS are full-turn extraction (2.5 usec), slow extraction (1-2 sec), and bunch-by-bunch extraction. These modes are applicable for both protons and heavy ions.

The peak apparent power required during acceleration is approximately 70 MVA while the maximum average power needed is less than 7 MW. In order to isolate this large power swing from the local power grid, a motor-generator (MG) set is used as a buffering source. The MG set stores approximately 315 Kilojoules of energy in its rotating mass. As energy is drawn to charge or discharge the ring magnets, the speed of the rotating mass changes in such a manner as to supply the required load power demand. The input to the motor is controlled by a power regulator that forces the input power to be equal to the average losses during each cycle. The line sees nearly a constant load equal to the system losses. The peak power requirements are met by changes in the stored energy of the rotating mass that translates directly into speed variations. Thus, for a fixed operating cycle, the losses during each cycle are reproducible, and the speed oscillates around an average value and is returned to the same value at the beginning of each supercycle.

II. POWER RECTIFIERS

The AGS Main Magnet Power Supply consists of a group of thyristor controlled power converters that operate from full rectify to full invert. In order to minimize ripple during the critical periods of injection and extraction twenty-four pulse converters are used for these portions of the cycle. The maximum voltage available in this mode is nominally 2000 volts. The converters that are functional during this portion of the cycle are called the flat-top bank or "F" bank modules. During acceleration and invert where voltages of up to 12,000 volts are needed and where the ripple requirements are less stringent, groups of twelve pulse converters are operational. These converters are called the Pulsed bank or "P" bank modules.

The original controlled rectifier system consisted of 96 large mercury filled excitron tubes divided equally between the P bank and F bank converters. These devices were extremely durable and ran successfully for over twenty years. In the 1980's excitrons of this class became obsolete and it became impossible to buy replacement tubes or to repair the existing tubes. In addition to the difficulties in replacing bad tubes the old system had significant operational draw backs. The characteristics of these tubes required that they be operated at an elevated temperature so that an elaborate water temperature regulation system was required. If the tubes were operated outside the correct temperature window they were subject to either random misfires or increased time delay and jitter. The tubes also required many hours of warm up time if they were allowed to cool and needed to be conditioned for several days after a prolonged shutdown. The energy lost in both the heating system and the arc drop of the tubes was quite significant compared to present day devices.

It was, therefore, decided to replace the excitron "farm" with multiple arrangements of three-phase, full-wave, bridge modules that utilize silicon controlled rectifiers (SCR's or thyristors) as the switching element. This technology provides the capabilities for controlling large amounts of power efficiently with the minimum number of series parallel devices. In order to match the existing transformer connections and buswork, eight identical modules were required; four for the P bank system and four for the F bank system. The D.C. output of the F bank modules is in series with the load and one P bank module is connected in parallel with each F bank module. Each of the eight modules consists of two full wave three phase bridges in parallel. Each leg of the bridge consists of two SCR's in series. The modules were designed and manufactured by Siemens, AG, of Erlangen Germany.

In order to reduce noise pickup and provide electrical isolation the high level SCR gate triggers are provided via fiberoptic cable. The low level triggering circuits were designed and built at BNL and have operated successfully in the Booster Main Magnet Power Supply. Isolated monitoring, in the form of DCCTs (current) and DCPTs (voltage), is necessary to minimize noise pickup in critical feedback loops. In addition, isolation of both analog and digital signals is extremely important due to the high voltages and power levels present.

The status of various parameters such as water flow,

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auxiliary power supply performance, trigger circuitry failure, over voltage , overcurrent, and loss of phase reference are monitored via a programmable logic controller (PLCs). The PLCs use isolated input and output modules for various voltage levels from TTL to 150 Vdc to 125 Vac. These devices are extremely flexible and have allowed modifications and improvements that have enhanced the performance over any equivalent hard wired system. In addition, the PLC's have allowed us to tie the converter controls to the existing MG set controls.

At the high power levels used for the AGS, protection of the SCRs during fault conditions is a very important consideration. The SCR's are not as "forgiving" as the old excitron tanks. The excitrons had tremendous capacity for current overloads and would generally switch to a conducting state during a severe overvoltage condition. These conditions, especially an overvoltage, could be disastrous to SCR's. In addition to the normal or "slow" overload and overtemperature protection, it was necessary to include very fast protection that acts in the 100 usec to low msec time range. When an overvoltage or overcurrent is sensed this level of protection is accomplished by: a)immediately commanding the rectifiers into invert, b) firing a set of free-wheeling SCR's, c)closing a fast 95 bypass mechanical switch, and d) opening a fast acting 52 (<3 cycle) circuit breaker. These interlocks are hardwired to their various control devices. In addition, for redundancy and logging, they are also connected to the slower acting PLC/relay interlocks. The PLC's are used to coordinate the various sub-systems in addition to logging all systems faults in sequential order for diagnostic purposes. These features were lacking in the old relay system and have greatly reduced the time required to diagnose and repair problems.

III. ANALOG CONTROLS

The SCR firing control range, or MMPS controlled dc output, is covered by an accurate set of ramp generators driven by analog, compensated amplifiers comprising an inner voltage loop and an outer current feedback loop. The ramp generators use stable components, ac low pass filters, and are synchronized to the MMPS generator/step-down transformer voltages. The loops track both voltage and current reference functions, thus resulting in very high effective loop gain. The current tracking during steady state conditions is typically < 1/5000. The sensors for the voltages and current are DCPT's and a DCCT.

As stated earlier the P and F bank modules are connected in parallel. The cycle typically begins with the F banks active at injection levels. As acceleration begins the P banks are turned on and as their voltage becomes greater than the F bank's voltage the F bank thyristors commutate off. The current through each bank is monitored and when the P bank is commanded on and the current through the F bank goes to zero the triggers are removed from the F bank. At this point the error amplifier in the F bank regulator is grounded to prevent the regulator from saturating. When flat-top is reached, the P bank voltage is gradually reduced and the F bank voltage regulator is reactivated. When the P bank voltage is less than the F bank's voltage, it will commutates off. When the P banks current reaches zero, its triggers are removed and its error amplifier is grounded. This process is repeated throughout the cycle. The transition period required to switch between P and F bank modules is typically 10 to 20 msec.

IV. COMPUTER CONTROLS

In order to increase AGS versatility it is highly desirable that the switchover between different cycles be easily and rapidly accomplished. In addition, pre-programmed cycle storage and retrieval is necessary. This is accomplished by designing a set of vector-driven function generator hardware and software. The devices are interfaced to the AGS's hierarchical networked control system. Thus functions can be constructed and executed from any place in the system. Up to four different functions can be stored in local buffer tables and can be executed upon issuing of a main supercycle timing event. The application code for the system begins from a definition of the desired main magnetic field function (beam momentum). Using the magnetic field measurement data, the required magnet current is calculated. Utilizing the electrical parameters of the MMPS circuit the total voltage and the voltage per module are calculated. The parameters are "tuned" to optimize the final results. Using generic application software tools, they are synthesized into a series of vectors defined by a beginning time and a slope, and sent to local device controller where they are stored in memory buffers. The voltages become reference inputs to the voltage loops and the current is sent to the overall outer current loop. Upon issuing an execution command, the table is sequentially sent to the analog loops via 16-bit DAC's. In actual operation, the voltage functions alone generate a magnet current that closely approximates the desired field. The outer current loop assures the final trimming which controls the field to a much higher accuracy, stability, and reproducibility over time and temperature variations. A simplified block diagram of the voltage and current loops is shown in Figure 1. A bode plot of the open loop transfer function for the F bank regulator is given in Figure 2.

The ultimate aim in the AGS MMPS is to be able to switch functions or cycles on a pulse-by-pulse basis. Presently this is not permitted by the high power circuitry of the MMPS and by the ac power line swing that is presently limited to +/-500 kW. The MMPS speed control and excitation systems are in the process of being upgraded to encompass computer and function control capabilities.

V. ACKNOWLEDGEMENT

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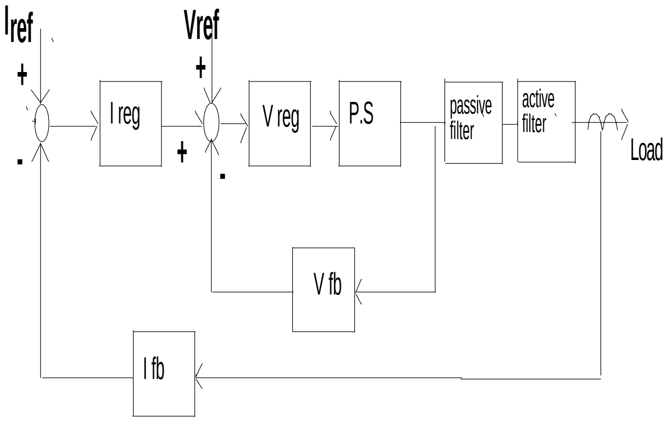

Figure 1

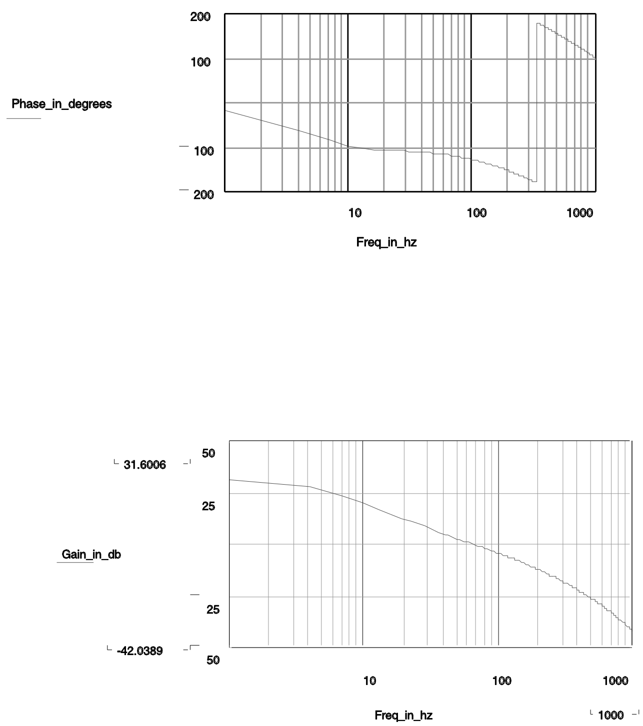

Figure 2