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# Design, Construction and Operational Results of the IGBT Controlled Solid State Modulator High Voltage Power Supply used in the High Power RF systems of the Low Energy Demonstration Accelerator of the Accelerator Production of Tritium (APT) Project\*

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## Abstract

The 1700 McV, 100 mA Accelerator Production of Tritium (APT) Proton Linac will require 244 1 MW, continuous wave RF systems. 1 MW continuous wave klystrons are used as the RF source and each klystron requires 95 kV, 17 A of beam voltage and current. The cost of the DC power supplies is the single largest percentage of the total RF system cost. Power supply reliability is crucial to overall RF system availability and AC to DC conversion efficiency affects the operating cost. The Low Energy Demonstration Accelerator (LEDA) being constructed at Los Alamos National Laboratory (LANL) will serve as the prototype and test bed for APT. The design of the RF systems used in LEDA is driven by the need to field test high efficiency systems with extremely high reliability before APT is built. We present a detailed description and test results of one type of advanced high voltage power supply system using Insulated Gate Bipolar Transistors (IGBTs) that has been used with the LEDA High Power RF systems. We also present some of the distinctive features offered by this power supply topology, including crowbarless tube protection and modular construction which allows graceful degradation of power supply operation.

## 1 POWER SUPPLY REQUIREMENTS

The High Voltage Power Supplies are required to convert standard AC distribution voltages to regulated HV DC power. The efficiency of this power supply was required to be greater than that of proven power supply technologies. The large number of power supplies required by APT implies that each power supply must be extremely reliable. Protection of the personnel who will service the power supply systems in the APT plant is of primary importance. Protection of the klystron from damage during a klystron arc is secondary to safety but still a crucial requirement. The humidity and temperature of the environment around the APT plant at Savanna River Site impose additional requirements on the power supply.

### 1.1 Performance

While over 100 of the klystrons in the APT plant will require a maximum of 17 A of current at 95 kV, the three

klystrons which drive the RFQ of the accelerator will require up to 21 A at 95 kV. In contrast, the RFQ klystrons will make up approximately half of the klystrons in the LEDA RF systems. The function and reliability of all candidate power supply designs must first be proven out in the LEDA accelerator before they can be considered for the APT plant. In order for candidate power supply designs to gain significant testing time on LEDA, all candidate power supply designs must be capable of providing currents of up to 21 A at 95 kV.

The output voltage regulation was required to be within  $\pm 400$  V around the setpoint and the ripple was required to be  $\leq 1100$  Vpp while the input line voltage varied  $\pm 5\%$  and the input voltage phase unbalance was  $\leq 3.8\%$ .

The input voltage of this power supply design was required to be 4160 V three phase service. The power supplies were required to have a power factor  $\geq 0.98$  for all output voltage levels between -60 kV and full power and all current levels between 10 and 21 amps. The harmonic distortion of the current drawn from the input lines was required to meet IEEE Std 519-1992 specifications.

When operating at -95 kV and currents between 17 and 21 amps, the efficiency was required to be  $\geq 97\%$ . When operating between -80 kV and -95 kV and currents between 12 and 21 amps, the efficiency was required to be  $\geq 96\%$ . When operating at or between -60 kV and -80 kV and currents between 10 and 21 amps, the efficiency was required to be  $\geq 95\%$ . The requirements on efficiency are summarized in Figure 1.

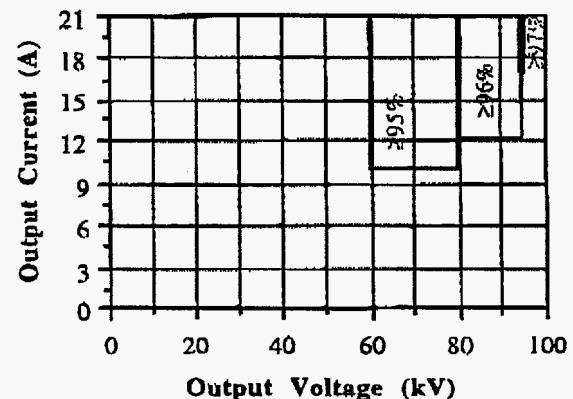


Figure 1: The efficiency requirements were specified over a range of currents and voltages.

### 1.3 Reliability and Maintenance

The goal for power supply Mean Time Between Failure (MTBF) was 25,000 hours. This goal was driven by the combination of the MTBF for all other components in each RF system and the large number of high power RF systems that will be required in the APT plant.

Serviceability was given consideration from the beginning the power supply design. The goal for the Mean Time To Repair (MTTR) of the supply was one hour or less to minimize the cost of maintaining the APT accelerator.

### 1.4 Safety and Klystron Protection

The Kirk® Key locks on the power supplies were required to integrate with the existing Kirk® Key lock system used in the existing LEDA High Power RF systems.

The power supplies were also required to meet all existing safety requirements at LANL including the requirement that debugging the low level power supply control circuits could be done without exposure to voltages in excess of 24 V.

The power supply was required to NOT use a crowbar but still limit the energy deposited in a klystron arc to less than 40 Joules and have a backup means of shutting off the power in the event that the principal system failed.

### 1.5 Environment

The environmental requirements were specified such that they covered both the expected environmental conditions at the Savannah River Site and the environmental conditions at LANL. The power supply was required to function over an ambient temperature range of 10°C to 32°C (50° F to 90° F) which was determined by the indoor location of the power supply. The power supply was required to function over a humidity range of up to 85% non-condensing which was chosen based on the environment at Savannah River Site. Finally, the power supply was required to function at an altitude of up to 2438 m (8000 feet) to allow it to be tested at LANL.

## 2 POWER SUPPLY DESCRIPTION

The design of the IGBT controlled Solid State Modulator High Voltage Power supply is based on the design of Solid State Modulators sold by Continental Electronics. Over 100 of these modulators are now in use and offer impressive AC to DC conversion efficiency.

### 2.1 Electrical Design.

The power supplies utilize 96 separate rectifying modules stacked in series. Each module is fed from an isolated secondary winding on one of four transformers as shown in Figure 1. The primary windings of each

transformer are extended by different amounts to produce 24 pulse rectification at the power supply output.

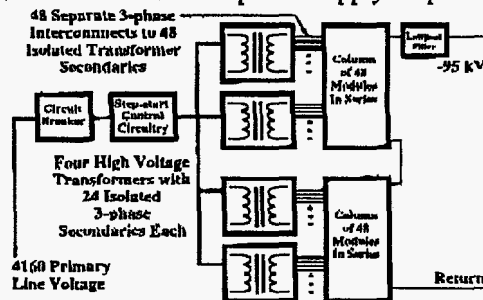


Figure 1: Two transformers serve each power column.

Each module uses an IGBT for current control as shown in Figure 2, eliminating the need for a crowbar. Each module also contains independent control circuitry to monitor the module output and inhibit the SCRs in the six pulse bridge in the event that an IGBT fails closed. Failed modules are bypassed by the control system to provide graceful degradation of operation. If more than five modules have failed, then the maximum voltage the supply can produce under the condition of 5% input voltage droop is reduced by roughly 1 kV per failed module after the first five.

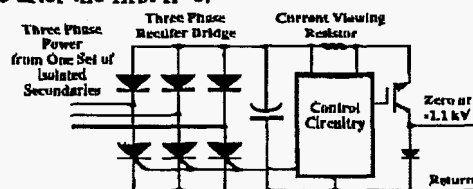


Figure 2: Each module contains independent control circuitry to disable the module in the event of module control failure.

### 2.2 Physical Structure.

The whole power supply is located behind a 6.1 by 5.5 m fence. Each module is contained on a removable circuit card. The circuit cards are arranged in the two power columns in four rows of twelve. This arrangement allows cooling air from fans at the bottom of the columns to be blown across each module. The columns support corona rings on each row to hide sharp edges on the modules from high electric fields and to grade the electric field as the potential increases toward the top of each column.

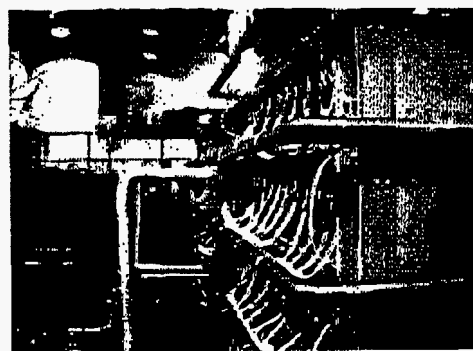


Figure 3: Each module is connected to a unique isolated 3-phase secondary on one of the four transformers.

The backplanes of the power columns contain connections to the 24 isolated 3-phase secondaries on each of the four transformers as shown in Figure 3. The backplanes also contain the shorting mechanisms that insure that all modules are shorted out before the fence is opened when the power supply is to be serviced.

### 2.3 Mean Time Between Failure and Mean Time To Repair

The MTBF was calculated after the design was finalized. The power supply was designed such that up to five modules could fail before the supply's ability to produce 95 kV under the conditions of a 5% input voltage droop was impaired. A block diagram of the method used to calculate the MTBF is shown in Figure 4.

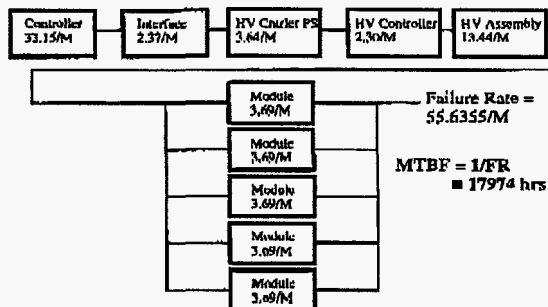


Figure 4: The total MTBF for the supply was calculated from published MTBF data for each component in the power supply.

The power supply was designed with serviceability in mind. A 44 minute MTTR was achieved in part by designing the power columns such that it possible to remove and replace any modules in the power columns without the use of tools once the Kirk® Key locked fence has been opened and the columns have been grounded.

## 3 ACCEPTANCE TEST RESULTS

Acceptance testing of the power supply is done in two parts. Almost all required functions of the power supply (including output power quality, safety systems and klystron protection systems) are tested at the vendor's facility before the power supply is shipped. The testing of power supply efficiency and a full power heat run is done at LANL due to the availability of a 95 kV, 2 MW resistive load at the LEDA facility.

Three of these power supplies are on order from Continental Electronics. The first has passed its factory acceptance tests and is being shipped to LANL.

### 3.1 Factory Acceptance Test Results

All methods of triggering the Fast Shut Down Mode (FSDM or the equivalent of a "crowbar") were tested successfully. The power supply shut down quickly enough to prevent a 0.614 meter long 35 gauge copper wire (40 Joules) from melting placed across the high voltage output. This test was performed 192 times at full

voltage over a period of 48 hours. Calculations made of the energy deposited in the wire indicate that the energy that will be deposited into a klystron arc will be less than 10 Joules when the power supply is operating at full voltage and current.

The power supply was tested into a 640  $\Omega$  load at 21 A for 48 consecutive hours. During this test a heat wave combined with an air conditioning failure at the vendor's facility caused the ambient temperature and humidity rise above the maximum specified levels. Despite the extreme temperature, the full current test was passed without failure. Figure 5 shows the core temperature of the first transformer during this run. The time required to reach a relatively constant core temperature was approximately ten hours, significantly less than the length of the 48 hour test.

The harmonic content of the input current during the 21 A output current tests showed magnitudes that were all below 20 dB down from the 60 Hz fundamental. While all of these values are significantly below the maximum allowed values of IEEE Std 519-1992, these measurements will be taken again at LANL where the test can be repeated with loads in the MW level. The utility connections at LANL are also expected to provide a more realistic source impedance to the supply.

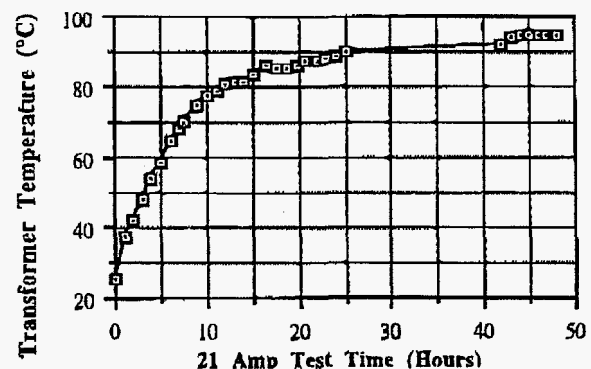


Figure 5: Transformer core temperature while running at 21 Amps in an ambient temperature of greater than 38°C.

### 3.2 Final Acceptance Tests

The final acceptance tests will be performed at LANL where a 2 MW, 95 kV resistive load is available. The power supply is being shipped to LANL for installation. Final acceptance tests will take place in September, 1998.

## 4 CONCLUSIONS

The first IGBT Controlled SSM High Voltage Power Supply has successfully passed the factory acceptance tests. This power supply is being shipped to LANL for final acceptance tests. Final acceptance tests will include measurement of efficiency at output power levels in the MW range and more detailed measurements of the input current harmonic content.