RF TECHNICAL NOTE

THE UVC SCR CATHODE VOLTAGE REGULATION SYSTEM
Circuit Analysis and Troubleshooting Techniques

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1. Introduction

The Universal Voltronics (UVC) power supply is a high voltage dc power supply capable of continuously adjustable voltage-regulated output from ~ 2kV to 95kV, at a maximum output current of 20A. Due to the high voltages and power levels involved, methodical attention to detail and a thorough understanding of the design and operating theory of the power supply is required to be effective in finding faults and implementing repairs without causing further damage or stepping outside of personnel safety envelopes. This technical note highlights the basic theory behind the design of the UVC cathode power supply, and basic steps involved in system troubleshooting.

2. UVC Power Supply Cathode Voltage Regulation System Topology

A block diagram of the UVC cathode voltage power supply is shown in Figure 1. Due to the high power output requirement, primary power for the cathode voltage power supply is derived directly from the 13.2kV ac line, with an input current of approximately 120A per phase at full output (95kV@20A). The 13.2kV input voltage is immediately stepped down to 1400V by a 2.5MVA matching transformer and then applied to the input of a three-phase full-wave silicon controlled rectifier (SCR) variable phase angle voltage control. The variable output of the SCR control is applied to the primary winding of the transformer-rectifier (T-R) set, which steps up the primary voltage and provides rectification and filtering to develop the continuously-variable dc output up to 95kV. The output of the T-R set is applied across an ignitron crowbar column which is designed to reduce the output of the power supply to less than 100v within 5-8µs in response to a fault condition.

Voltage regulation of the cathode voltage output is achieved by sampling the rectified output voltage from the T-R set and comparing that value to an operator-selected output voltage setpoint. Based on the amplitude relationship between these two signals, an analog voltage regulation loop commands the SCR phase angle voltage control to adjust its output in whichever way is necessary to make until the output voltage and setpoint equal, within a small error band.

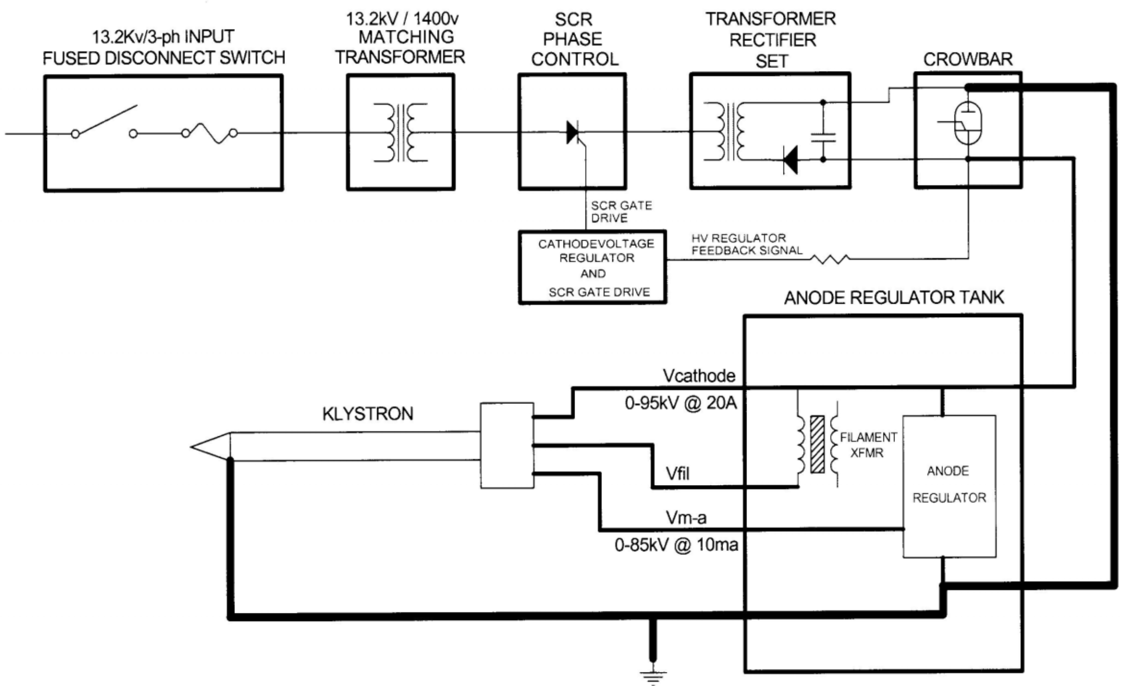


Figure 1: Block diagram of UVC cathode voltage power supply.

Figure 2 shows a schematic of the UVC power supply SCR cabinet, indicating the position of the three full-wave SCR stacks in the 1400V power flow. The SCR stacks are located immediately after the series combination of fast-acting fuses (F601, F602, and F603) and the main 1400V contactor 601A-B-C.

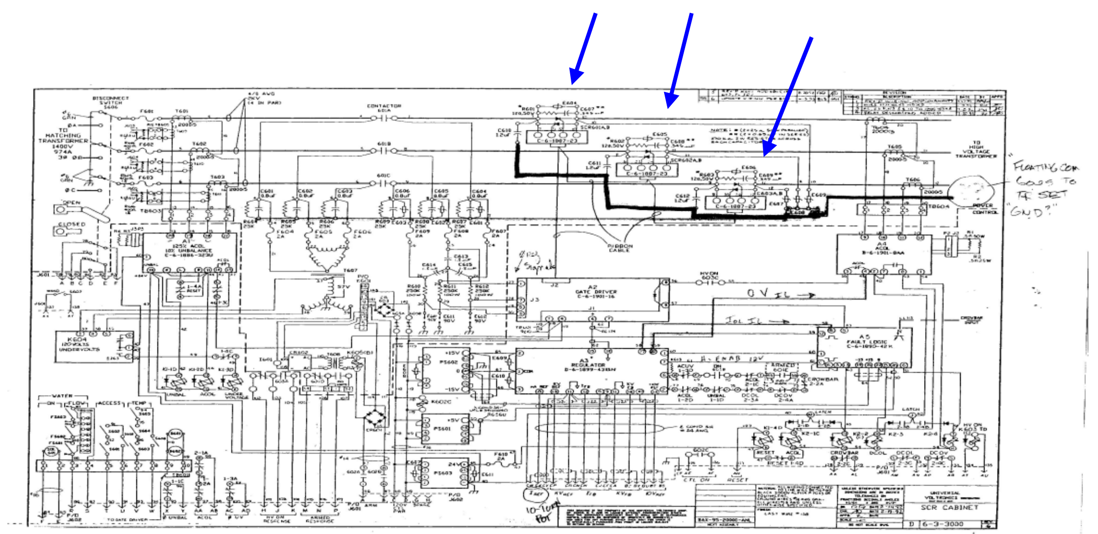


Figure 2: Location of the full-wave SCR stacks in the
UVC 1400-volt primary power circuit.

3. Basic Silicon Controlled Rectifier Theory

A silicon controlled rectifier (SCR, or “thyristor”) is a three-terminal device that acts as a gate-controlled switch with diode characteristics. The schematic symbol for an SCR is shown in Figure 3 below.

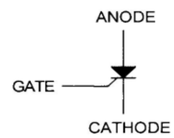


Figure 3: Schematic symbol of an SCR.

A two-transistor equivalent circuit of the SCR is shown in Figure 4. Essentially, the SCR acts as a very fast dc switch with the application of gate current, and will latch in the conducting state until forward bias conditions cease. This behavior is the foundation of several unique characteristics that make the SCR particularly useful in 60-Hz ac power control:

a) It will not conduct until a gate signal is present, even if forward bias voltage is applied.

b) The turn-on time of an SCR is very fast (rise time in microseconds) with the application of gate current, thereby limiting dissipation in the off-on transition.

c) Once in the conducting state, the gate looses control and the SCR will remain in conduction until the current through the device falls below the “holding current” value (typically the next zero-crossing in ac applications).

A graphical presentation of SCR characteristics is shown in Figure 5.

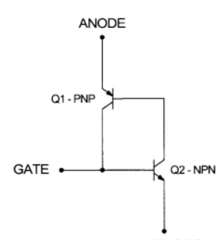


Figure 4: The two-transistor equivalent circuit of an SCR.

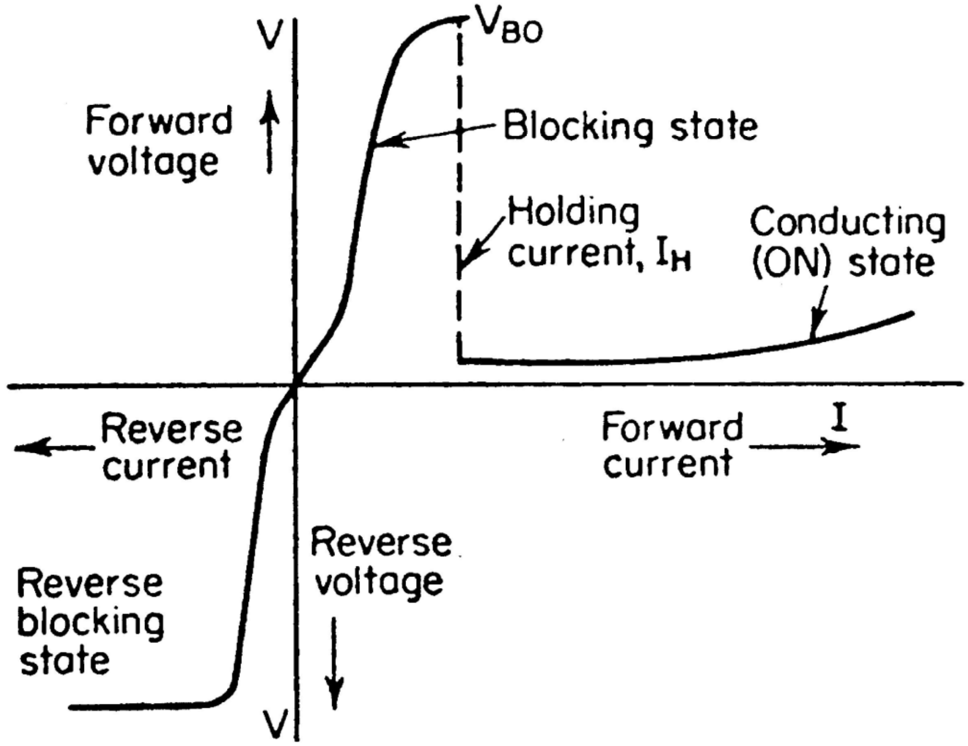
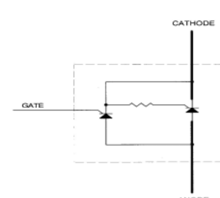


Figure 5: Typical voltage-current characteristic curve for an SCR. (Image from "Standard Handbook for Electrical Engineers", Tenth Edition, Fink & Carroll, McGraw-Hill.)

From the graph in Figure 5, if the forward current through an SCR is above the minimum "holding current" value, the SCR will act as a rectifier diode and continue to conduct until the forward voltage drops to the point that the forward current falls below the "holding current" value. At that point, if no gate current is present, the SCR will turn off and remain in the off-state until gate current is re-applied.

The power handling capability of SCR devices varies from a few hundred milliwatts to megawatt-level applications like the UVC power supply. Very high power SCR devices typically consist of the equivalent of two internal SCR's, as shown in Figure 6, where a smaller "pilot" SCR provides gate current to a much larger SCR that conducts the heavy load current. Such a device is referred to as an "amplified gate" SCR.

Figure 6: Schematic representation of the amplified gate SCR.



4. Application of SCR Control in the UVC Cathode Power Supply

A photo of the UVC SCR cabinet interior, highlighting the location of the main 1400V contactor, 1400V line fuses, and the three SCR stacks, is shown in Figure 7. For cooling, the SCR devices are press-fit into water cooled aluminum heat sinks that are supplied water by the clear hose water lines seen entering and exiting the cabinet on the right-side rear wall.

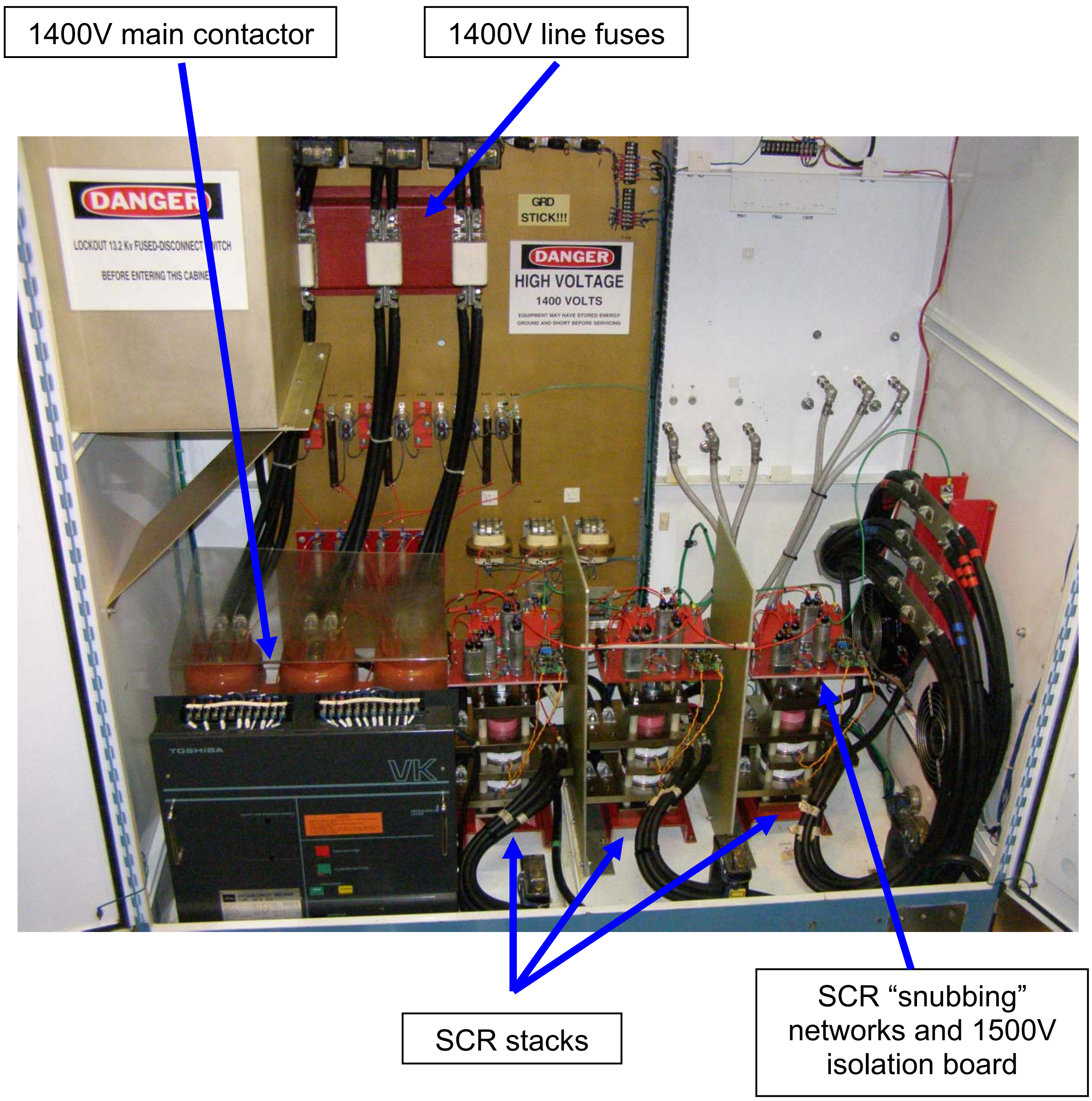


Figure 7: Photo of UVC SCR cabinet interior.

The SCR's are arranged in parallel to provide full-wave control of the applied ac power. The series-parallel combination of an r-c network and a metal oxide varistor (MOV) is placed in parallel with the SCR's (see Figure 8) to limit potentially damaging voltage spikes that are generated due to the rapid changes in current in the load inductance during turn-on and turn-off.

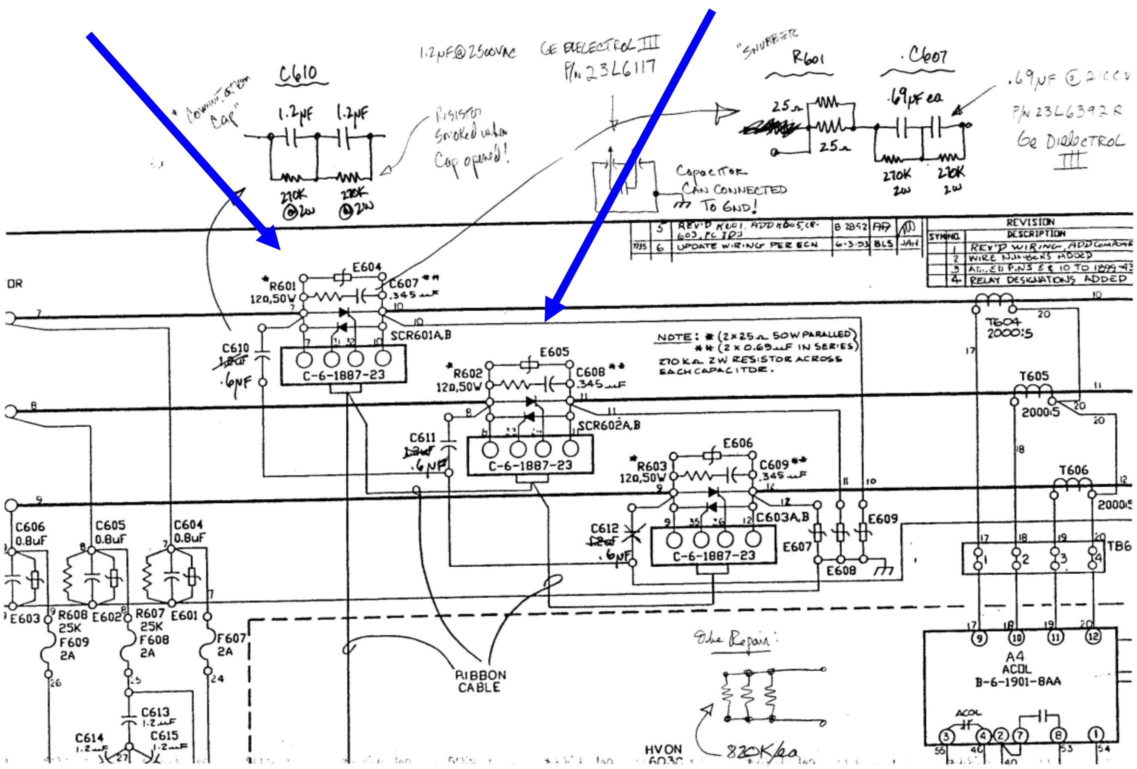
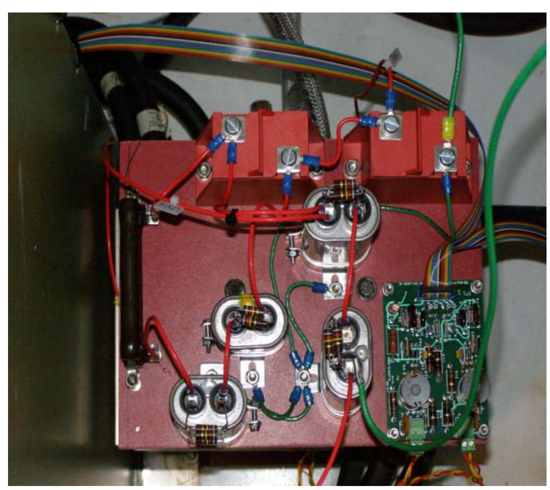


Figure 8: Details of SCR "snubber" circuits.

Figure 9: Photo of SCR snubber network and 1500V isolator board.



Gate signals to provide turn-on commands to the SCR's are generated by sampling the voltage on each phase of the incoming 1400V power utilizing resistive voltage dividers on each phase to limit the voltage to approximately 30V p-p, and forming a phantom neutral with three capacitors (see Figure 10). The three sample signals are then fed to the input of the A2 gate driver card, where they are signal-conditioned and compared to a phase-back command dc input voltage (see Figure 11).

The A2 gate driver card utilizes back-to-back 5V zener diodes to clip the incoming 30V p-p sample signals and produce a +5/-5V square wave, which is then applied to the inputs of comparators U1a-b, U2a-b, and U3a-b to generate a 10ms linear ramp waveform. These linear ramp waveforms and the phase-back command input dc signal are then fed to the inputs of U1c-d, U2c-d, and U3c-d. These comparators generate variable-width positive-going square waves for each phase (120º phase displacement), which vary in width coinciding with the point in time when the ramp voltage at each comparator is greater than the phase-back command input dc value. The A2 gate drive card also utilizes U12d as an oscillator to generate 10µs pulse at approximately 80µs intervals (~12.5 kHz), which are amplified by FET Q9 and sent out to drive the SCR gates. The 12.5 kHz oscillator pulses are used to chop the variable-width square-wave outputs of the gate driver card to limit the SCR gate dissipation.

The three variable-duration gate drive outputs and the 12.5 kHz oscillator output from the gate driver card are sent to the inputs of the 1500-volt isolator boards located on the top of each SCR stack on a paralleled ribbon cable. Referring to the schematic of the 1500-volt isolator board shown in Figure 12, the correct gate drive signal (A, B, or C-phase) is selected from the ribbon cable connector by a hard-wire ("A-B-C") jumper soldered in place on the board. This signal is then applied to the gate of two IGFET switches (Q3 and Q4), each of which drives the primary winding of a 1500-volt isolation transformer used to electrically-isolate the low-voltage gate driver circuitry from the 1400-volt primary power potential applied to the SCR's. The secondary winding of the isolation transformer drives the gate terminal of each SCR directly. The 12.5 kHz oscillator signal from the gate driver card is also applied to the 1500 isolation board input from the paralleled ribbon cable, and is used to drive two bipolar transistor switches that force each gate pulse driver transistor (Q3 and Q4) into cutoff at a 12.5 kHz rate, resulting in an variable-duration SCR gate drive signal that is composed of a series of 10µs-wide pulses separate by 80µs.

Cathode voltage regulation control is achieved by linear operational amplifiers on the A3 regulator card (see Figure 14), utilizing voltage follower U1a, amplifier U1b, and an error amplifier consisting of U1c and U1d. A dc setpoint voltage generated by the UVC operator controls is summed with an output voltage read-back signal, forming an error voltage that is then amplified by the error amplifier, buffered, and then sent to the gate driver card to control the SCR gate pulse width. This signal, referred to as “trigger drive” on the A3 regulator card schematic (Figure 14), is the same signal referred to as “phase back command” on the A2 gate driver card schematic (Figure 11) that was discussed in the previous paragraph. It is a dc voltage typically in the range of +4v to +7v, which varies inversely proportional to the cathode voltage output, resulting in a widening of the SCR conduction angle when the cathode voltage is commanded to increase. Figure 15 is a photograph of the SCR Control Cabinet, showing the locations of the A2 gate driver card and the A3 regulator card.

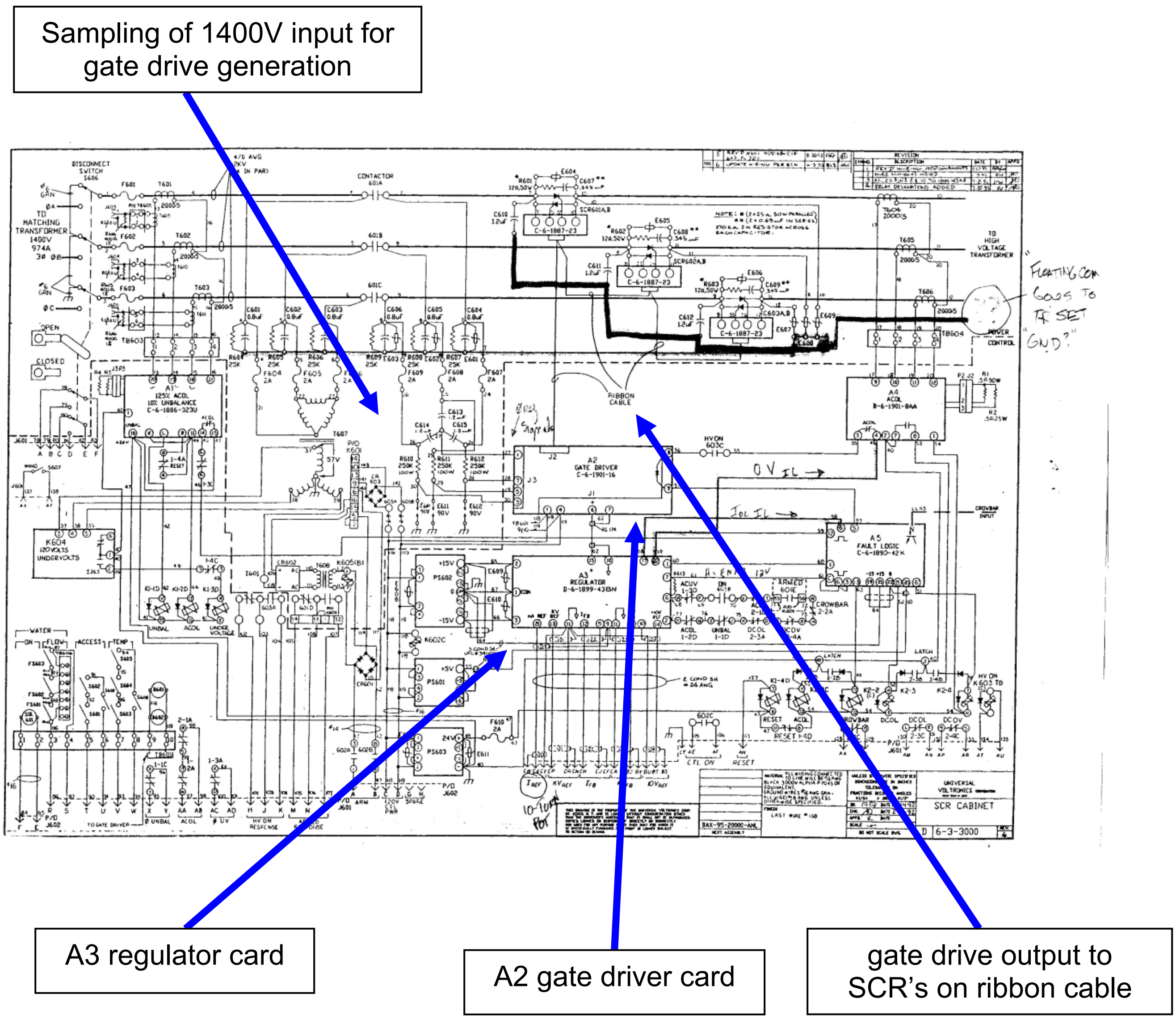


Figure 10: Source of SCR gate drive signals.

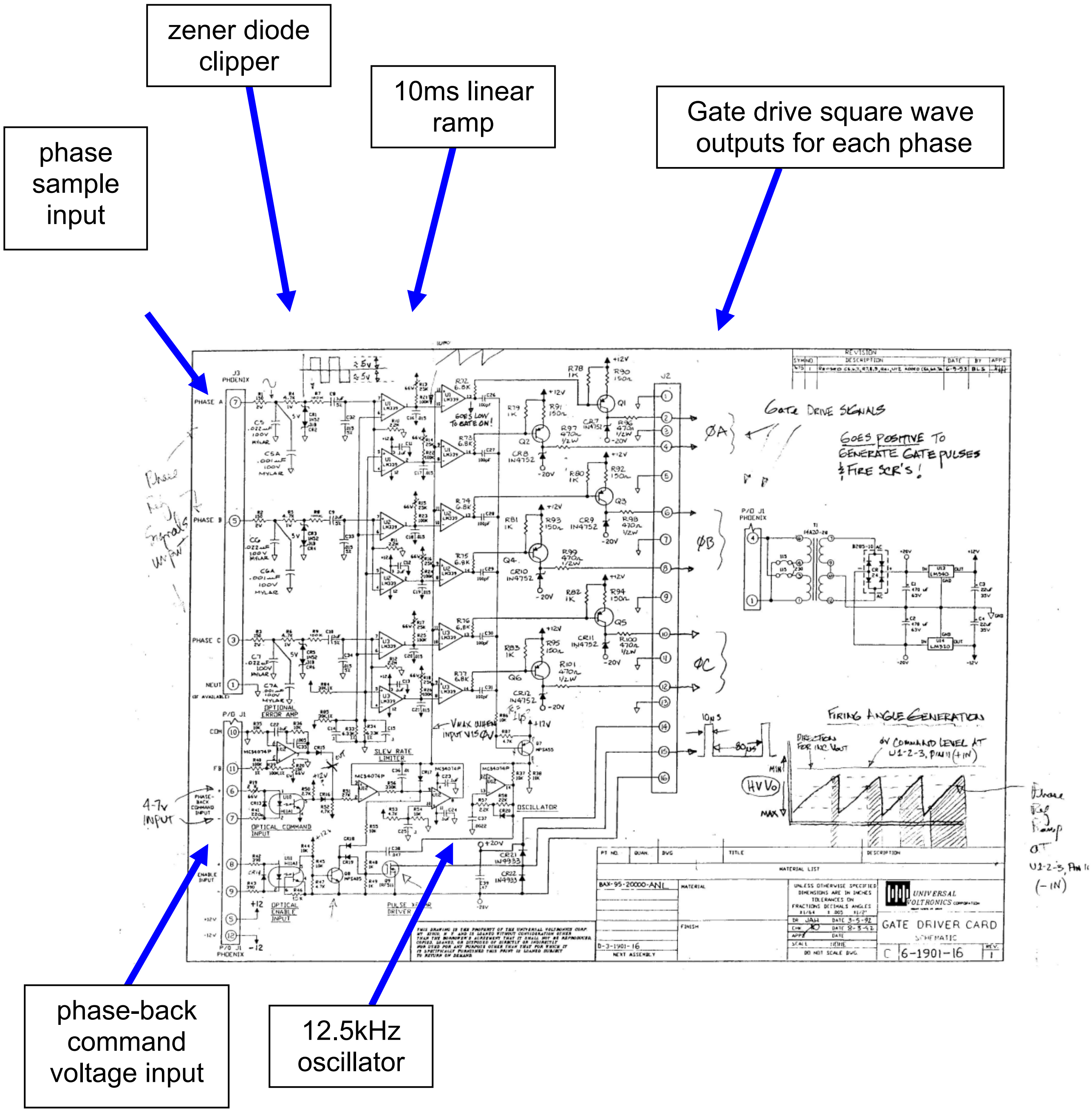


Figure 11: Functional details of the A2 gate driver card.

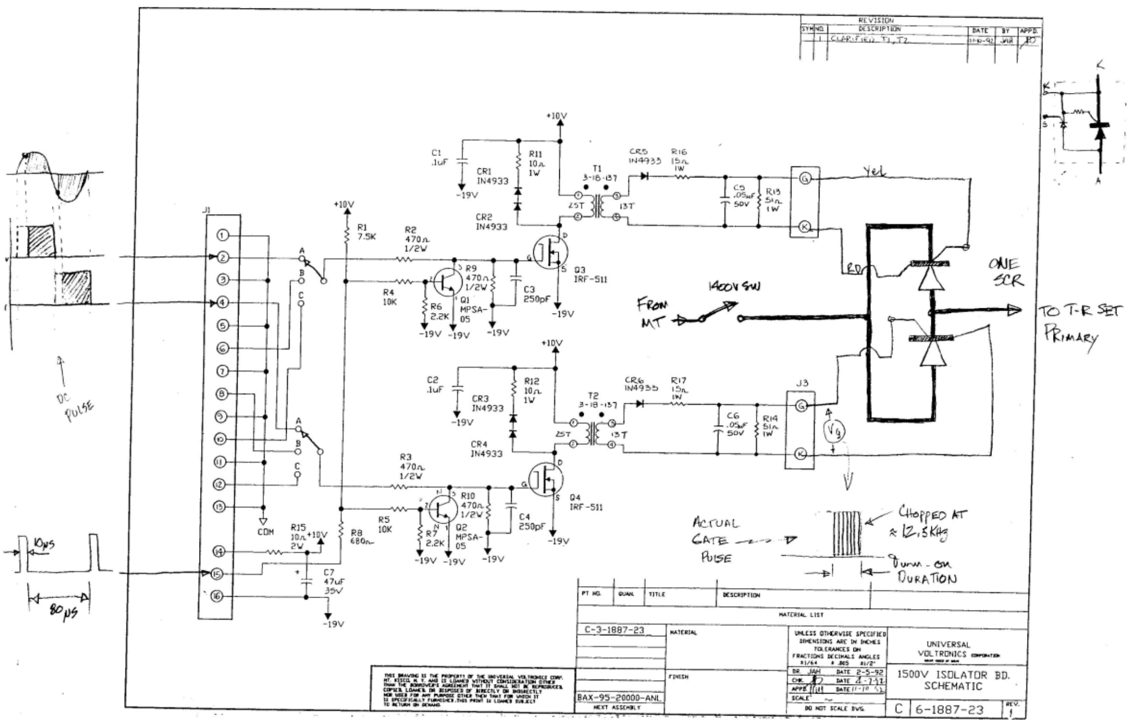


Figure 12: Schematic of the 1500-volt isolator board.

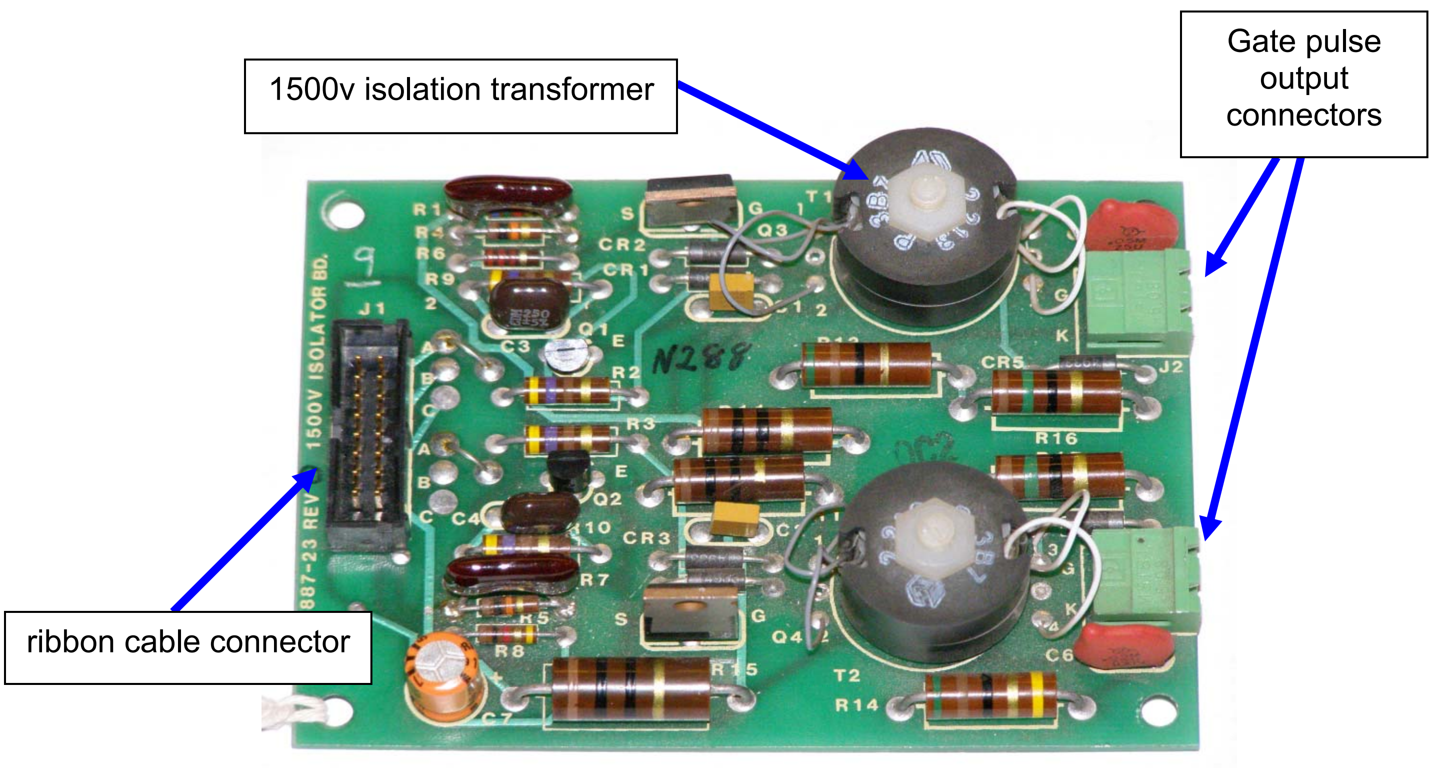


Figure 13: Photo of the 1500-volt isolator board.

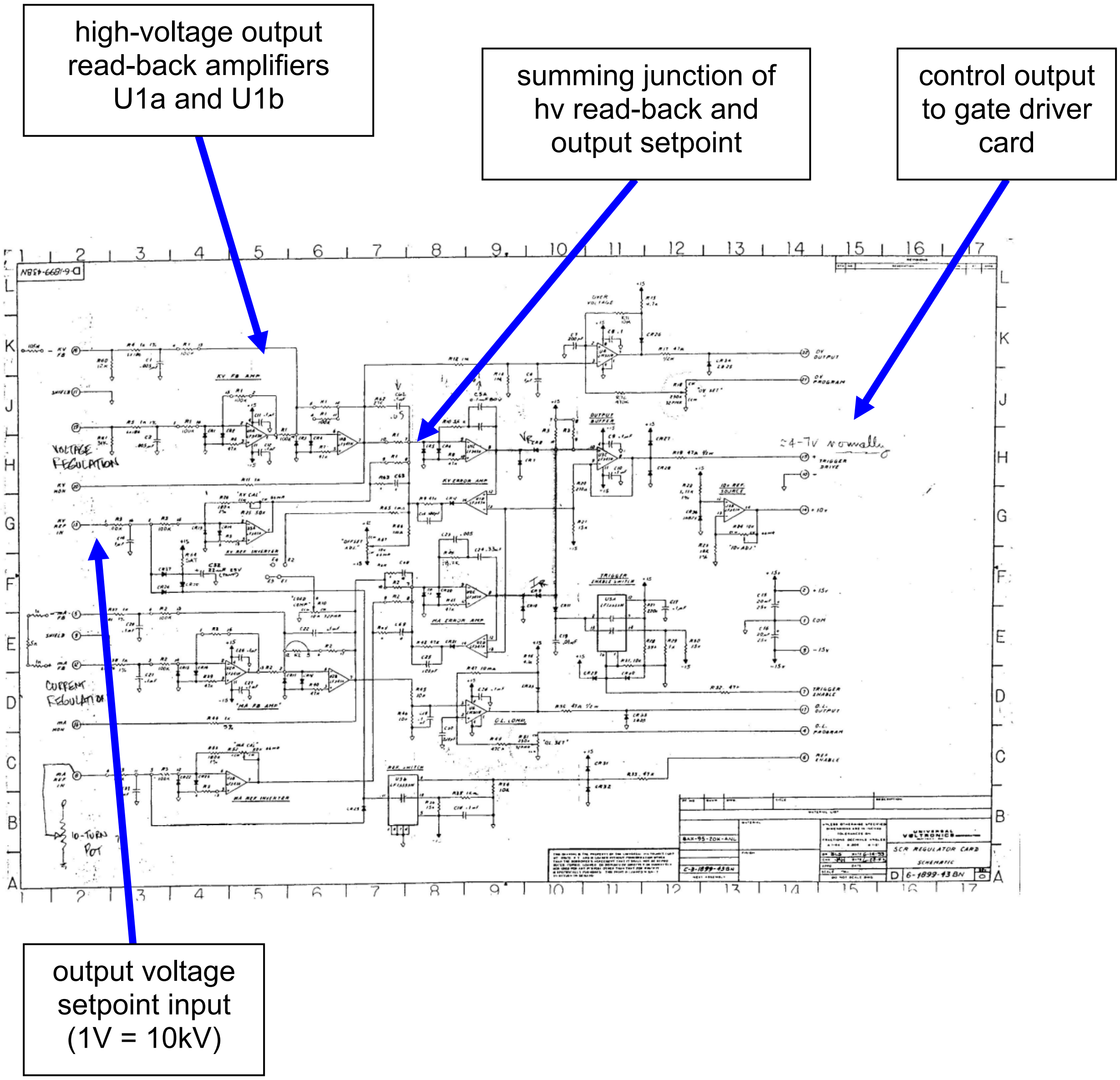


Figure 14: Functional detail of the A3 regulator card.

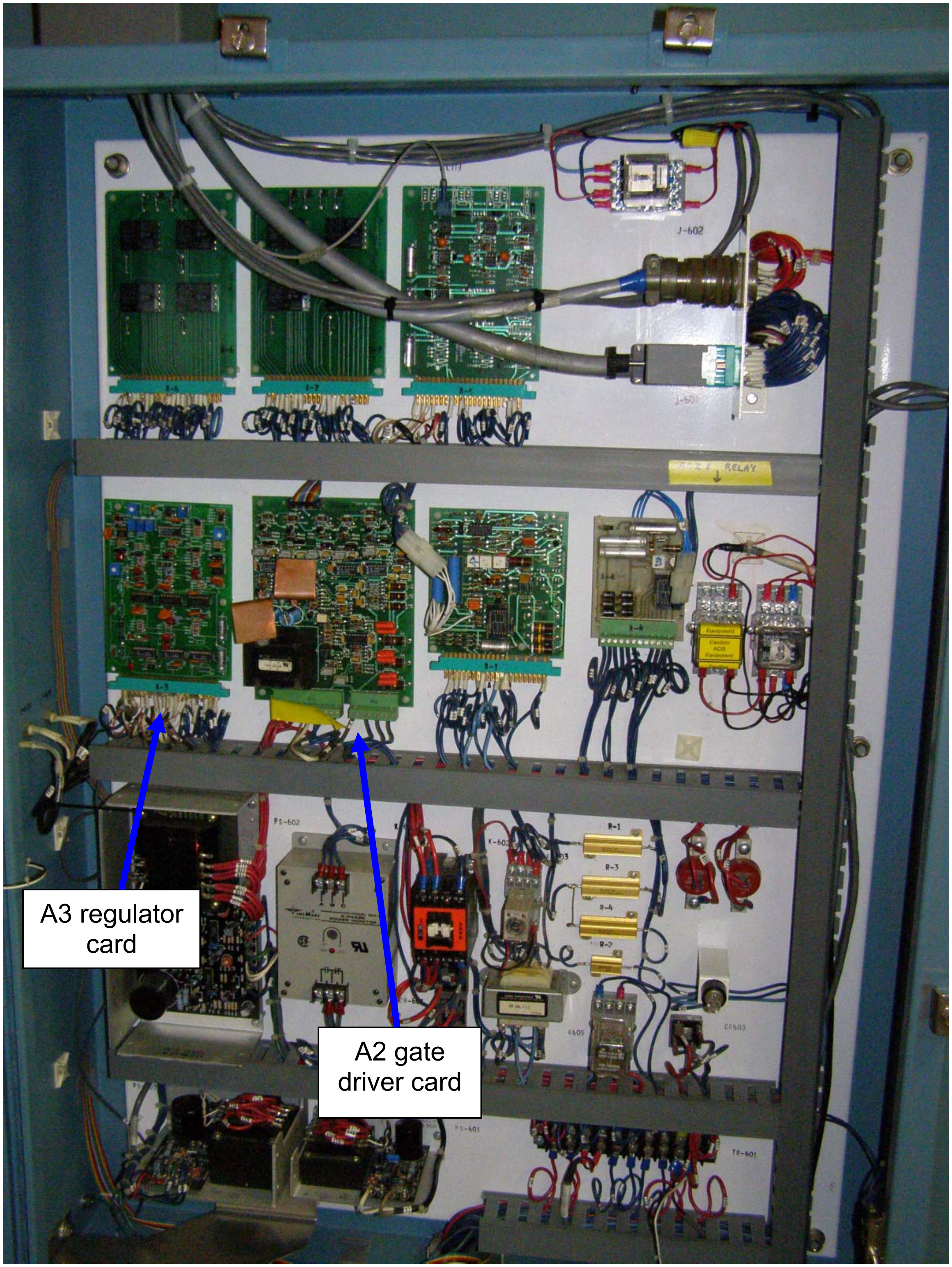


Figure 15: Interior view of the SCR Control Cabinet.

5. Troubleshooting the UVC Cathode Voltage Regulation System

Due to the high voltages and power levels involved, special attention must be paid to troubleshooting methods and practices when working with the UVC power systems. Component failures or un-intended faults at the 1400-volt level will result in significant equipment damage, and, as was demonstrated during three previous failures involving the UVC SCR cabinet at APS, an elevated risk to personnel in the immediate vicinity of the SCR cabinet.

Figure #16 shows photographs of the first UVC SCR cabinet failure, which occurred on July 6th, 1994. The root cause of the damage was traced to the failure of a capacitor on the left-side SCR stack (note the oil on the capacitors). When the capacitor initially failed, wires connected to it were blown off of their terminals and caused 1400-volt phase-to-phase and phase-to-ground faults. These short-circuit conditions resulted in significant arcing, plus destruction of two SCR stacks, all six 1400-volt fuses, and the gate driver cards. Hardware costs to recover from this event totaled approximately $25k. The arc blast from the 1400-volt faults also caused the SCR cabinet doors to fly open, which destroyed the keyed-interlock latch hardware on the doors. Subsequent analysis of this failure resulted in the addition of cable reinforcements on the cabinet doors to prevent them from flying open during an electrical fault, and installation of G-10 insulating barriers between the SCR stacks to reduce the possibility for 1400-volt short circuits caused by loose wiring.

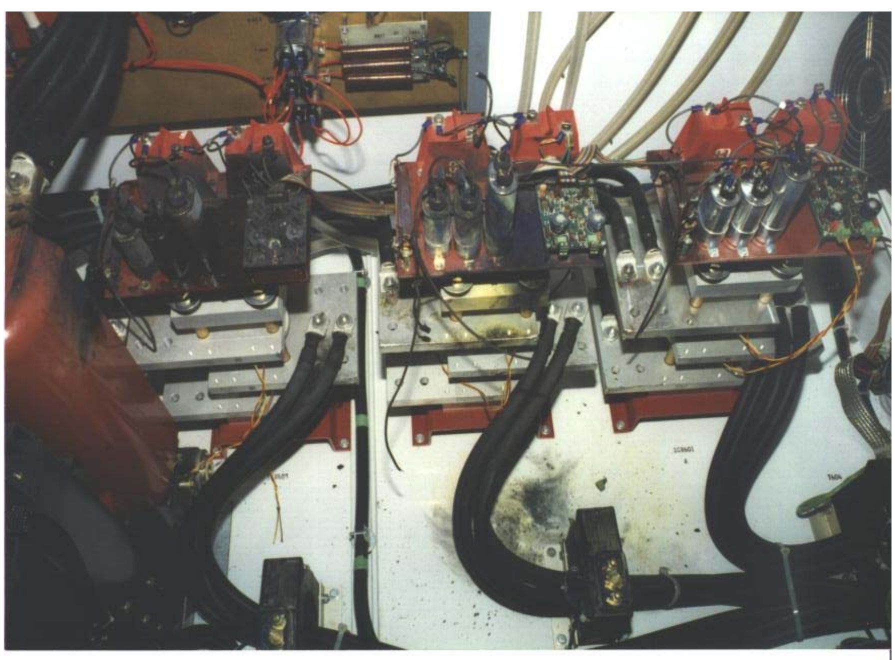


Figure 16: UVC SCR cabinet failure on July 6th, 1994.

Figure 17 is a photograph of the second UVC SCR cabinet failure, which occurred on September 6th, 1996. This failure was caused by energizing the 1400-volt contactor with the SCR cabinet grounding stick hanging on one 1400-volt phase. Equipment damage from this event included blown 1400-volt and 13.2kV fuses, plus destroyed cabinet hardware and wiring. The security cables prevented the cabinet doors from opening totally during the fault, but they were forced open enough to allow the release of arc blast overpressure gases.

Figure 17: UVC SCR cabinet failure on September 6th, 1996.

The most recent SCR cabinet failure occurred on July 17th, 2007. Figure 18 shows photos of the damage that resulted from the event. The root cause of the failure was traced to the failure of a snubbing capacitor on the center SCR stack, which again resulted in flying wires and 1400-volt level faults between phases, and between phase and cabinet ground.

From the analysis of the previous SCR cabinet failures, it is best to assume that any electrical fault at the 1400-volt level inside the SCR cabinet will be a violent event, resulting in physical damage that is easy to see. Any system malfunction that results in blown fuses at the 1400-volt or 13.2kV level calls for a mandatory power-off (LOTO) and cabinet inspection to inspect for damage and shorted components. The fast-acting fuses used as system protection devices are not fast enough to component damage under fault (shorted) conditions.

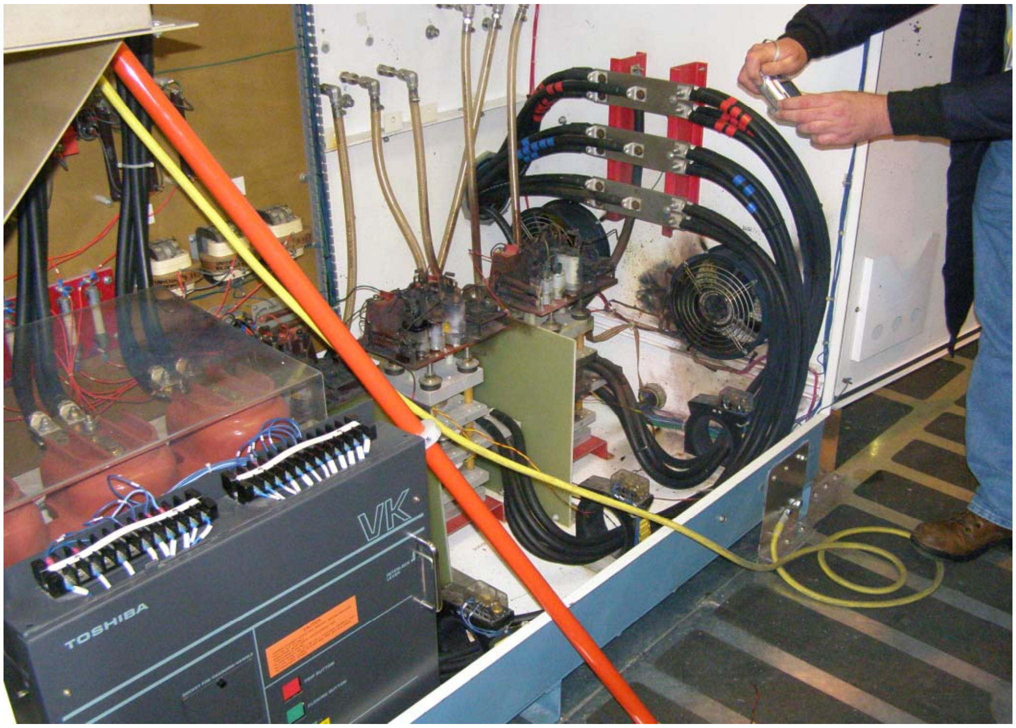


Figure 18a: UVC SCR cabinet failure on July 17th, 2007.

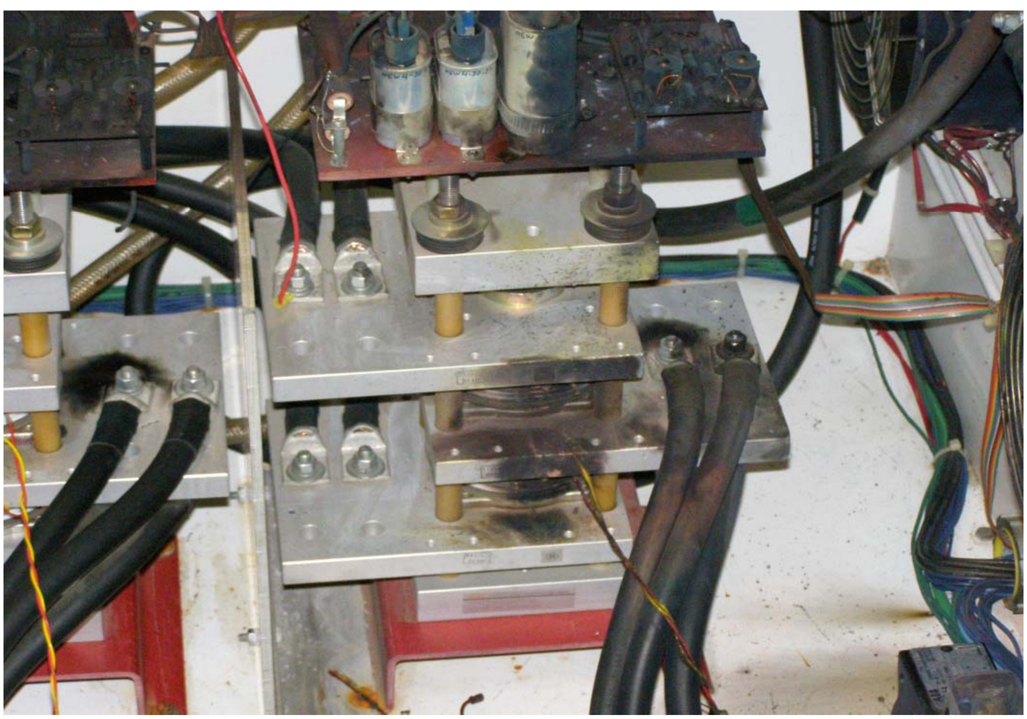


Figure 18b: UVC SCR cabinet failure on July 17th, 2007.

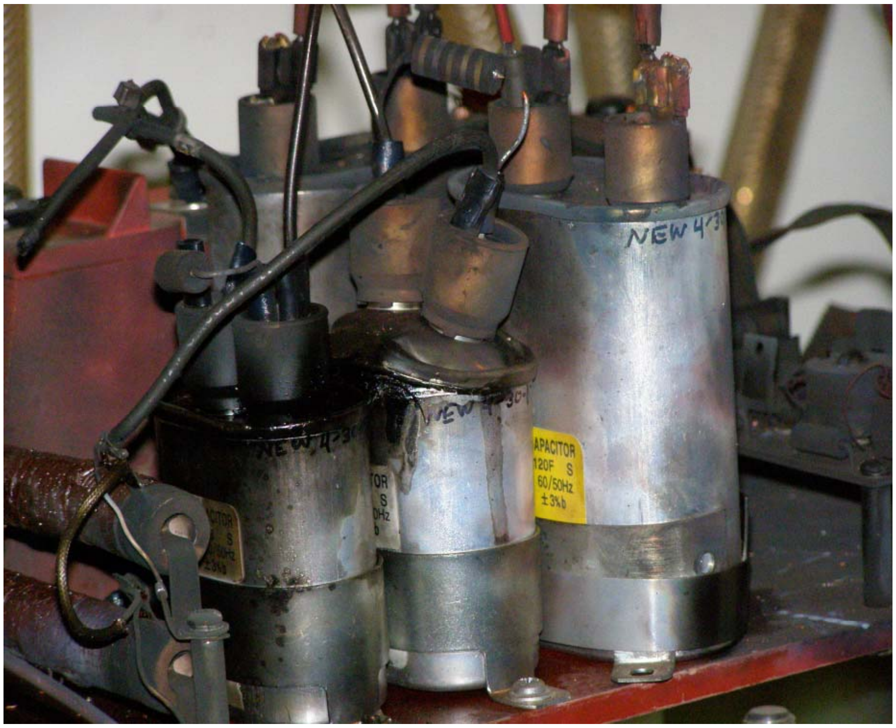


Figure 18c: Failed snubbing capacitor that caused the UVC SCR cabinet damage on July 17th, 2007. Note the ruptured capacitor case.

As with any complex electrical system, an adequate understanding of the design and operation of the UVC SCR cathode power supply regulation system is a basic requirement for effective and safe troubleshooting. The technical personnel performing such work must be familiar with the system design and operating fundamentals, be able follow schematic diagrams of the system down to component level in a logical troubleshooting flow, and to correctly interpret the symptoms of malfunction in order to determine the root cause of operating problems. The following sections of this technical note include some general troubleshooting tips that I have learned in over 30 years of component-level troubleshooting, plus some concepts that are specific to the UVC system.

5.1 <u>General Recommendations for Successful Troubleshooting</u>

a) Create a detailed work plan for the job.

→ *Include hazard analysis and control information in the plan.*

→ *Have the work plan reviewed by other experienced staff members.*

→ *Review the work plan with all personnel involved in the work.*

b) Understand how the system or equipment operates when functioning properly.

→ *Some knowledge of "normal" system or equipment operation is necessary to effectively diagnose subtle performance problems.*

c) Create large-format copies of accurate system schematics where notes can be made to clarify understanding of the system, and to record test and measurement data as troubleshooting progresses.

→ *This cannot be over-emphasized………it is one of the most effective measures to insure successful troubleshooting. Nothing beats pencil and paper!*

→ *The best way to maintain progress if a crew change is necessary during the troubleshooting/repair process.*

→ *Use big paper, not 8.5" x 11"*

→ *Be prepared!…………make a set of working drawings now so that you are ready for the next time they are needed.*

d) Refresh your understanding of the design and operation of the system, at both the board and component levels.

→ *If you are working as part of a crew, take time to go over the system drawings with everyone involved in order to bring all crew members to the same level of understanding.*

→ *Every person involved in the work can be a source of insight and ideas that will help find the problem, but only if they understand how the system functions.*

c) Avoid the "shotgun" repair approach of replacing multiple boards and/or system sub-assemblies at one time.

→ *"Shotgunning" risks injecting multiple un-related problems into the system, which will only complicate symptoms and delay or prevent progress.*

→ *Replace one board or sub-assembly at a time! If it doesn't fix the problem, put the original part back in and move on to the next logical component or step.*

d) Take detailed notes of test and measurement data and important findings so that you and others can keep track of progress.

→ *Make frequent descriptive entries into the system maintenance logbook.*

→ *Avoid "changed A2 card"-type entries………..take the time to write useful information detailed enough to be valuable in the future. Concise and clear log entries can save someone (possibly yourself) a lot of time if a similar problem arises at a later date.*

→ *Start and maintain your own notebooks!*

e) If time permits, take a break if you are stuck and cannot find the problem.

→ *Any experienced troubleshooter knows that thought patterns can fall into a rut and hide the obvious from view.*

→ *Take a break and clear your mind…………more often than not, when you return you will find the problem in very short order.*

f) Resist influences by outsiders or authority figures to "hurry up" the troubleshooting and repair process.

→ *Even subtle pressure to complete the job can cloud your judgment and disrupt thought patterns, which can lead to mistakes that risk equipment and personnel safety.*

→ *Follow your instincts and sharpen your "sixth sense" for impending disaster..............if your gut feeling tells you things are going too fast or too many shortcuts are being taken, stop the work and take the time to think about the situation.*

g) Minimize unnecessary distractions and interference in the work area.

→ *Poor housekeeping in the work area causes unnecessary distraction which can lead to mistakes and accidents.*

→ *Remove any non-essential material and equipment from the work area.*

→ *Keep non-essential personnel out of the immediate work area.*

5.1 <u>UVC Symptom: No Cathode Voltage Output</u>.

a) Output voltage setpoint cannot be entered.

- Is UVC control computer interface accepting setpoint value?

b) Output voltage setpoint can be entered, but there is no output voltage.

- Is setpoint voltage present at setpoint input of A3 regulator card?

  → *Measure directly at input of A3 card with a voltmeter or scope.*

- Is the A3 regulator card generating a trigger drive signal?

  → *Measure directly at input of A3 card with a voltmeter or scope.*

5.2 <u>UVC Symptom: No Cathode Voltage Control</u>.

a) Setpoint has no control of output voltage; dc output stays at zero, or goes to maximum and fires crowbar on over-voltage fault.

- **DC output stays at zero (less than ~ 2kV)**

→ *Check for gate pulses at output of A2 Gate driver card.*

• DC output goes to maximum (greater than 95kV)

→ *Verify that the feedback voltage from output high-voltage divider is present at the input of the A3 regulator card.*

→ *Verify that the trigger drive signal generated by the A3 regulator card is not railed positive due to a component failure.*

5.3 Symptom: Unstable Cathode Voltage

a) Poor voltage regulation under loaded conditions.

• Is the dynamic range of the regulator being restricted?

→ *Verify that all +/- linear power supplies have correct output voltage.*

→ *Monitor dc voltages on A3 regulator card and A2 Gate Driver card at various output voltage settings to detect non-linear behavior due to component failure.*

b) Excessive 60Hz-related ripple in dc output.

→ *Verify that all +/- linear power supplies have clean dc output voltage.*

→ *Monitor analog signals on A3 regulator card at various output voltage settings to detect signs of oscillation or motorboating.*

c) SCR "searching", resulting in phase current imbalance.

→ *Monitor analog signals on A3 regulator card for instabilities (ac component superimposed on dc operating point).*

→ *Check linearity of ramp generator signals on the A2 Gate Driver card.*

5.4 Signal Analysis on the A3 Regulator Card

Analysis of critical signals on the A3 Regulator Card will require a dc voltmeter and an oscilloscope. The A3 Regulator Card is located in the SCR control cabinet (see Figure 15), which contains exposed electrical conductors at voltages up to 208VAC.

When working inside the UVC SCR Control Cabinet with the UVC control power energized, you must follow all energized test and measurement safety rules, including the use of proper PPE for the work involved. PPE requirements for this work are listed on the APS Energized Electrical Test & Measurement Authorization # ASD/RF007. Only RF Group Personnel who have signed the form as authorized workers may perform this work.

Utilize the clear plastic barriers provided to cover the exposed 120/208VAC terminals.

Critical voltages and signals on the A3 Regulator Card are indicated in Figure 14.

It is important to keep in mind that signals on this board will appear "normal" only if the power supply is on and functioning properly. When the cathode supply is off, the voltage and current feedback loops are essentially open. Under these conditions, control voltages will be at levels consistent with a command for full output in a UVC system with no faults.

5.5 Signal Analysis on the A2 Gate Driver Card

Analysis of critical signals on the A2 Gate Driver Card will require a dc voltmeter and oscilloscope. Again, the A2 card is located inside the SCR Control Cabinet (see Figure 15), which means the rules and PPE requirements specified in the **APS Energized Electrical Test & Measurement Authorization # ASD/RF003** must be followed. Refer to section 5.5 for complete details.

Under normal operation, generation of SCR gate drive signals is inhibited unless the 1400-volt contactor is in the closed position. If test and measurement work is being done in the absence of 13.2kV input power (no 1400VAC input to the SCR Cabinet), several interlocks must be bypassed in order to allow the 1400-volt contactor to close:

1) Bypass the Phase Unbalance Circuit: SCR Card A1, jumper pins 15 and 16.

2) Open the SCR Phase Unbalance reset circuit: SCR Card A1, pin “R”.

3) Bypass the SCR Three-Phase Monitor: SCR Monitor Card, jumper pins 1 and 2.

Critical waveforms on the A2 Gate Driver Card are shown in Figure 19. Note that the waveforms shown were observed under a cathode-voltage-off condition, and with a function generator supplying a simulated 1400-volt sine wave reference signal to the “phase A” input to the card. Under these conditions, the voltage regulation loop is open, and the gate drive signals from the card are full-width (calling for maximum output) due to the open-loop condition.

Note also that the A2 Gate Driver Card has it’s own +/-12V linear power supply on the card, and that the card inputs 120VAC to provide power to the linear supply transformer primary winding.

5.6 Measuring the SCR Gate Drive Signals

Measurement of the actual SCR gate drive signals requires access to the interior of the SCR cabinet with 208VAC control power applied, the SG-R3 13.2kV feed to the rf system involved opened and under LOTO, and the UVC 13.2kV fused-disconnect switch for the rf system involved opened and under LOTO. Also, the 13.2kV fuses must be removed from the rf system 13.2kV fused-disconnect switch.

Refer to the following ASD Procedures for information on UVC power supply operation and LOTO:

→ “Lockout/Tagout Procedures for the Synchrotron and Storage Ring RF Power Supplies for the Purpose of RF Power Supply Troubleshooting, Maintenance or Repair and Accelerator Access”, ASD Procedure # 3104-00032 (1110-00070) (APS_1192905)

→ “Safety Procedure for Access to the APS-RF 13.2kV Cabinets”, ASD Procedure # 3104010202-00027 (1110-00032) (APS_1194664)

→ “Universal Voltronics Klystron Power Supply Operating Procedure”, ASD Procedure # 3104010202-00026 (APS_1194661)

Force the 1400-Volt contactor to close by jumpering the required interlocks (see Section 5.5 above).

NOTE: Measurement or viewing of the SCR gate drive signals is typically only performed after a major SCR cabinet repair to verify the presence of SCR gate drive.

MEASUREMENT OR VIEWING OF THE SCR GATE DRIVE SIGNALS IS NEVER PERFORMED WITH 1400VAC POWER APPLIED!

Waveforms of the SCR gate drive signals are shown in Figure 20. Note that these waveforms were viewed using a function generator to simulate 1400VAC applied power to the input of the A2 Gate Driver Card, and under "open-loop" conditions. This will result in gate pulse widths in only two possible states, very narrow (minimum dc output voltage condition), or maximum width (full dc output voltage condition).

5.7 1400-Volt Level Failures

A component failure at the 1400-volt level in the UVC system is highly unlikely without visual or audible evidence. Almost any fault at the 1400-volt level will be easy to see.

Any failure involving blown fuses at either the 1400-volt or 13.2kV level calls for a mandatory power-off (with LOTO) cabinet inspection to inspect for damage before power is re-applied. Open and LOTO both 13.2kV fused-disconnect switches (UVC and SG-R3) before entering an SCR Cabinet when damage to the high-power circuits is suspected.

Direct voltage measurements of 1400VAC applied power are NEVER TO BE PERFORMED, UNDER ANY CIRCUMSTANCES! The personnel safety and equipment safety risks involved in the event of a mistake or metering failure are too great.

Rely on interlock and metering systems built into the UVC control system to confirm that 1400VAC power is present and correct.

→ *NOTE: Use the stepped-down signals from each 1400VAC phase at the inputs to the A2 Gate Driver Card to determine the presence of 1400VAC (see Figure 11).*

THE MAIN SCR CABINET DOORS ARE TO REMAIN CLOSED, LOCKED, AND SAFETY-CHAINED AT ALL TIMES WHEN 1400VAC POWER IS APPLIED TO THE CABINET.

Personnel should remain outside the perimeter fence whenever 1400VAC power is applied, unless work activity requires entry past the fence. Do not remain inside the perimeter fence any longer than necessary to complete work.

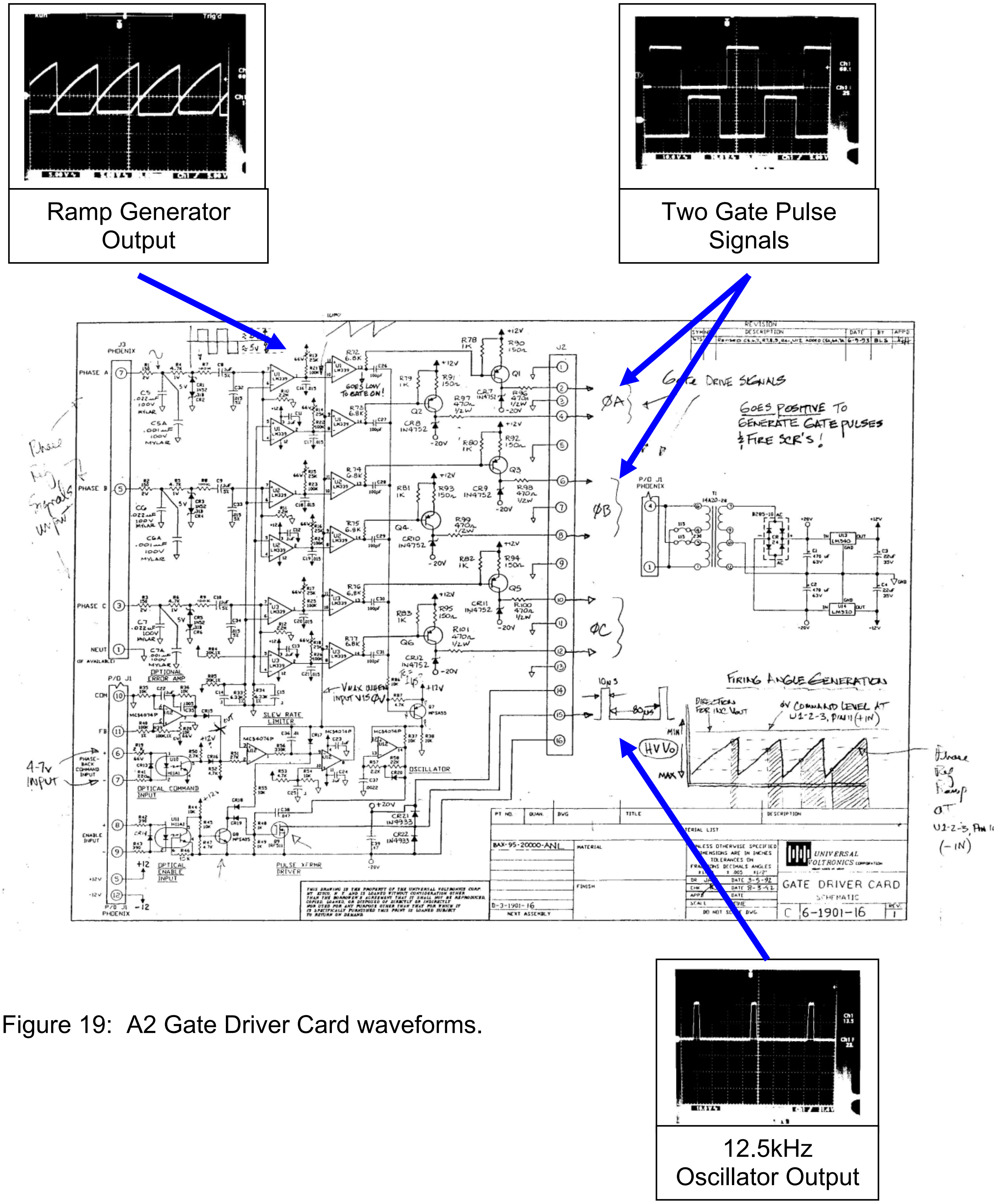


Figure 19: A2 Gate Driver Card waveforms.

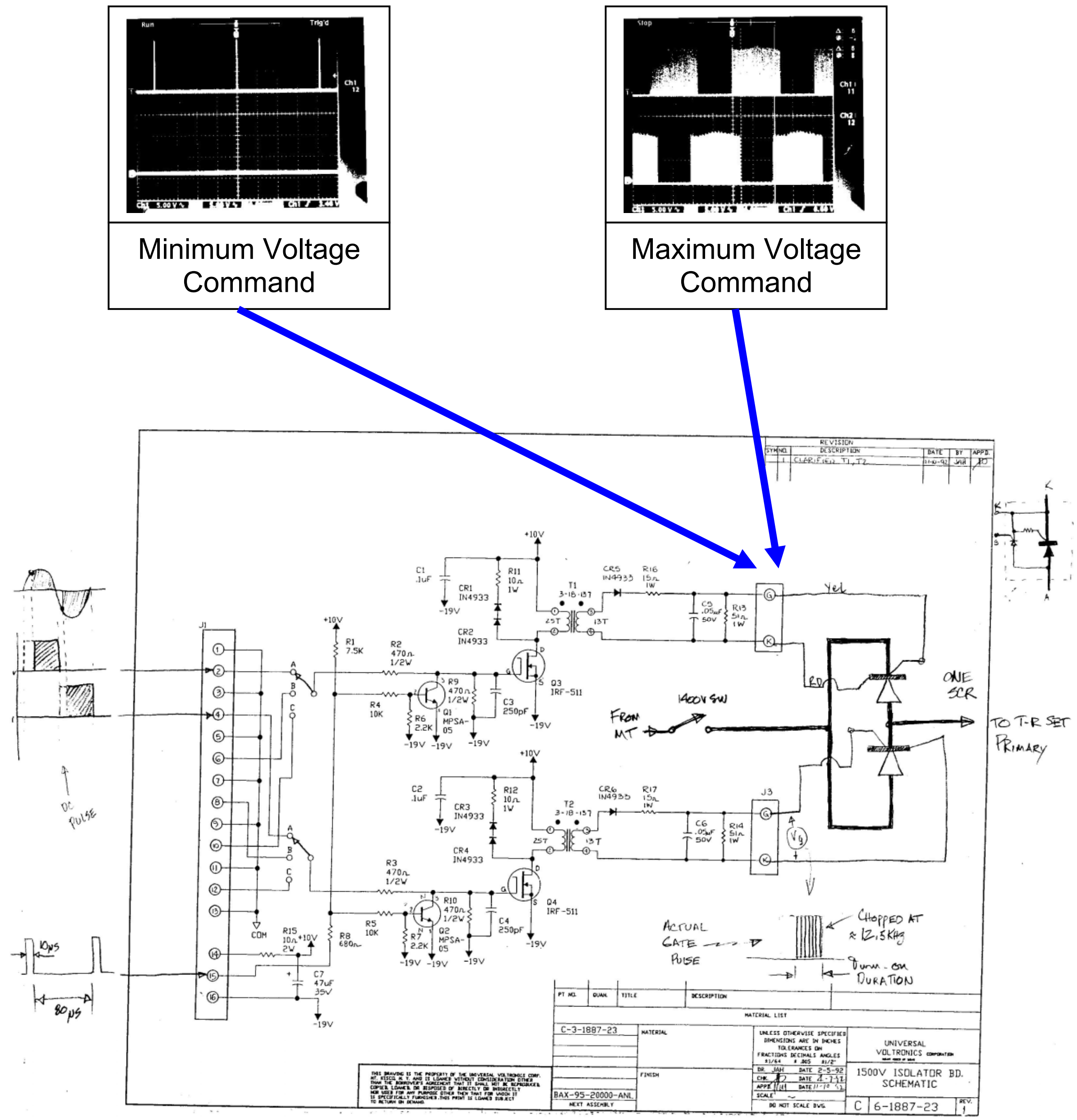


Figure #20: Gate drive signals on 1500-Volt Isolation Board.