RECENT UPGRADE OF THE KLYSTRON MODULATOR AT SLAC*

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Abstract

The SLAC National Accelerator Laboratory employs 244 klystron modulators on its two-mile-long linear accelerator that has been operational since the early days of the SLAC establishment in the sixties [1]. Each of these original modulators was designed to provide 250 kV, 262 A and 3.5 µS at up to 360 pps using an inductance-capacitance resonant charging system, a modified type-E pulse-forming network (PFN), and a pulse transformer. The modulator internal control comprised of large step-start resistor-contactors, vacuum-tube amplifiers, and 120 Vac relays for logical signals. A major, power-component-only upgrade, which began in 1983 to accommodate the required beam energy of the SLAC Linear Collider (SLC) project, raised the modulator peak output capacity to 360 kV, 420 A and 5.0 µS at a reduced pulse repetition rate of 120 pps [2]. In an effort to improve safety, performance, reliability and maintainability of the modulator, this recent upgrade focuses on the remaining three-phase AC power input and modulator controls. The upgrade includes the utilization of primary SCR phase control rectifiers, integrated fault protection and voltage regulation circuitries, and programmable logic controllers (PLC) - with an emphasis on component physical layouts for safety and maintainability concerns. In this paper, we will describe the design and implementation of each upgraded component in the modulator control system. We will also report the testing and present status of the modified modulators.

I. BACKGROUND

Considered state-of-the-art engineering in the sixties, the SLAC-design 6575 klystron modulator – the number is designated for its original parameters of 65 MW and 75 kW of peak and average powers - has been operated continuously and reliably at SLAC National Accelerator Laboratory. This proven, line-type modulator technology was adapted and modified to provide drive power to a variety of klystron tubes in other laboratories both in the U.S. and abroad. The modulator structure consists of three compartments. The first one houses a thyratron, a charging transformer, and an end-of-line clipper circuit component. A short triaxial cable connects the PFN output to a step-up 1:15 pulse transformer residing in the klystron oil tank. The second compartment consists of two parallel PFNs containing eight sections each. Components in these two compartments have been upgraded in the 1980s to increase output powers to the current levels [2]. The third compartment, which houses a high voltage (HV) power supply, a modulator control system, and various auxiliary power sources for supporting thyratrons and klystrons, remains unchanged from its original form since creation almost 50 years ago.

The current HV power supply is a conventional, unregulated 24 kVdc power source. It takes a three-phase AC input power from a variable voltage substation (VVS) and steps up through a rectifier transformer, which the secondary is then rectified, filtered and delivered to the PFN capacitors through a charging transformer. Each VVS supplies up to 590 Vac power to 16 modulators. The output voltage of each modulator is adjusted by manually moving five tap changers, 2.5% for each step, from the rectifier transformer primary. The control system uses a variety of mechanical relays and pushbutton switches to pass 120 Vac logic signals for operation controls, interlock, and external interfacing. These devices do not meet modern requirements for reliability and the availability of parts is increasingly difficult to procure. In addition, auxiliary power sources for the thyratron and klystron employ unregulated power supplies that require constant tuning to maintain modulator performance.

Obsolete components, 120 Vac operator control interfaces, and fire risks due to the use of resistive elements to limit inrush current for the 600 Vac step start circuit are the main reasons to bring the third compartment both electrically and mechanically, up to date. This recent, third-generation upgrade addresses the modulator safety and serviceability concerns while improving the performance of the HV power supply and the modulator protection and control system.

II. UPGRADE OVERVIEW

Table 1 shows the operating parameters for the current 6575 modulator. The maximum peak and average powers are 152 MW and 120 kW, respectively. However, constraints made by the VVS power in the accelerator housing have limited the modulator operation to 120 pulses per second at 80 kW of average power.

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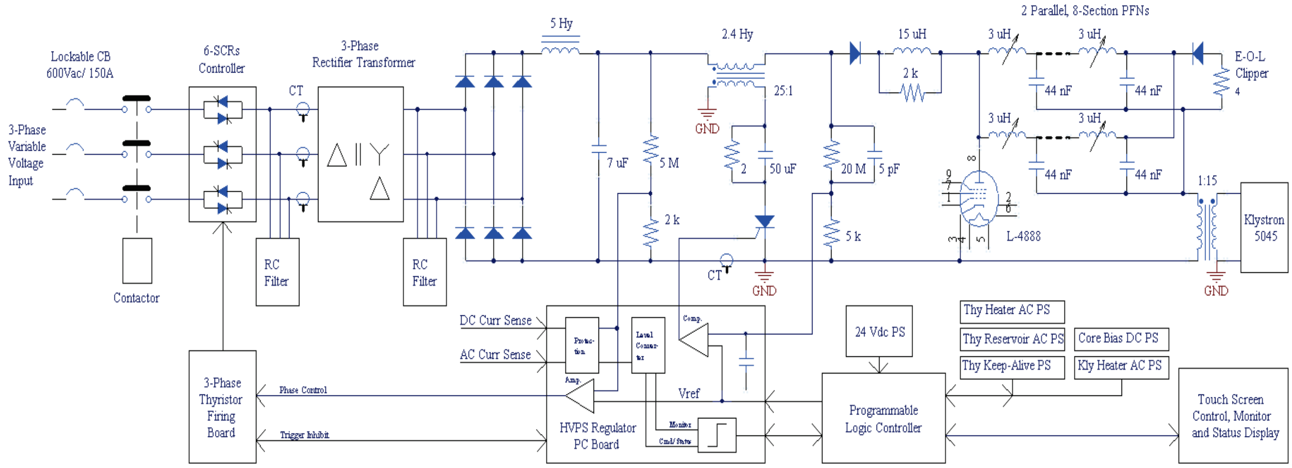

Figure 1. Simplified schematic diagram of the upgraded 6575 modulator.

Table 1. SLAC 6575 modulator specifications.

Parameter (max)	**Value**
Output voltage pulse	360 kV
Output current pulse	420 A
Pulse flattop	3.7 µS
Pulse repetition rate	180 pps
DC power supply voltage	24 kV
DC power supply average current	4.9 A
Output pulse stability	
– Short-term jitter	0.1 %
– Long-term drift	1.0 %
Time jitter	10 nS

A simplified schematic diagram of the modulator system is shown in Fig. 1. Main upgraded components include a three-phase control SCR circuitry, an integrated control and protection circuit board, a PLC, and a TFT touchscreen. Mechanical designs for operator's safety and serviceability dictated the placement of these upgraded components. They are grouped into four chassis which are consisted of the main contactor chassis, the SCR phase control chassis, the HVPS regulator chassis, and the PLC control chassis.

Each chassis was designed to be easily serviceable. All modules on each chassis are accessed from the front with the removal of the front panel. Grounding and bonding is accomplished by the mounting hardware to the modulator frame making a solid connection. Each chassis has various harness connectors to interface with each other. There are two such harnesses, one for the control circuitry and one for the AC distribution. Each plug is keyed specifically to the jack on each chassis making it difficult to accidentally insert the wrong connector into the wrong slot. By making each front panel accessible with screws, all maintenance can be done from the front and there is no need to enter the third compartment in the modulator for practically any job.

A. Main Contactor Chassis

The main contactor chassis of the modulator contains the input 600 Vac three-phase voltages into a circuit breaker and a main contactor that electrically controls the distribution of the 600 V. A plastic and metal shielded AC input section is brought in from a conduit line preventing any accidental touching or access of the 600 V when the VVS is on. This lessens the need for extra safety gear as the high voltage cannot be accessed without tools. The circuit breaker is a Cutler-Hammer type HFD3150L 150A breaker with a factory installed lockout indication to allow the control system to determine if the circuit breaker is open or closed.

The main contactor itself is the original 150A Clark Controller Co. contactor that has been rebuilt using all new springs and contacts. Due to the nature of the design with the SCRs phasing the input AC back during fault conditions and normal operation, the likelihood of wearing out the contacts is greatly reduced from the existing 6575 modulator design. The contactor has a set of contacts to indicate its open and closed status and is controlled by a key switch in the chassis and by the PLC determining the proper state to allow for the contactor to be closed.

To comply with the lock-out tag-out safety procedure for zero voltage verification, the upgraded modulator uses three Grace R-3W Voltage Vision voltage indicators. These contain LEDs that flash to indicate the presence of voltages greater than 25V on the hooked up line. The LED does not light if any one of three phases is missing. The device will also light the GND light to indicate a ground fault. This device is present for the three-phase input to the modulator, the three-phase voltage on the other side of the main circuit breaker, and for the single phase 120 Vac control power circuit. A typical main contactor chassis is shown in Fig. 2 below.

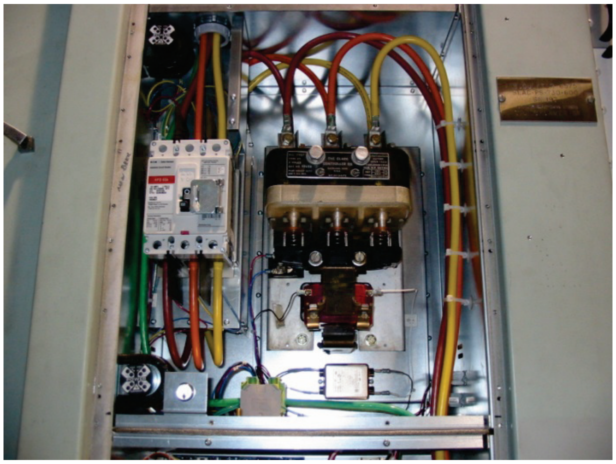

Figure 2. Main contactor chassis with the front panel removed.

B. SCR Phase Control Chassis

The 24 kVdc power supply inside the modulator is regulated via an SCR phase control assembly as shown in Fig. 3. A standard six-pulse, primary controlled in-line SCR topology was chosen for its low voltage component requirements and simple implementation. It requires no wiring reconfiguration of the rectifier transformer. The SCR and phase controller are readily available. Three, one for each phase, half-bridge thyristor modules from Semikron type SKKT 25016E were selected. Each SCR, which is rated at 1600 V and 250 A, is mounted to a heatsink and is cooled via fans. The SCRs are controlled by a general purpose, three-phase firing circuit board FCOG-6100 from Enerpro. It is configured to provide a conduction angle close to 180° for maximizing power control.

DC reference voltage source for voltage regulation is provided by a compact voltage output analog module from Allen-Bradley type 1769-OF8V. Its output voltage range is 0-10 Vdc with a resolution of 330 µV/bit, and is stable to 0.1%. The temperature drift is specified at ±86 ppm/ °C.

The precision HV divider for regulation feed-back signals uses a pair of resistors from EBG type 969.105. It is rated for 96 kVdc and 105 W with a temperature coefficient of ±100 ppm / °C. In addition, these HV resistors double as a bleeder for the 7 µF HV filter capacitor. Per standard safety requirements, the divider resistance value of 5 MΩ was chosen to bleed off a charged capacitor voltage of 24 kVdc to less than 50 Vdc in 5 minutes.

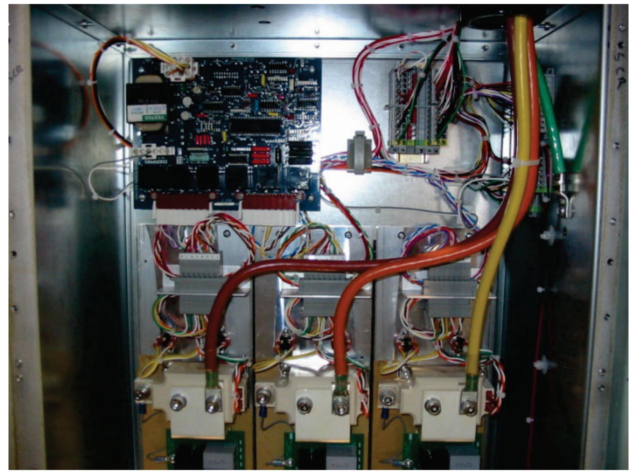

Figure 3. SCR phase control assembly.

C. HVPS Regulator Chassis

A new high voltage power supply (HVPS) regulator board was designed to facilitate all fast control signals and to interface with the PLC for the modulator's control, protection, and monitor. The printed circuit board receives 30 Vdc power from the Enerpro firing board. It supports several LED indicators for modulator diagnostics and is mounted vertically inside the chassis to provide fast access for monitoring and troubleshooting purposes. A 0-10 Vdc analog output from the PLC provides a common DC reference source to both the DC power supply and the de-Q'ing circuitry to determine the modulator output voltage. The DC reference, which is further low-pass filtered at frequencies less than 1 Hz, is compared with feed-back signals from the HV divider for "coarse" 24 kVdc voltage regulation, and from the de-Q'ing divider for "fine" regulation of the PFN charging voltage.

A current transducer from CR Magnetics Hall Effect type CR5410 is used to monitor the DC HV current. Three, one for each phase, Flex-Core 60RBT-151-1current transformer outputs are rectified and summed together to provide AC input current senses. Depending on the modulator operating condition, the regulator board provides a soft-start and two modes of phasing back, or turning off, the phase control SCRs. A soft-stop mode, where the SCRs slowly phase back, allows the HV filter capacitor to completely discharge its stored energy in normal conditions. In hard-stop mode, the SCRs are instantly inhibited from firing to protect the modulator and klystron in various over-current and over-voltage conditions.

The circuit board interfaces with the PLC through its analog and digital I/O modules. Analog signals such as HV DC voltage, HV DC current, AC input current, de-Q'ing current, and de-Q'ing voltage are conditioned and converted to DC levels for display on the touch panel. When faults such as thyratron latches, klystron arcs, and rectifier transformer breakdowns occur, the circuit board will detect and process the signals to shut off the modulator. After a few seconds have elapsed, the board automatically restarts the soft-start circuit to turn the modulator back on. A counter in the PLC keeps track of the number of these faults in an hour. When that is exceeded, the PLC opens the main contractor and intervention from an operator is required to manually reset the modulator. Status of the abnormal condition is then reported to the PLC through one of the digital input channels and will eventually display on the touchscreen. In addition, a trigger on/off interlocking feature is implemented. The regulator board detects the presence of the modulator trigger and will immediately turn on the HV power supply. This allows the soft-start circuit to kick in to limit AC in-rush current when the modulator is started, and prevents unnecessary large energy storage inside the modulator when HV pulse outputs are not required. Figure 4 shows the regulator printed circuit board and its assembly.

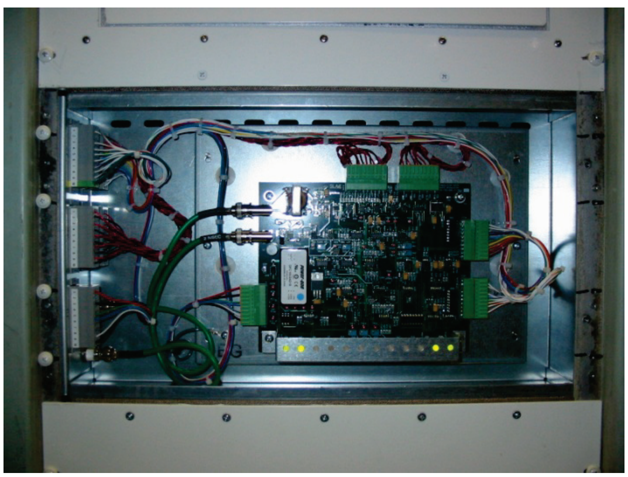

Figure 4. Installed HVPS regulator chassis.

D. PLC Control Chassis

The PLC chassis contains the control circuitry of the modulator. Two SOLA 24V, 10A type SDN10-24-100P power supplies are used. One powers the PLC alone and the other powers the remaining 24 Vdc used throughout the rest of the modulator. The PLC itself uses an 8-channel analog output module, two 8-channel analog input modules, a 32-channel digital input module, and a 32-channel digital output module. It interfaces the rest of the modulator and the control lines by driving an interface board which contains numerous reed relays to switch on and off the various items of the modulator internals. The PLC chassis also contains all of the auxiliary power supplies for the modulator in an easy to remove and install form.

The new control scheme is designed using an Allen-Bradley CompactLogix type 1769-L35E Programmable Logic Controller. This PLC was chosen for its reputable manufacturer support, compatibility with the experimental physic and industrial control system (EPICS), programming expertise at SLAC, and relatively low cost. The PLC centralizes the monitoring and controls and provides a platform to easily accommodate future changes from the current modulator-klystron support unit (MKSU) control system. An IDEC type HG3F touch panel provides a user interface for local control, status and diagnostics of the modulator. This model was chosen primarily because of its low cost compared to Allen-Bradley equivalents. While it incurred NRE costs, it only needed to be designed once and is only deployed in production.

The original 6575 state machine implemented with relay logic is replicated in the ladder logic program of the PLC such that the functionality of the modulator remains mostly unchanged. However, additions and modifications are necessary to accommodate the new HV regulator and performance improvements. Discrete and analog interlocks are monitored to ensure the modulator operates safely to protect itself, the klystron, and personnel. Given the appropriate commands and condition of interlocks, the PLC controls the operation of the modulator and its sub systems. It interfaces with the MKSU control system using a limited set of discrete signals for status and control, while providing a second Ethernet interface to EPICS with practically limitless monitoring and control capabilities. While most discrete signals were converted to industry standard 24 Vdc, there are some legacy signals at -24 Vdc and 120 Vac. Interface relays provided the necessary level shifting from 24 Vdc to -24 Vdc and 120 Vac. All AC and DC analog signals are converted to either 0-5 Vdc or 0-10 Vdc using transducers.

Auxiliary power sources for the pulse-transformer core bias, thyratron reservoir, thyratron heater, and klystron heater utilize off-the-shelf SCR-based AC controllers from Eurotherm type TE10A. These units accept a 0-10 Vdc control signal that is readily available from the PLC. The PLC also monitors the output of the AC controllers for interlocking and to employ a feed-back loop, which is provided by either CR Magnetics CR4510 voltage transducer or CR4110 current transducer, for voltage or current regulation. The modulator's original core bias DC supply is duplicated in a modern function while re-using the original transformer and line inductor. Modern electrolytic and film capacitors replace the vintage components. A 120 V, 90 A diode rectifier package from Crydom type F1892CCD400 is used in place of the original discrete diodes because they were prone to failure. A CR Magnetics Hall Effect current transducer is used to regulate the output of the bias supply.

The 10.4 inch TFT touchscreen panel provides local monitor, status and control for modulator tuning and maintenance, taking the place of a large panel of meters, indicators, switches and knobs. A typical modulator main control display is shown in Fig. 5.

Figure 6 shows a photograph of the complete upgraded modulator.

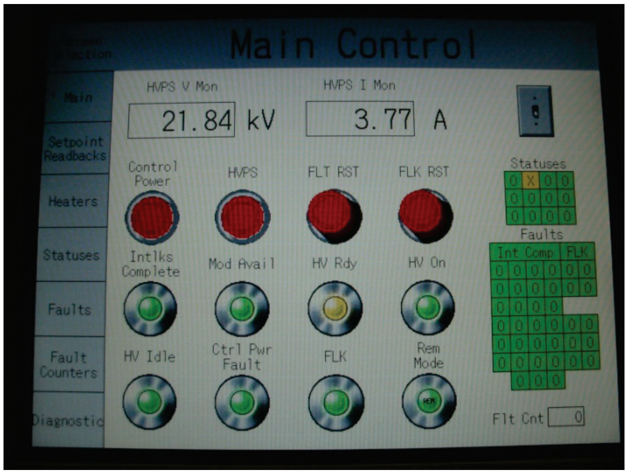

Figure 5. Screenshot of one of the panels on the 10.4 inch TFT touchscreen.

Figure 6. Overall view of the upgraded modulator.

III. PERFORMANCE TESTS

Each upgraded modulator is functionally tested in various operating conditions. The modulator voltage is individually adjusted and is able to provide full power output at 350 kV to the klystron while safely protecting itself under abnormal conditions. Both short-term and long-term klystron beam voltage (BV) stability are measured to meet the requirement.

In order to accurately measure the modulator output voltage jitter in the parts per million (PPM) level, SLAC has developed a pulse stability measure device [3]. This level-shifting device can provide an offset voltage of up to ±80 Vdc, and is used in conjunction with the statistics function of the Tektronix DPO 4054 oscilloscope to directly measure the BV jitter from a HV capacitor divider inside the klystron tank.

For a set number of samples per second, the RMS BV stability is calculated as the ratio of the standard deviation of the zoomed-in flattop over the total BV pulse amplitude. Figure 7 shows a typical short-term BV jitter waveforms. The RMS stability over a period of 5 seconds is calculated as follows

BV Stability =

= 7.14 m / 62.4 = 0.114 m

= 114 PPM

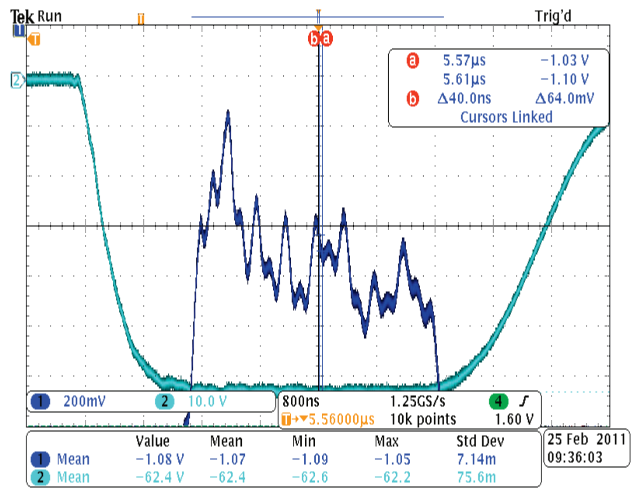

Figure 7. Short-term klystron BV stability measurement. Cyan trace is the pulse amplitude. Blue trace is the zoomed-in flattop.

A typical klystron beam voltage plot as recorded by the SLAC control program over a period of 24 hours is shown in Fig. 8. The long-term BV stability is well within the modulator specification.

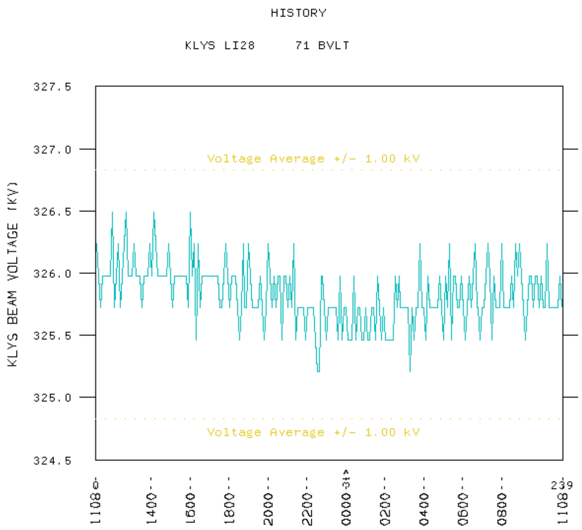

Figure 8. Typical plot of klystron beam voltage drift of 0.3% over a period of 24 hrs.

IV. CONCLUSION

SLAC is currently under going a project to upgrade the third compartment of all eighty 6575 modulators in the accelerator housing for the Linac Coherent Light Source. Fifteen modulators have been successfully upgraded as of this writing. The newly modified modulator has enhanced operation safety for the operator as well as improvement of the modulator performance and serviceability.

V. ACKNOWLEDGEMENTS

The authors would like to thank P. Seward, P. Stiles, J. Olszewski, J. Craft, and L. Fernandez for their contributions to the mechanical design, component layout, and construction of the new chassis. We would also like to thank R. Cassel for providing valuable comments and suggestions.

VI. REFERENCES

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