A 350 kW AVERAGE POWER THYRATRON SWITCHED LINE TYPE MODULATOR

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Abstract

A line type modulator has been designed, manufactured, and successfully tested which delivers -600 kV, 870 A, 14 µs output pulses at rep-rates of up to 50 Hz, resulting in peak powers of over 520 MW and average powers of over 350 kW available for testing high power R&D klystron tubes. A center point, phase-controlled power supply transforms the incoming three phase, 480 V ac power up to dc voltages of up to 45 kV at 10 A and regulates the output voltage on a filter capacitor bank. A solid state, series array of twenty SCRs is used as a command charging switch to initiate resonant charging of the Pulse Forming Networks (PFNs). An additional SCR device is used as the de-Qing switch on the secondary winding of the charging inductor to halt the charging cycle and maintain precise regulation of the PFN charging voltage to less than ± 0.2%. Four parallel, air insulated, 75 kV, twenty stage Rayleigh PFNs, each with a nominal 10 ohm impedance, are used to provide the pulse shaping for the output. Adjustable slugs in the PFN solenoidal inductors allow tuning of the PFN impedances to compensate for droop introduced by the pulse transformer and to reduce the flat top ripple on the pulse to less than ± 0.5%. These PFNs are switched into the primary of a 1:16 pulse transformer by two parallel, four-gap, 100 kV, ITT F-237 thyratrons. A phase controlled power supply provides current limited power through the bi-filar wound pulse transformer secondary for the klystron heater. Operation of the modulator may be performed from a local control panel on the modulator enclosure, or a remote control panel or remote computer controller located up to 300 meters away from the modulator. The computer based system uses an Apple MacIntosh IIFX controlling computer, a CAMAC crate along with digital and analog I/O modules, a GPIB crate controller, a fiber optic GPIB bus extender, and National Instruments LabView software. Two cooling subsystems are also provided with the modulator including a 500 kW rated air cooled heat exchanger and pump system for providing cooling water for the klystron and a 70 kW rated chiller system for providing cooling water to the modulator. Additional design details and test results are presented in the paper.

Introduction and Modulator Requirements

In the last several years, more and more research has been focused on developing higher power klystron rf tubes for a variety of applications from advanced particle accelerators to defense related high power microwave research. In order to support this testing effort, high power modulators, such as the one described in this paper, are needed to provide the initial electrical pulse energy.

Modulator Electrical Requirements

The electrical requirements for the klystron modulator are shown below in Table 1. The requirements which became the primary design drivers for this modulator were the output voltage, peak and average power, and the output pulse rise time.

TABLE 1: KLYSTRON MODULATOR ELECTRICAL SPECIFICATIONS

Modulator Parameters	Value
Output Voltage	-600 kV
Output Current	870 A at 600 kV
Output Peak Power	520 MW
Output Average Power	350 kW
Output Pulse Flat Top Width	> 10 µs
Flat Top Ripple	< ± 0.5%
Output Pulse Rise Time	≤ 1 µs
Peak Amplitude Variation (shot to shot)	< ± 0.2%
Rep-Rate	Up to 50 Hz

The first step in the design process was to allocate the voltage requirements for the different modulator subsystems. Given the high output voltage for the modulator of 600 kV implied that the pulse transformer either have a high step-up ratio or a large primary voltage. In this case, the requirement for a fast risetime (1 µs or less) tended to drive the transformer turns ratio in the opposite direction (a lower step-up ratio). After preliminary calculations of the transformer leakage inductance were generated, a compromise between these two driving factors was reached, resulting in a transformer turns ratio of 1:16. Assuming a matched PFN discharge condition then required an input to the transformer of 37.5 kV, which implied a PFN charge voltage of 75 kV. Thyratrons capable of operation up to 100 kV were therefore selected. A voltage gain of ~1.8 was assumed in the resonant charging process which resulted in the requirement for a high voltage power supply capable of delivering ~42 kV. Other subsystem requirements were tiered down from the overall requirements in a similar fashion.

Other Modulator Requirements and Design Drivers

In addition to these electrical requirements, several other issues were also critical. Because it was very important to minimize the physical space (particularly the floor space or footprint) required by the modulator, significant attention was paid to the system packaging and high voltage insulation. As will be described in the following sections, several major components, such as the T/R set, were designed and manufactured specifically to minimize the footprint, as well as meet the required electrical parameters.

Since other sensitive electrical equipment would be operated in the general vicinity of the modulator and since additional modulators might have been added to the facility at a later date, it was crucial to minimize the harmonics induced on the incoming power lines. Operation of the modulator at the 50 Hz rep-rate would tend to generate low frequency harmonics, particularly at 10 Hz due to the difference in 50 Hz modulator rep-rate and 60 Hz power line frequency. Close attention was therefore paid to the design of the high voltage power supply subsystem and the filtering provided by both the power supply filter inductor and filter capacitor bank so that the harmonics would be reduced to levels acceptable to the user.

Reliability, maintainability, and value were important to the customer and, as a result, the modulator was designed for an operational lifetime of over 50,000 hours (9×10^9 shots at the full 50 Hz rep-rate) with maintenance simplified wherever possible. Realistic de-ratings for components and other techniques were implemented to ensure that the modulator lifetime was maximized. Even though the modulator physical layout was closely packaged to minimize the floor footprint, items were carefully arranged so that maintenance work could be performed with a minimum of effort.

Dissipation of thermal losses into the customer's ambient air environment was to be limited to ~10 kW or less. As a result, water cooling was implemented to remove the majority of the heat dissipated within the modulator from such items as the phase controller, T/R set, filter inductor, charging inductor, de-Qing switch and resistor, and pulse transformer.

Modulator Description

In many ways, the overall modulator design is very similar to the classic line type modulator that has been produced for a variety of applications, such as rf particle accelerators, etc.[1,2]. The most obvious differences associated with this particular line type modulator are it's high average power level, the high output voltage, and the use of a solid state command charging switch assembly. Details of these features, along with a general description of all of the modulator subsystems and support equipment, are provided in the sections which follow.

As mentioned above, it was extremely desirable to the customer to minimize the footprint of the modulator. The resulting main modulator enclosure, as shown in Figure 1, is 7' wide x 11.5' long x 9' tall while the attached oil tank is 7.5' wide x 4.75' long x 5.25' tall.

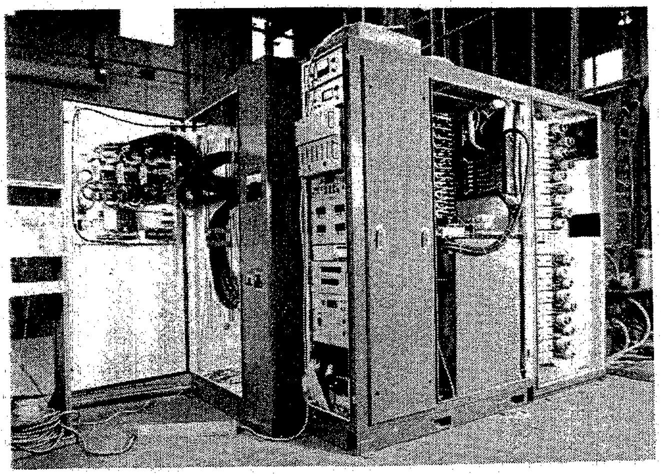

Figure 1. Side View of the 350 kW Average Power Line Type Modulator Showing (L-R) the High Voltage Power Supply Phase Controller, Controls and Auxiliaries Compartment, Resonant Charging Subsystem, and PFN.

For comparison purposes, we have calculated two figures of merit for the packaging efficiency and compared these numbers to those of the standard SLAC modulators. The results are shown in Table 2.

TABLE 2: KLYSTRON MODULATOR PACKAGING EFFICIENCY COMPARED TO THE STANDARD SLAC MODULATORS

Modulator	Footprint Figure of Merit	Volume Figure of Merit
Standard ~90 kW (avg.) SLAC Klystron Modulator	~2.2 kW/ft^2	~0.28 kW/ft^2
350 kW (avg.) Klystron Modulator	~3.0 kW/ft^3	~0.38 kW/ft^3

Although it can be argued that some savings in volume and size would be expected at the higher power level due to advantages in component scaling, some increase in size would also be warranted due to the higher voltages and the associated additional space needed for electrical insulation at the higher voltages. In any case, this analysis is meant to be more qualitative in nature than quantitative.

High Voltage Power Supply Subsystem

The High Voltage Power Supply Subsystem for the klystron modulator is made up of an input power circuit breaker, ac contactor, center point SCR phase controller with filter inductor, high voltage Transformer / Rectifier (T/R) set, high voltage filter capacitor bank, crowbar diode stack, diagnostics monitors, and control electronics.

A center point, six pulse phase controller topology was chosen because of several advantages over other topologies, such as in-line or in-delta. In this configuration, a filter inductor is used in conjunction with the high voltage filter capacitor bank to reduce the power line harmonics, as well as the power supply output ripple. The advantage of the center point topology is that the filter inductor can be located on the primary (low voltage) side of the T/R set, making voltage insulation of the inductor much simpler. The phase controller and 2 mH filter inductor were procured from the patent holder for this particular controller topology. Included with the phase controller is a "crowbar" SCR switch which dissipates any stored energy in the filter inductor in the case of a phase controller shut down. This feature minimizes additional "follow through" energy which could be deposited into a fault.

A T/R set transforms the 480 V ac input power into 45 kV, 11 A (rms) power for charging the filter capacitor bank. The custom T/R set is contained within a water cooled, oil insulated tank measuring 24" x 68" x 64" tall in order to minimize the footprint. Transformer taps on the top of the T/R set oil tank allow connection of the primary windings in several different configurations, allowing for phase shifts of 0, +15, or -15 degrees with respect to the input lines. This would allow for further reduction in power line harmonics if multiple modulators were to be run from the same power source. In order to implement this option, one modulator would have +15 degrees phase shift and the other modulator would have -15 degrees phase shift, resulting in a 30 degree shift between the two and producing the same overall effects as a "12 pulse" system instead of a "6 pulse" system.

Eight Maxwell, 45 kV, 6.67 µF high voltage capacitors form the filter capacitor bank of the power supply subsystem. These capacitors are mounted in a metal frame support structure which is isolated from the enclosure ground since the modulator single point ground is located at the cathode of the thyratrons. As with the filter inductance, the total capacitance value of 54 µF was selected based upon computer simulations of the power supply and expected harmonics which would be induced on the incoming power lines.

In the case of a fault on the load side of the filter bank, the voltage will attempt to reverse due to the under-damped circuit configuration. However, the T/R set output rectifier diodes will act as a crowbar in this case, preventing the voltage reversal and carrying the fault current until the circuit resistance has dissipated the energy. Because these diodes are only required to carry normal average currents of ~10 A, they are not particularly suited for handling these large possible fault currents. As a result, a high voltage, crowbar diode stack assembly was placed across the filter capacitor bank and a small amount of series resistance (~1 Ω) inserted between the T/R set and filter bank. This prevents the T/R set from carrying any sizable fraction of the fault current which is now conducted through the larger crowbar diode stack. The use of a single crowbar diode stack external to the power supply is less expensive than sizing all six of the T/R set rectifier stack legs to handle the fault current levels.

The compensated resistive divider, voltage monitor and power supply dump system are mounted to the ceiling of the modulator enclosure above the T/R set to make the most use of space within the enclosure. AC current transformers are located on the power lines between the contactor and T/R set and a Hall probe dc current monitor is located in the common return to the T/R set from the filter capacitor bank.

The High Voltage Electronics are located in a shielded box, also on the ceiling of the modulator enclosure near the phase controller. This chassis interfaces the modulator control signals with the phase controller electronics and monitors the power supply output voltage, ac current, and dc current for trouble-shooting diagnostics and interlock purposes.

Figure 2 shows a simplified schematic diagram of the High Voltage Power Supply Subsystem from the input prime power through the T/R set. As mentioned earlier, the advantage of the center point, or star point, phase controller topology is the use of a filter inductor on the primary (low voltage) side of the T/R set.

Figure 3 shows many of the components associated with the High Voltage Power Supply Subsystem. On the left edge of the photo is the phase controller subassembly which is seen hanging on the enclosure door. Inside the enclosure on the left side is the tall narrow oil tank housing the T/R set with the 480 V primary power cables entering from the top. To the right of the T/R set on the floor of the enclosure is the filter inductor oil tank with additional 480 V power cables being routed from the phase controller. The 800 A circuit breaker for the prime power can also be seen mounted in the enclosure wall to the right of the access door.

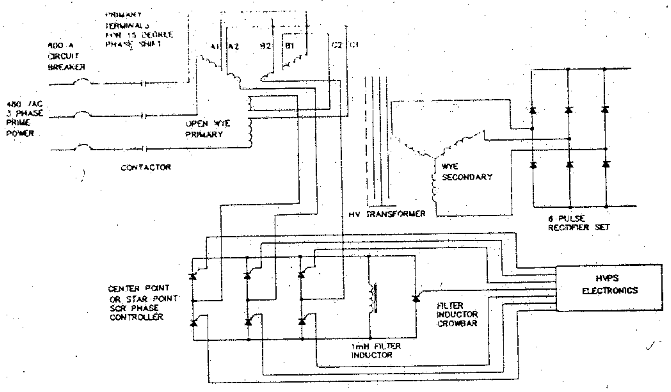

Figure 2. Simplified Schematic Diagram of the High Voltage Power Supply Subsystem Showing the Circuit Breaker, Contactor, Phase Controller, Filter Inductor, and T/R Set.

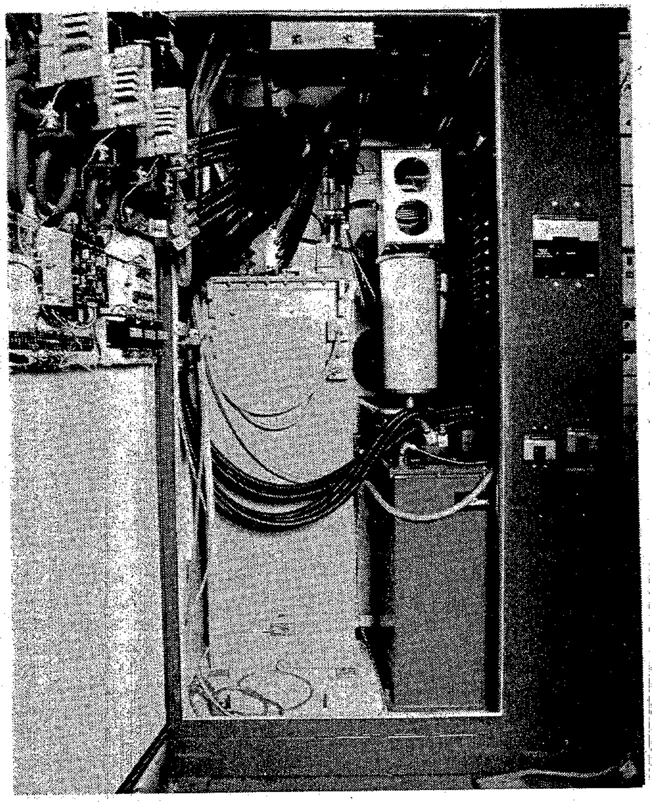

Figure 3. High Voltage Power Supply Subsystem in the 350 kW Average Power Modulator Enclosure.

Resonant Charging Subsystem

The Resonant Charging Subsystem is responsible for charging the PFNs to the required voltage on a rep-rated basis and regulating the charge voltage so that the modulator output pulse amplitude will also be regulated to the desired precision ($<\pm 0.2\%$). The major components or assemblies in this subsystem include the de-spiking networks, command charging switch, charging inductor with de-Qing secondary winding, charging diode, de-Qing circuit and switch, diagnostic monitors, and control electronics. A separate paper at this conference provides more detail on the design and testing of this particular subsystem[3].

Two de-spiking networks are used in the resonant charging circuit. Each is made up of a ~1 mH inductor in parallel with a 200 Ω ceramic resistor. The de-spiking inductance was selected so that the command charging switch di/dt rating would not be exceeded in the case of a fault on the primary side of the charging inductor.

The command charging switch is made up of 20 series-connected SCR switches sandwiched between buswork plates. Both resistive and RC grading are used across each switch stage to ensure proper voltage division during both steady state and transient conditions. Triggering of the overall switch is accomplished through fiber optic signals to each stage which trigger a circuit into discharging the snubber capacitor energy into the SCR gate. This eliminates the need for trigger transformer or ac power isolation transformer schemes with high voltage isolation requirements since the inexpensive fiber optic cable can provide the voltage isolation.

The charging inductor is a 1 H inductor with a 1:40 secondary winding for the de-Qing circuit. The iron-core inductor is oil insulated and contained within its own tank which measures 30" x 32" x 50" tall. Connections for the de-Qing winding, as well as the high voltage bushings for the main winding, are located on the top of the tank.

The de-Qing circuit is made up of a single SCR de-Qing switch, a capacitor bank, and a resistor assembly. Six parallel Maxwell 50 µF, 2 kV capacitors form the de-Qing capacitance. The de-Qing resistor assembly is made up of twenty-four, 0.4 Ω, ceramic resistor slugs which are sandwiched between water cooled, heat sinks. This compact assembly, which measures ~6" deep x 24" wide x 14" tall, is conservatively designed to normally operate at approximately half its power dissipation capability of 40 kW.

The Charging diode assembly is a set of 30, series-connected, 4000 V (V_{RRM}) diodes in a clamped heat sink assembly with MOVs connected in parallel to assist with voltage sharing.

The Resonant Charging Electronics generate the command charge trigger, interface the modulator control signals with the resonant charging electronics, and monitor the PFN charging voltage and current, and the de-Qing current for trouble-shooting diagnostics and interlock circuitry.

Pulse Forming Network Subsystem

The Pulse Forming Network Subsystem is made up of four, parallel PFNs. Each of these is designed as a twenty section, Rayleigh type PFN with a nominal impedance of ~10 ohms. The PFNs are air insulated in a separate compartment of the modulator enclosure. Air insulation was chosen over oil or gas insulation in order to minimize and simplify maintenance time. As a result, careful attention was paid to the buswork and physical layout of the PFN subsystem. The high voltage, or hot, bus for the PFN is located in the center of the compartment with the nominally common side towards the outside panels. Buswork penetrates the compartment to connect the PFNs to the Resonant Charging Subsystem and to the thyratrons and pulse transformer.

Maxwell 85 kV, 33.5 nF, Type SS, double ended, plastic case capacitors provide the capacitance needed for the modulator PFN. These units were designed to yield more than 10^9 shots at the full charge voltage of 75 kV with a 95% survival rate. A Multi-contact connector plug is attached to one end which mates with a matching receptacle located on the high voltage buswork in the center of the compartment, allowing for easy removal and replacement of the capacitors. Capacitors can also be removed in this fashion in order to operate with a reduced pulse length.

The PFN inductors are simple solenoids wound from 0.5" diameter copper tubing on a 4" diameter, G-10, cylindrical support structure. A copper tuning slug is mounted on an axial, threaded rod for adjustment of the inductance. A slot in the end of the tuning slug allows for insertion of a dielectric tuning wand to turn the slug and adjust the inductance during modulator operation. In addition, an external tap is provided on the inductor windings to short out 2 of the 11 turns. This allowed for an inductance range of ~3-6 µH.

The End Of Line Clipper (EOLC) assemblies are made up of a high voltage diode stack, a set of five 18" long, 50 Ω, ceramic resistors, cooling fans, and air ducting hardware. The diode stacks were procured from IR and are made up of 26 series connected, 5 kV diodes for a combined voltage rating of 130 kV.

A wire mesh screen over a polycarbonate sheet just inside the modulator access panels in the PFN compartment is provided to allow the operator to tune the PFNs while pulsing. An insulating rod with a grounded sleeve is inserted through holes in the screen to rotate the PFN inductor tuning slugs. A water cooled, forced air driven heat exchanger is also mounted on the wall of the PFN compartment to assist in removing heat dissipated in the PFNs.

Figure 4 shows one side of the PFN compartment in the modulator enclosure with two of the four PFNs visible in the photo. Both PFNs are assembled in U-shape layouts with the sections nearest the load located in the middle on the right side where they are attached to ~8 inch wide output buswork. The sections most removed from the load are on the left side in the middle with the End of Line Clippers located behind the inductors. For clarity in the photo, the tuning safety screen has been removed. The opposite side PFNs are laid out in an equivalent mirror image.

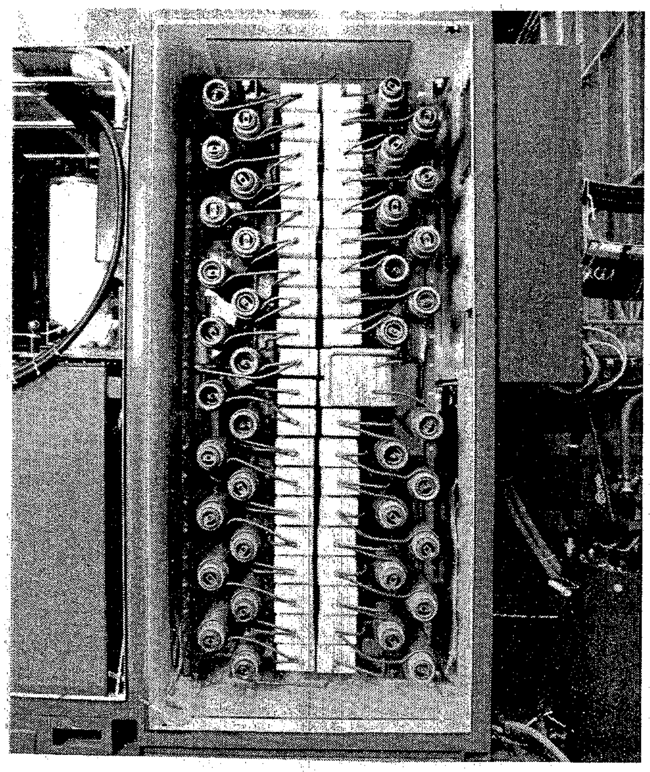

Figure 4. PFN Compartment in the 350 kW Average Power Modulator Enclosure.

Thyratron Subsystem

The Thyratron Subsystem is made up of the two thyratron switches and all of the auxiliaries required to support the switches. ITT F-237 thyratrons were selected for this application and Table 3 shows the tube capabilities compared with their design ratings for this particular application under normal conditions. These four gap tubes have been designed and manufactured with dispenser cathodes in order to maximize their lifetime.

TABLE 3: THYRATRON CAPABILITIES AND REQUIREMENTS FOR THIS APPLICATION

Parameters	Capabilities	Requirements
Voltage	100 kV	75 kV
Normal Peak Current	15 kA	~7 kA
RMS Current	400 A	171 A
Average Current	10 A	4.2 A
Plate Dissipation Factor	1000 x 10^9	~26 x 10^9
Maximum di/dt	50 kA/µs	15.3 kA/µs

The driving factor in this design is the peak current rating of the tube. As can be seen from the data, the normal operating peak current is just under half the peak current rating of the tube. Since this can double in the case of a load fault, the tube will experience peak current levels near its rated capability on a single event basis.

Each thyratron is mounted on top of a deep drawn aluminum housing which contains the heater and reservoir step-down transformers, grid 1 keep alive, and grid 2 negative bias circuits.

The Thyratron Trigger Generator is mounted in an EMI shielded enclosure on the outside of the pulse transformer tank. A fiber optic receiver initiates the trigger after receiving the light signal from the Signal Conditioning Chassis. A pair of amplifier stages boost the trigger signal and drive a pair of IGBTs which discharge a set of energy storage capacitors into a 1:4 step up pulse transformer. The resulting output pulse is ~2 kV into an open circuit with very little jitter. The solid state trigger design ensures a long lifetime of the unit and has been used reliably on several other programs.

The Thyratron Auxiliary Control Chassis is located in the electronics compartment of the modulator enclosure and contains four single phase, SCR phase controllers which are used to adjust and regulate the power for the reservoir and heater of each thyratron. Potentiometers and digital panel meters allow control and monitoring of these parameters and time delay relays inside the chassis ensure that the tubes have sufficient time to warm up prior to modulator operation. Additional electronics circuitry inside the chassis monitors these auxiliary current levels for interlock purposes.

Pulse Transformer Subsystem

The modulator pulse transformer was procured according to a detailed specification with the major parameters listed below in Table 4. As noted in the table and required by the contract, the input and output voltages are specified as 120% of the maximum expected operating levels for the modulator in order to ensure high reliability.

TABLE 4: PULSE TRANSFORMER PROCUREMENT SPECIFICATIONS

Parameters	Specification
Input Voltage	45 kV
Input Current	13.9 kA
Output Voltage	720 kV
Output Current	870 A
Turns Ratio	1:16
Magnetizing Inductance	≥ 290 µH wrt primary
Leakage Inductance	≤ 1.56 µH wrt primary
Size	33" x 33" x 48" tall
Weight	~4000 lb.

Bi-filar windings were also provided on the transformer secondary for routing the klystron heater power to the klystron from ground level. Taps were also supplied on the secondary at the 25%, 50%, 75%, and 100% levels for use by the klystron electron gun.

Controls and Auxiliaries Subsystem

The Controls and Auxiliaries Subsystem is made up of a number of chassis which are contained within the single bay modulator controls compartment or located at a remote location.

Operation and monitoring of the modulator functions is possible from any of three different locations depending upon the settings of two key switches at the local and remote control panels. As implied by its name, the Local Control Panel in the modulator controls compartment allows the operator to run the unit from that location. The Remote Control Panel duplicates those same control and monitoring functions at remote locations of up to 325 m away. A single, individually twisted, shielded pair cable provides the connection from the local panel to the remote unit.

The Interlocks chassis monitors 42 different interlocks in order to inhibit the klystron heater, modulator high voltage, or modulator pulsing. The Signal Conditioning chassis contains interlock circuitry as well as six analog fiber optic transmitters for remote diagnostics monitoring. The Power Distribution chassis contains circuit breakers for ac power supplied to the various other chassis and auxiliary subsystems. As mentioned earlier, the

Thyratron Auxiliaries Control chassis contains the phase controllers which regulate power for the two thyratrons and their heater and reservoir circuits. The Klystron Heater Power Supply also houses a phase controller for control purposes.

In addition to the customized electronics chassis, several "off the shelf" power supplies are used. Two Varian Vac-Ion pump power supplies provide up to twenty different outputs for driving vac-ion pumps. A 8 V, 125 A, switching power supply is used to provide bias current to the pulse transformer.

Operation of the modulator from the remote control computer utilizes a number of CAMAC digital and analog I/O modules in a CAMAC crate in the modulator. A IEEE-488 GPIB crate controller and fiber optic, GPIB bus extender are used to communicate with the remote computer system.

A MacIntosh IIFX computer, running National Instruments LabView software and several customized software routines, emulates the same control and monitor functions as the manual control panels. Additional software panels are provided to monitor individual interlock status, control the digital delay generator, and control the HP digital oscilloscope. More information on the modulator controls system, particularly the computer control, can be found in another paper to be presented at this conference[4].

Auxiliary Support Subsystems

Two separate Cooling Subsystems were also provided. The 70 kW Modulator Cooling Subsystem was procured as a standard 20 ton chiller to generate cooling water for use by the modulator. The 350 kW Klystron Cooling Subsystem consisted of a 250 gallon stainless steel reservoir, 40 HP motor and pump, filter, and air cooled heat exchanger with six 1-1/2 HP motor driven fans. It was designed to provide over 265 gpm of cooling water to the klystron collector, body, window, and magnet. An Oil Storage Subsystem consisted of a 1000 gallon cylindrical oil reservoir tank mounted on a welded steel pallet with a built in gear pump and oil filter system.

Modulator Testing Results

Typical resonant charging current and PFN voltage waveforms are shown in Figure 5. In this case, the modulator was operating at the full rated 50 Hz rep-rate and a HVPS output voltage of 38.5 kV, representing ~95% of the rated output voltage. This corresponds to an average power of > 300 kW delivered to the load.

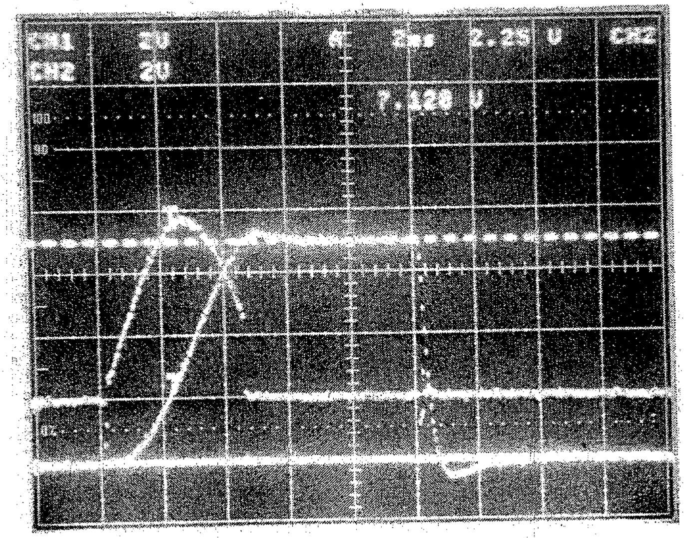

Figure 5. Oscilloscope Photo of Typical Resonant Charging Current (upper trace, 20 A / division) and PFN Charging Voltage (lower trace, 20 kV / division) During 50 Hz Rep-Rated Operation (V_{Filter}=38.5 kV).

Figure 6 shows the output current waveform corresponding to this same operating point. In this case, the resistance of the load is slightly lower than the nominal design load value and the output current is higher as a result (~950 A versus the nominal 870 A).

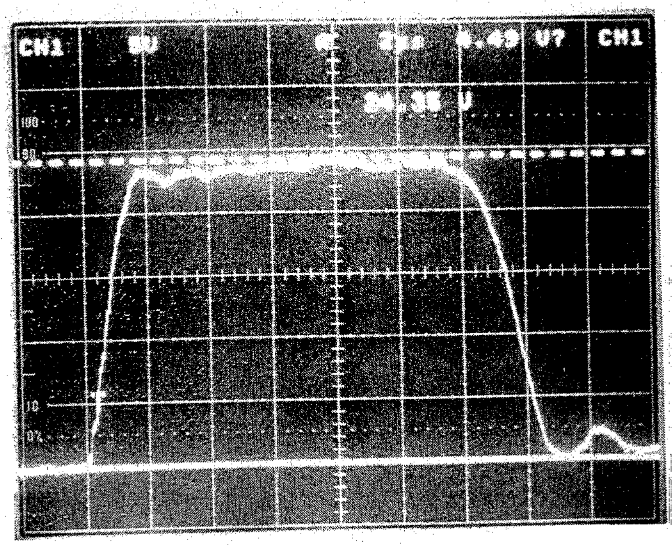

Figure 6. Oscilloscope Photo of Typical Modulator Output Current waveform (200 A / division) During 50 Hz Rep-Rated Operation (V_{Filter}=38.5 kV).

Summary

A 350 kW average power line type modulator has been demonstrated which delivers -600 kV, 870 A, 14 µs pulses to the load at rep-rates of up to 50 Hz. Unique features included a HV power supply subsystem design which minimizes input power line harmonics and allows the use of a primary side filter inductor and a 50 kV SCR command charging switch using fiber optics and energy stored in the RC snubber capacitors to trigger the SCR switches.

Careful packaging of the modulator components has resulted in a compact, yet easily maintained, system layout. For comparison purposes, several figures of merit were developed and compared to other existing modulator designs:

- ~3.0 kW/ft^2 vs. ~2.3 kW/ft^2 for the ~90 kW SLAC modulator.
- ~0.4 kW/ft^3 vs. ~0.3 kW/ft^3 for the ~90 kW SLAC modulator.

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