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THE POWER CONDITIONING SYSTEM FOR THE ADVANCED TEST ACCELERATOR

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Introduction

The Advanced Test Accelerator (ATA) is a pulsed, linear induction, electron accelerator currently under construction and nearing completion at Lawrence Livermore National Laboratory's Site 300 near Livermore, California. The ATA is a 50 MeV, 10 kA machine capable of generating electron beam pulses at a 1 kHz rate in a 10 pulse burst, 5 pps average, with a pulse width of 70 ns FWHM. Ten 18 kV power supplies are used to charge 25 capacitor banks with a total energy storage of 8 megajoules. Energy is transferred from the capacitor banks in 500 microsecond pulses through 25 Command Resonant Charge units (CRC) to 233 Thyratron Switch Chassis. Each Thyratron Switch Chassis contains a 2.5 microfarad capacitor and is charged to 25 kV (780 joules) with voltage regulation of ± .05%. These capacitors are switched into 10:1 step-up resonant transformers to charge 233 Blumleins to 250 kV in 20 microseconds. A magnetic modulator is used instead of a Blumlein to drive the grid of the injector (see Figure 1).

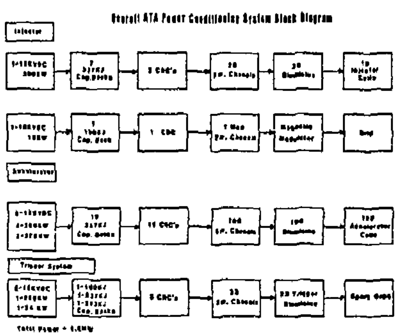

Figure 1

The Experimental Test Accelerator (ETA) has served as a technology base for all of the major components of the Power Conditioning System for the ATA, although many changes have been incorporated into the ATA system to improve reliability and performance.[1] A prototype test stand incorporating all major power conditioning components was constructed and used for development work and testing of the major components for millions of shots. Another test system was built to test all 233 Thyratron Switch Chassis for at least 100,000 shots at full voltage (25 kV) and current (10 kA). This system was also used for the development and testing of the electronic control circuits for the power conditioning system.

Overall Power Conditioning System

There are three separate power conditioning systems in ATA which are identical except for output power level (Figure 1). The largest power conditioning system is used to drive the 190 accelerator cells while the other two systems separately drive the 10 injector cells and the trigger system. The power conditioning was arranged in this manner to allow the accelerator to operate at different levels than the injector since the spark gap gas systems are separate. The injector and trigger systems, however, are tied to a common gas system and their output levels cannot vary by more than 20% before jitter begins to be intolerable. A block diagram of the basic power conditioning system is shown in Figure 2.

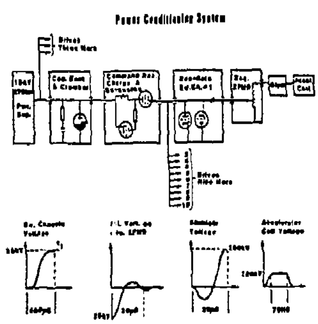

Figure 2

Power Supplies

There are ten power supplies in the system of four different ratings. Except for component sizes, they are essentially identical. The basic schematic is shown in Figure 3. SCR phase control is used in the primary to vary the output voltage level. The output current level is sensed by current transformers in the primary. These signals are rectified and compared to a dc reference to limit the power supply output current. As the output voltage nears the requested level, the voltage feedback loop takes over and stops the charging of the capacitor bank at the requested voltage. The

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loop gain of both feedback loops is about fifty, which provides more than adequate regulation for the purpose. The only unusual feature of these power supplies is the inclusion of resistance and reactance in the primary circuit. This is required to limit fault currents to a reasonable level when the system is crowbarred. The rectifier transformers are actually power-distribution pole transformers purchased for another application but never used. The impedance of these units is about 2%, so additional impedance had to be added.

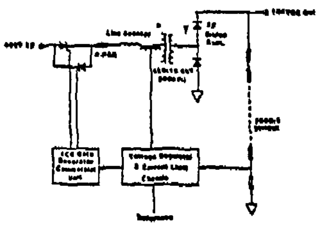

Figure 3

Capacitor Banks

The ATA design requirements for ten pulses at one kilohertz with 5 Hz average, dictated that the peak power of a few hundred megawatts during a burst be derived from capacitor banks. The schematic of the basic capacitor bank is shown in Figure 4. It consists of forty 50 μF 18 kV capacitors. Each capacitor has an energy limiting fuse and a 12.5 ohm resistor in series with it. The resistor limits the crowbar current to a reasonable value (58,000 A). The fuses are required to prevent rupture of a capacitor case if it breaks down inside. Two ground switches are included to discharge the bank on normal shutdown. The soft-ground switch closes first and the stored energy is dissipated in 144-660 watt glow-coil heaters. About one second later, the hard-ground switch closes. The delay is provided by energy stored in a capacitor connected in parallel with the solenoid. Since several banks are connected to a single power supply, a diode is provided on the input of each bank to prevent discharging several banks through one crowbar or grounding switch.

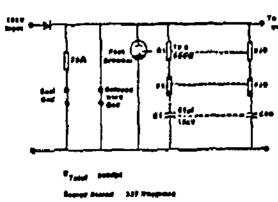

Figure 4

Command Resonant Charge Unit

Each CRC charges 10 switch chassis or 25 microfarads. The mean charge time is approximately 500 microseconds with a peak current of 1500 amps in a single pulse mode (5 pps) and 1600 amps in a regulated burst mode (1 kHz). Droop in the capacitor bank voltage (~16% for ten pulses) during a burst would cause a decrease in the switch chassis voltage, and ultimately the accelerating potential, on each successive pulse, if unregulated. Therefore it is necessary to regulate the charge voltage on each switch chassis. Regulation is obtained by de-queing or resistive clipping. The CRC Unit is shown in Figure 5. It contains six parallel EEV CX-1538 hydrogen thyratron tubes for the series switch (V1-V6) and four parallel CX-1538R tubes for the de-queing switch (V7-V10). Six tubes in parallel were used for the series switch in order to keep the RMS current through the tubes approximately the same as the RMS current in the switch chassis tubes. The series resistors insure current sharing. Four tubes were used in parallel for the de-queing switch for the same reason. The resistors in series with each of the de-queing tubes were chosen to limit the RMS current through the tubes and yet dissipate as little energy as possible, since the de-que current commutates back to the capacitive load.

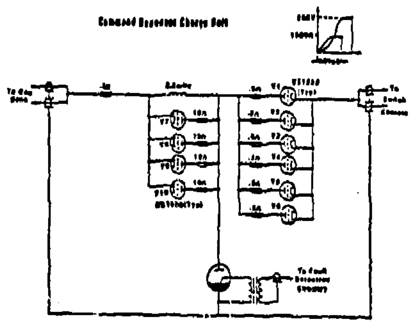

Figure 5

If the de-queing tubes are triggered at the correct time, the voltage to which each switch chassis is charged during each pulse will be constant. The triggering of these tubes is controlled by the circuit in Figure 6. The circuit, which consists primarily of a comparator and a burst amplifier, compares the voltage waveform from a fairly low-impedance divider (50 kΩ) to a 0 - 10 VDC reference. A trigger pulse is generated when these two voltages are equal. There is an unavoidable delay time, τ_D, from the time the correct voltage is sensed to the time V7-V10 begin conduction. Because of the inherent τ_D, which is typically a couple of microseconds, the best regulation that could possibly be obtained is several tenths of a percent depending on the capacitor bank droop and τ_D. Figure 7A shows the exaggerated effect of firing time delay. In order to compensate for this time delay, it is necessary for the voltage from the voltage divider to be slightly ahead in time with reference to the actual switch chassis voltage so that at a time τ_D after the voltage divider signal reaches V_{REF}, the actual switch chassis voltage is equal to V_{REF} as shown in Figure 7B. On ATA, this is accomplished very simply by placing the voltage divider on the CRC side of the current limiting resistors in series with each switch chassis as shown in Figure 6; this output phase lag corresponds to shifting ahead the comparator signal. Since this phase difference is considerably larger than that which is required to offset τ_D, the signal from the voltage divider must also be phase shifted later in time. This is accomplished with R1 and C_1. Using R1 as fine-tuning, voltage regulation of ± .025% has been obtained in burst operation (See Figure 8).

The ignitron in Figure 5 is used to dump any energy stored in the CRC in the event of a fault. The trigger signal originates from a CMOS logic circuit designed to detect any abnormal current or voltage waveforms. If an abnormal waveform is detected, a trigger pulse is sent to the ignitron in the CRC as well as the one in the capacitor banks. The CRC ignitron prevents excessive current in the series tubes in the event of a short on the output of the CRC, such as the prefire of a switch chassis.

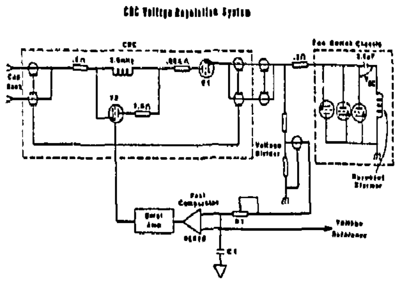

Figure 6

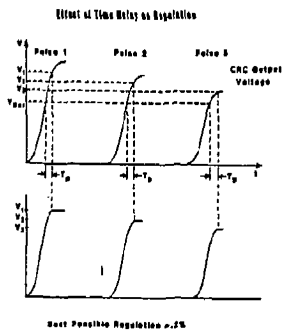

Figure 7A

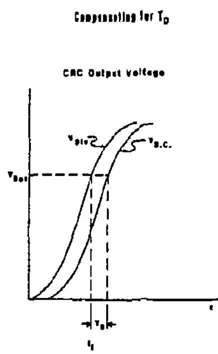

Figure 7B

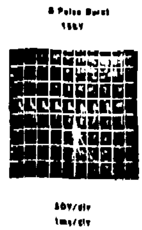

Figure 8. Regulated CRC Output

Switch Chassis

Each Thyratron Switch Chassis contains 6 EEV CX-1538 hydrogen thyratron tubes which are used to switch the energy stored in the 2.5 microfarad, 25 kV capacitor into the primary of the resonant transformer. The CX-1538 thyratrons were developed by English Electric Valve Company to meet LLNL specifications in a competitive development program. They were specifically developed for use in the ATA switch chassis. The switch chassis will run at 1 kHz, 10 kA peak (2.5 kA/tube) at 25 kV. A schematic of the switch chassis is shown in Figure 9.

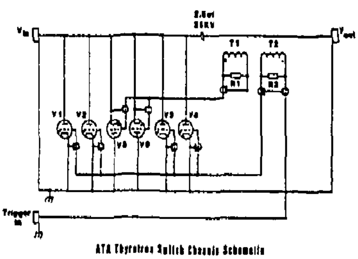

Figure 9

The switch chassis contains a bi-directional switch with 4 parallel tubes (V1-V4) conducting current during the first half cycle (forward direction) of the Blumlein charge cycle and 2 parallel tubes (V5, V6) conducting current during the second half cycle (reverse direction). Tubes V5 and V6 are automatically triggered using a small, saturating, iron-core pulse transformer (T1), which uses the output cable as a primary and has an air gap so the generated pulse occurs just prior to the zero crossing as shown in Figure 10. The same basic pulse transformer (T2) is used in series with the thyratron grid trigger for the "forward" tubes in order to trigger all four tubes in the event that one of the thyratrons prefires (see Figure 10). The negative pulses are diode clipped so that the thyratron grids only see a positive pulse.

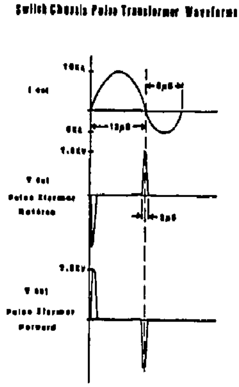

Figure 10

Resonant Transformer

The 12 , 14 nf Blumleins are charged by using a 10:1 step-up, air-core, dual-resonant transformer. A resonant transformer is a very efficient way of charging a capacitive load such as a Blumlein. An optimum mode of charging with a resonant transformer is with the coefficient of coupling, k = .6, and with the primary and secondary tuned to the same frequency. With this configuration, the primary voltage and current and the secondary current are equal to zero at the same time the secondary voltage is at its peak (see Figure 11). Theoretically this is a condition for 100% energy transfer although in practice, because of transformer and switch losses, the efficiency drops to less than 90%.[2] An additional benefit of this charging mode is that spark gap recovery time is enhanced as there is no energy remaining in the transformer to maintain the arc.[3]

Figure 11. Resonant Transformer Waveforms

This mode of operation requires a bi-directional switch in each Thyratron Switch Chassis because the primary current in the resonant transformer reverses polarity before the secondary voltage reaches its peak as seen in Figure 11. This is the reason that each switch chassis has 'forward' conducting tubes and 'reverse' conducting tubes.

Control System

A multiprocessor control and monitor system is used to facilitate the control and monitor requirements of the Power Conditioning System as well as all other ATA systems. The control and monitor systems consists of dual DEC VAX 11/750 minicomputers, five DEC LSI 11/23 microprocessors, four Modicon 584 programmable controller systems (PCs), and a CAMAC data acquisition system (see Figure 12). The computers and programmable controllers are organized as a dual hierarchial network. The function of the minicomputer is to act as the operator interface, make high-level decisions, and do data archival and retrieval. The microprocessors are the interface between the minicomputer and the PCs. The PCs, with its remote I/O structure, are the interface between the equipment and the computer system. The PCs are used to collect data, effect control commands, and make low-level decisions. The operator interface to the control system is through a color graphics system for information display, transparent touch panels, digital knobs and a few switches for command inputs.

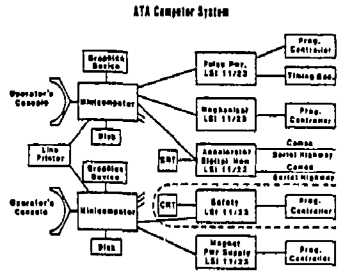

Figure 12

The programmable controllers are programmed in a symbolic language known as ladder logic, the microprocessors and minicomputers use mostly Pascal, with some assembly language. Standard vendor operating systems and network communications packages are being used. A data driven software architecture provides the flexibility and expandability necessary for this experimental system. Utilization of graphically defined controls and displays allow the operator complete freedom to interact with the machine in a convenient fashion.

Present Status of ATA

ATA is scheduled for completion in October of 1982. Testing and check-out of the power conditioning systems has already begun and will continue to October. An upgrade of ATA to a burst rate of 10 kHz is already under study. Photographs of the power conditioning equipment for ATA are shown in Figures 13-15.

FOOTNOTES

1. Overview of the ETA/ATA Pulse Power by L. L. Reginato and R. E. Hester, Fourteenth Pulse Power Modulator Symposium, Orlando, Florida, 1980.

2. Off-Resonance Transformer Charging for 250kV Water Blumlein by E. G. Cook and L. L. Reginato, IEEE Transactions on Electron Devices, Volume ED-26, No. 10, October 1979.

3. Advanced Test Accelerator (ATA) Pulse Power Technology Development by L. L. Reginato, et. al. IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981.

Figure 13
ATA Power Conditioning Area

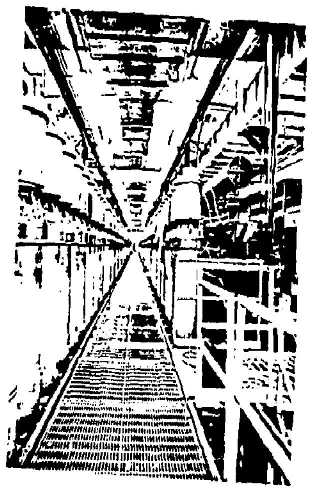

Figure 15
ATA Blumlein Assemblies

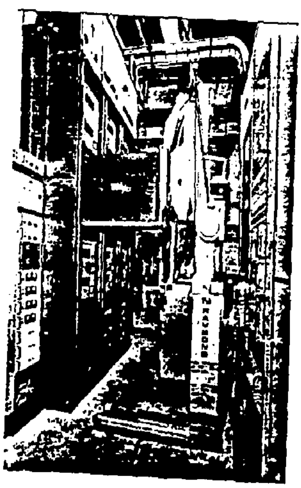

Figure 14
ATA Switch Chassis Bay