AVO CT 160 Modifications

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The modifications described here were made on a CT160 with serial number ACW330LB.
I had purchased this VCM in 2011 from a gentleman in Eindhoven/Netherlands. Except for the original power cord socket which had been replaced by a standard IEC type and a poorly repainted case the cosmetic appearance looked acceptable. Back at home a closer inspection revealed:

- Partially burnt Grid voltage potentiometer RV2. The pot still worked but the coil body was deformed by heat and did not look very trustworthy.
- Worn out Anode current backing off potentiometer RV4. Even after disassembling, cleaning and lubricating all the wipers and contact areas with contact grease contacting remained unreliable.
- RL1 winding on protective relay and light bulb LP2 open.

I decided to repair these defects, to replace the two EB91 valves with silicon diodes and to partially rework the original circuit.

Basic Circuit and Modifications

I relied much on the circuit diagram drawn by Martin Forsberg, his elaborate explanations in the forum (http://www.vintage-radio.net/forum/showthread.php?t=58088) and other private information from him.
Fig. 1 shows the areas of modification, Fig. 2 shows the details. All additional circuits have been mounted on standard epoxy breadboard material.

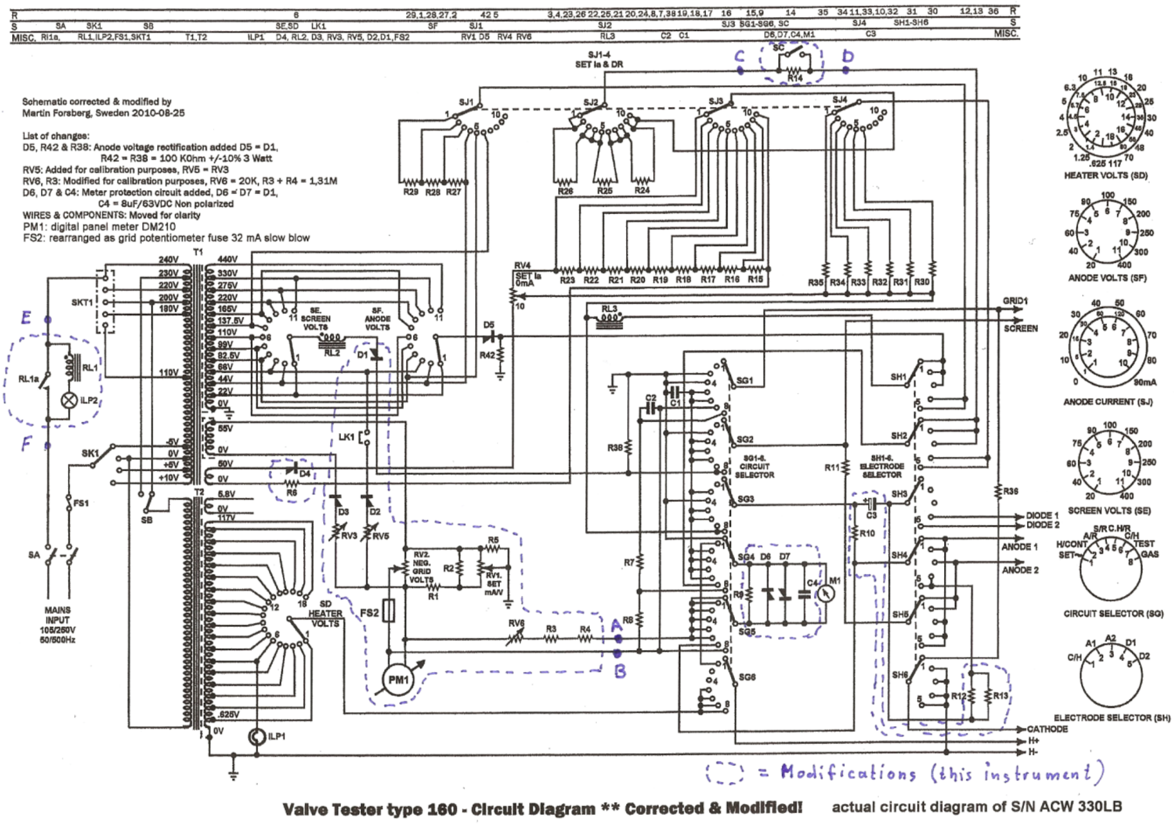


Fig. 1 – Diagram of original circuit with indicated areas of modification

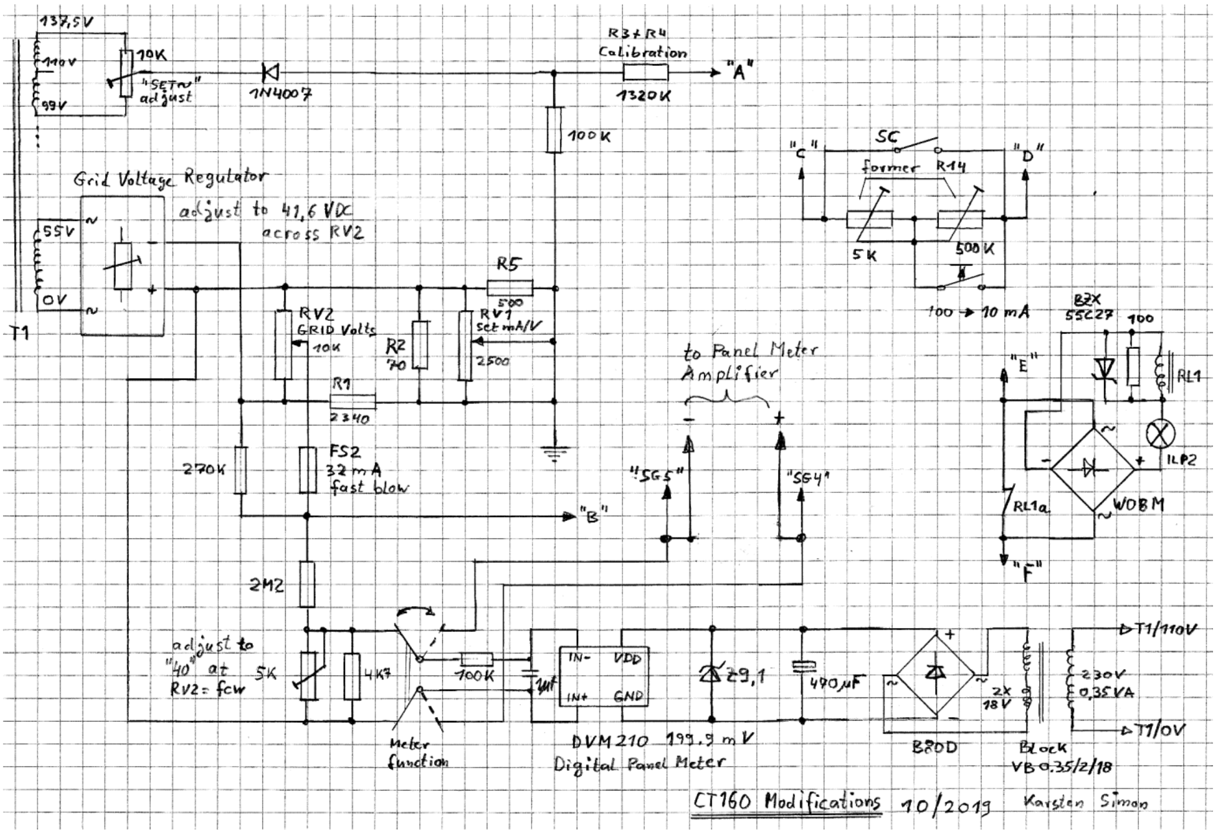


Fig. 2 – Modifications of original circuit

Replacement of Grid Voltage Potentiometer

The burnt 10 KΩ potentiometer RV2 was replaced by a vintage surplus MIL grade wire wound single turn potentiometer (Waters Mfg. Inc., Ebay) and a 3½ digit 199.9 mV digital panel meter (DVM 210, Conrad).

Grid Voltage Potentiometer Protection

For protection against destructive currents on the potentiometer wiper (caused by erroneous setting of Roller Selector switch or faulty valve with inter electrode shorts) the second front panel fuse FS2 has been rewired in series with the wiper and fitted with a 32 mA fast blow fuse. This leaves only one fuse in the mains input circuit which is still compliant with most (if not all) national electrical safety regulations.
In case the fuse blows the 270 KΩ resistor will protect the tube under test by pulling the grid potential to -41.6 V.

Regulated Grid Voltage

Regulated grid voltage makes the tester less susceptible to supply voltage variations and inaccuracy of pre use calibration. The waveform of the regulated voltage must remain sinusoidal in order to maintain the overall accuracy of the tester. The circuit described here regulates the full wave rectified mean DC with both half waves having the same amplitude. This differs from the original circuit which uses half waves with different amplitudes, the lower being used for grid control and the higher being supplied to the grid to suppress grid current during the negative anode/screen cycle. However tests have shown that different half cycle amplitudes are not necessary and equal amplitudes do suppress grid current equally well. This simplifies the regulator circuit.

Circuit description

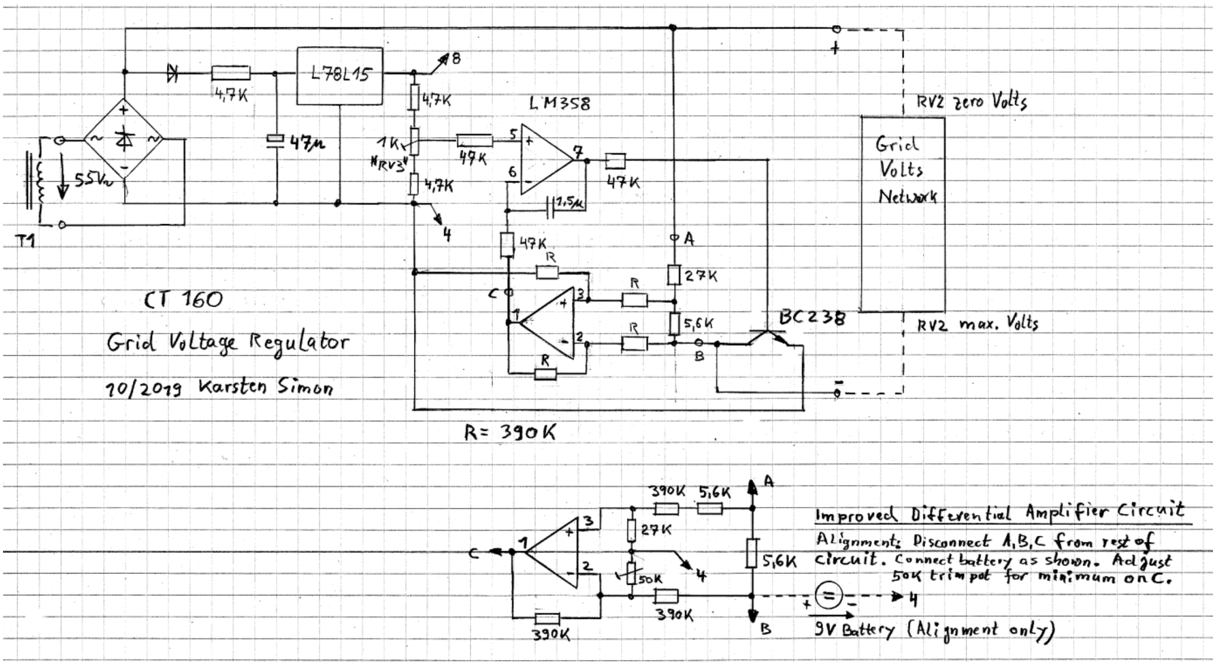
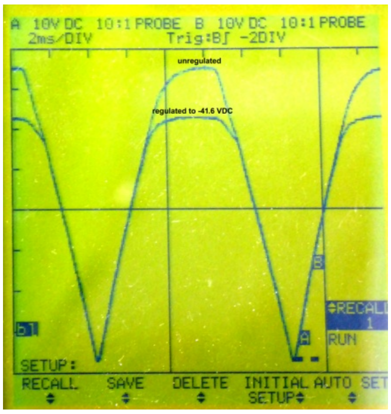


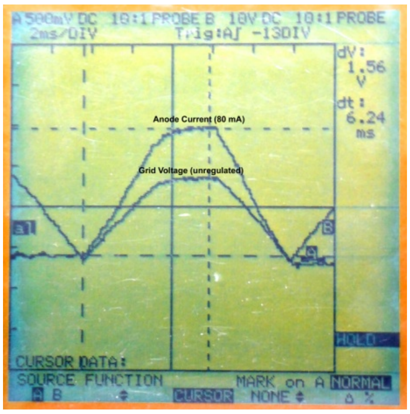
Fig. 3 – Grid Voltage Regulator Circuit

Fig. 3 shows the circuit diagram of the regulator. The 55 VAC raw grid voltage is full wave rectified and fed to the grid volts network. The diode on the input side of the 78L15 supply regulator prevents reverse discharge of the 47 μF filter capacitor. A BC 238 npn transistor acts as an actuator for the excess voltage drop. The network voltage is measured by a voltage divider and differential amplifier. An integral regulator compares the actual voltage with the DC nominal value and controls the transistor actuator accordingly. The resulting grid network voltage has the original sinusoidal shape with rounded maxima adjusted to the mean DC setpoint value (41.6 V).
The differential amplifier stage is not compensated for the varying common mode error caused by the transistor actuator because the corresponding error voltage at the amplifier output can be regarded as constant and is taken into account by adjusting the set point accordingly. Full common mode compensation can be accomplished with the improved circuit shown but has turned out to be unnecessary.

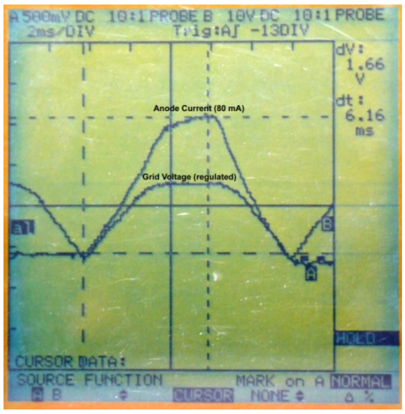
Results
Grid voltage remains constant within +- 10% mains voltage variation.
Extensive $I_a = f(U_g)$ and mutual conductance measurements with unregulated and regulated U_g were carried out with a 6L6 valve. The results showed no significant difference so AVO's 4% fudge factor (41.6 VDC for 40 V max. U_g) can be maintained.
Due to the compressed form of the grid voltage curve anode current peaks with grid voltage regulation are approx. 10% higher than without regulation (135/127 mA @ 80 mA mean anode current).
Fig. 4 are oscillograms of the U_g and I_a curve shapes without and with grid voltage regulation.



Effect of grid voltage regulation on curve shape



Anode current @ unregulated grid voltage:
peak at 1.56 V == 127 mA



Anode current @ regulated grid voltage:
peak at 1.66 V == 135 mA

Fig. 4 – Grid Voltage Regulator Oscillograms

Measurement of Grid Voltage

Grid voltage is measured with a DVM 210 +-199.9 mV digital panel meter. A voltage divider is adjusted to display the 41.6 V maximum mean DC grid voltage as "40.0" [mV]. A 100 ms low pass filter (100 KΩ / 1 µF) stabilizes the reading. The DVM 210 requires isolated 9 VDC which is supplied by a small separate transformer.
The input can be toggled between grid voltage and voltage to the analogue instrument. This is particularly convenient when nulling out anode current because the DVM 210 can display negative values with a "-" sign.

Calibration Voltage

The half wave rectified negative calibration voltage is taken from the 99 V and 137.5 V taps of T1 via a 10 KΩ trimpot. This circuit is similar to the one in the CT160A. At nominal mains voltage (use a Variac) the trimpot is adjusted to the SET ~ mark (= 90% f.s.) on the analogue meter = "90.0" on the digital panel meter.

Replacement of Backing Off Potentiometer

The worn out wire wound 90 Ω potentiometer was replaced by a military grade type with 100 Ω nominal resistance. A 1 kΩ parallel trimpot is adjusted to align its setting with the markings on the panel.

Anode Current Shunt

Anode current is measured as the voltage drop across a 200 ohm shunt resistor. This shunt increases the internal resistance of the C.T. 160 anode circuit which can cause noticeable error when measuring mutual conductance of valves with low dynamic resistance ΔUa/ΔIa.
The shunt resistance and anode circuit internal resistance can be greatly reduced by replacing the 200 ohm shunt with e.g. 4.7 ohm followed by an op amp with v=200/4.7=42.5. The output voltage swing of this circuit must go up to >24 V in order to measure the 120 mA maximum in rectifier mode correctly.

Circuit description

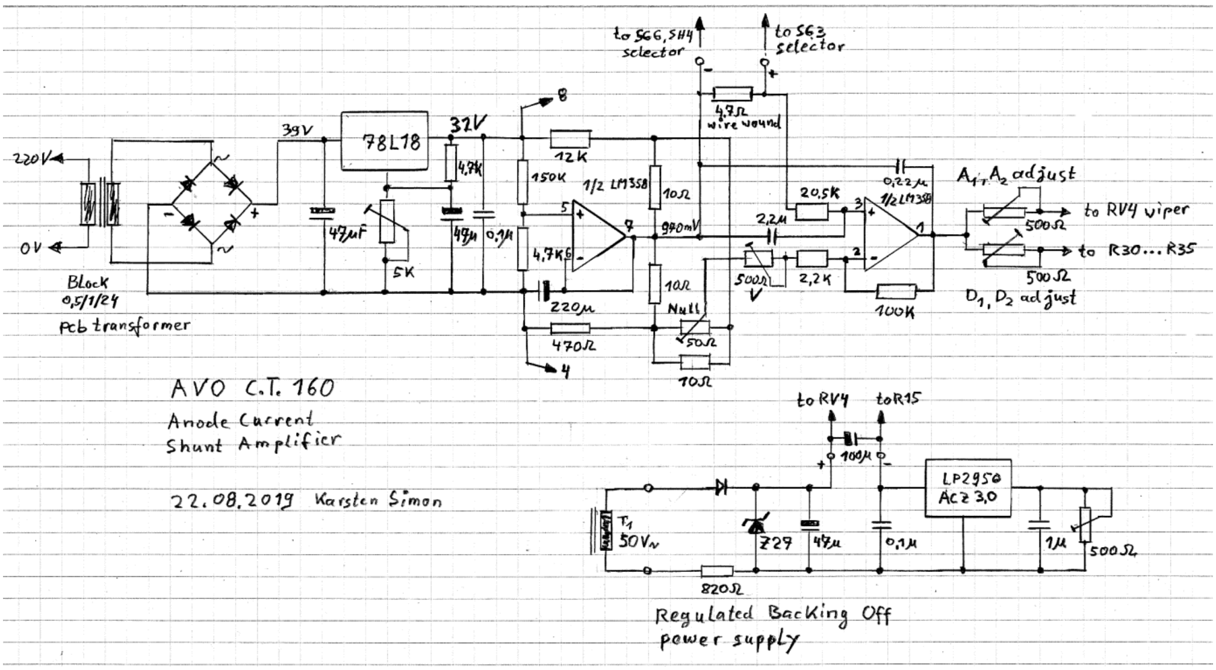


Fig. 5 – Anode Current Shunt Amplifier Circuit

Fig. 5 shows the circuit diagram. The circuit operates from a 31 V isolated supply and uses a standard LM358 dual op amp. Virtual ground is at 970 mV. At this level the amplifier output has sufficient current sinking capability. Max. output voltage is >28 volts above virtual ground, limiting measurable current to approx. 130 mA. This is sufficient as the overcurrent relay will trip at slightly above 120 mA.

The 20.5 KΩ / 2.2 µF network smoothes anode current pulses to values within the >+28 V output span. A short time constant is desirable for a fast settling meter display but it also increases output ripple. $Ua_{mean} + Ua_{peak} <$ (max. possible output) must apply, otherwise mean DC output will be falsified (reduced) by clipping.

Output ripple can be estimated as follows: 120 mA mean DC half wave rectified input would cause an equivalently shaped 24 V mean DC output voltage caused by a single peak amplitude of π*24 V = 75.4 V_{peak} per 20 ms (50 Hz) period. The RC input network has a time constant R*C = 45 ms. The output of this network is a triangular shaped 50 Hz signal. Its peak amplitude on the amplifier output can be estimated to

(triangular symmetric Ua_{peak})/(half wave rectified Ue_{peak}) = $0.5/\omega RC$ = 0.035 (at 50 Hz)
*triangular symmetric Ua_{peak} = 0.035 * 75.4 V =* ***2.64 V_{peak}***

For details see the chapter on ripple analysis.

This peak voltage plus the 24 V mean DC is still within the >+28 V output span of the amplifier.

Individual trimpots instead of a single common 200 ohms resistor on the amplifier output enable independent adaption to the A and D measuring circuits.

Together with this circuit the original power supply for the backing off resistor network should also be replaced by a supply feeding a constant DC current (12.5 mA) to the network. This reduces dancing of the panel meter needle when measuring mutual conductance. A LP2950 LDO regulator delivers a highly stable output voltage across the 500 Ω trimpot resulting in a precisely regulated network current.

Installation

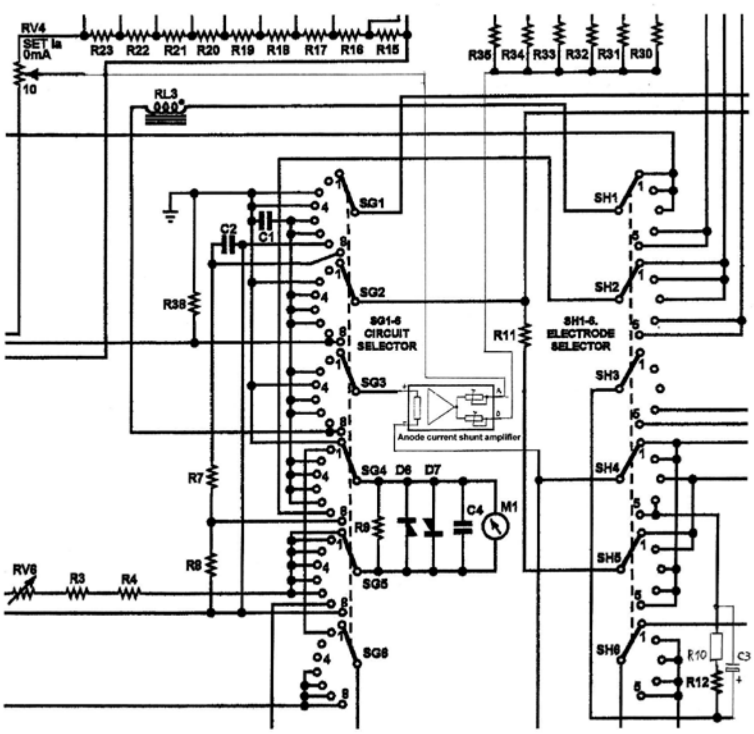


Fig. 6 – Shunt Amplifier Wiring

This schematic detail is a section from the C.T. 160 circuit diagram together with the necessary wiring modifications (thin lines).

Alignment

A. Basic alignment

Adjust V^+ trimpot to 31 V. Connect a DC voltmeter between amplifier output (pin 1) and **–** input.

- Tune Null adjust trimpot to 0 V on output.
- Apply 120 mA DC between **+** and **–** inputs. Tune V adjust trimpot to 24 volts on output.
- Increase DC input to 130 mA. Output should read 26 volts.

B. Adaption to A measuring circuit

Set Anode current controls to 0 (fully counterclockwise), Anode Volts to 20 and Electrode Selector to A1. Connect a 25 kΩ resistor (variable from 15 to 25 kΩ) in series with a DC mA meter between A1 and cathode. Alternatively use a suitable valve.

- Turn Circuit Selector to Test and adjust current to 0.5 mA. Now advance mA/V disc to "Set Zero" and adjust A1,A2 trimpot to the 1 mA/V mark on the panel meter scale (center of green "good" area).

C. Adaption to D measuring circuit

Set Anode current control to 1 mA (inner dial) and Electrode Selector to D1. Connect a DC mA meter in series with a silicon diode (anode to D1) between D1 and cathode.

- Turn circuit selector to Test. Measured current should be close to 1 mA. Adjust D1,D2 trimpot until panel meter reads 72*(measured current). Example: measured current = 1.05 mA => panel meter should read 72*1.05 = 75.6.

Results
The following internal resistances of the anode circuit were measured:

Anode Volts	Internal Ohms
400	150
300	108
250	85
200	69
100	63

Measurement method: for each anode volts setting vary anode current and plot measured values (Ua, Ia). The internal resistance is the linear regression gradient of the plotted curve.
The C.T. 160 manual states 375 Ohm internal resistance for Va = 400 V. This complies quite well with the now measured resistance (150 Ohm) of the improved circuit: 375 Ohm – 200 Ohm (deleted shunt resistor) + 4.7 Ohm (new shunt resistor) = 180 Ohm.
From these results the graph Fig. 7 can be drawn. It shows the approximate correction factor for a measured mutual conductance. As can be seen from the graph, mutual conductance values for valves with Ra >3000 Ohm need not be corrected even when measured at 400 V anode voltage.

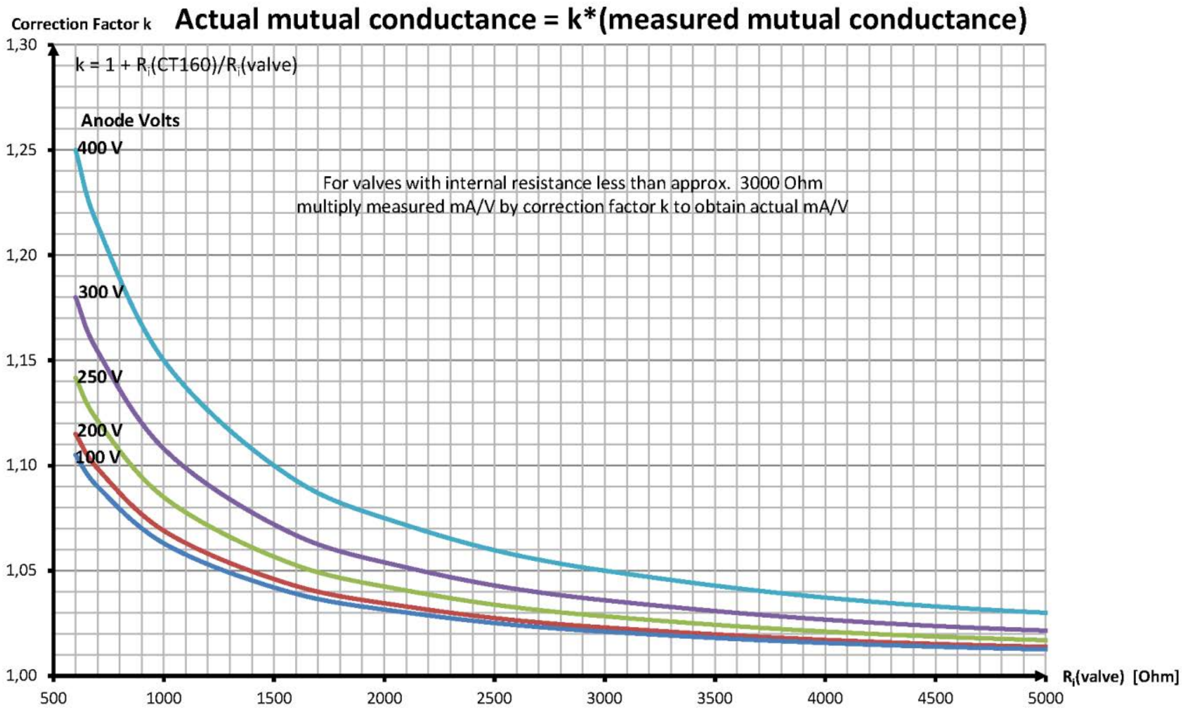


Fig. 7 – Mutual Conductance Correction Factor for valves with low R_i

Direct Measurement of Anode Current

Resistor R14 was replaced by a 5 KΩ and a 500 KΩ trimpot in series. The 500 KΩ trimpot can be switched out by a normally open pushbutton contact on the front panel. With the mA/V dial parked and the anode current backing off controls at zero the trimpots are adjusted to 10 mA f.s. with pushbutton depressed / 100 mA f.s. with button released. This modification greatly assists in backing off an unknown anode current and avoids the need for an external meter in most cases.
A similar modification has been described by Craig Sawyers:
http://www.vintage-radio.net/forum/showthread.php?t=78402&highlight=ct160 .

Improved Analogue Meter Protection

It was found that the original meter circuit (30 µA f.s. deflection) can be most efficiently dampened (swift needle motion, no overshoot) by a parallel resistor of approx. 900 Ω in place of the existing 10 KΩ. Compensation of such a low damping resistance requires an operational amplifier for the tester to still see the original instrument resistance.

The op amp circuit should also limit the current through the meter movement to between zero and full scale deflection in order to prevent the needle from being slammed against its end stops by overcurrent.

This can be accomplished by full wave rectifying and limiting the meter current to a value slightly above 30 µA so in case of an overload the needle just "kisses" the right end stop. The rectification also makes the needle "dip" to zero which greatly facilitates precise nulling of anode current prior to mA/V measurement.

Circuit description

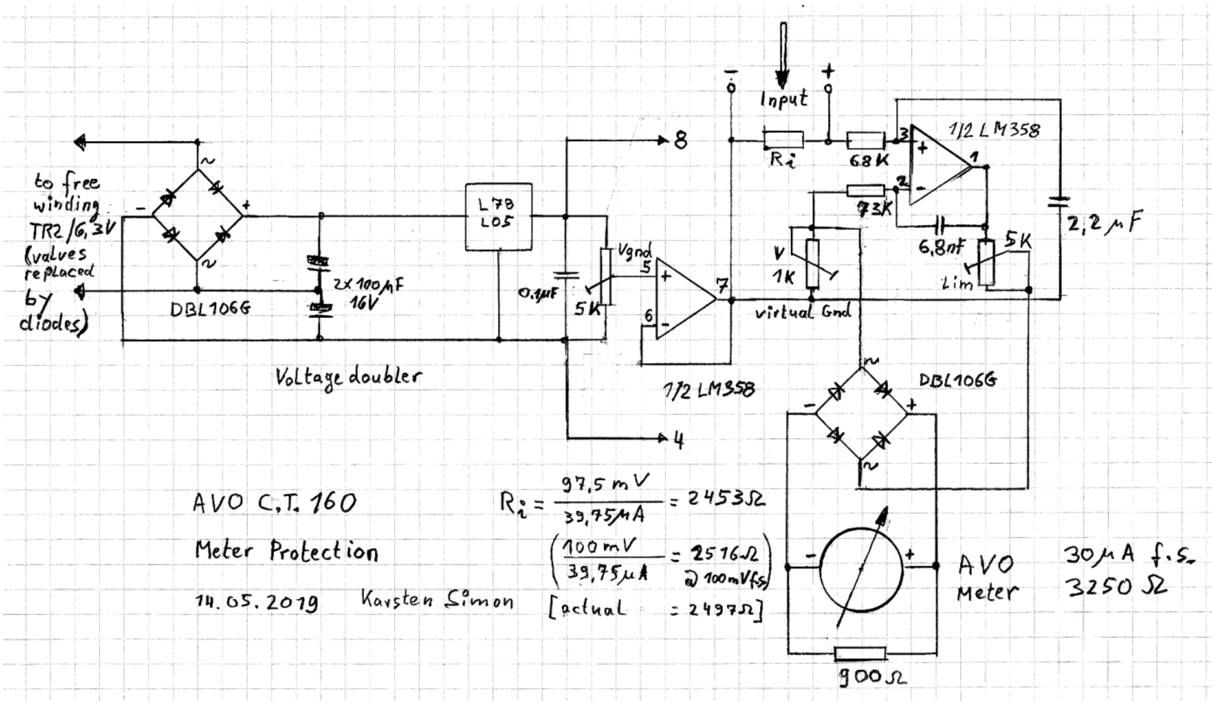


Fig. 8 – Meter Protection Amplifier Circuit

Fig. 8 shows the amplifier circuit. It operates from a single 5 V supply and uses a standard LM358 dual op amp. The supply voltage is derived from the now unused isolated 6.3 V filament winding on TR2. Its AC is rectified, doubled and regulated to 5 V DC.

One op amp is a low output impedance unity gain voltage follower providing a virtual ground between the V^+ and ground rails. The other op amp serves as a non inverting high input impedance amplifier.

Input resistance R_i is set to 2497 Ω =~ 100 mV / 39,75 µA because input can also be measured by the digital panel meter which then displays "100.0" [mV] at full scale (="100") of the analogue meter.

The 73 KΩ resistor on the + input together with the 68 KΩ resistor at the – input neutralizes the influence of the + and – input bias currents.

The voltage across R_i is smoothed by the 68 KΩ / 2.2 µF RC low pass network, The maximum triangular shaped ripple amplitude on the current shunt amplifier output occurs when the maximum mean DC anode current (50 mA) is backed off (meter zero): 50/120*2.64 V = 1.1 V_{peak}. Attenuation of the backing off network is 2497/(200+720+2497) = 73% resulting in 73%*1.1 V = 803 mV_{peak} at meter amplifier input.

The RC network dampens this input signal to a sinus shaped output. Its peak output amplitude can be estimated to:

(sinusoidal symmetric Ua_{peak})/(triangular symmetric Ue_{peak}) = 0.8/ωRC = 0.017 (at 50 Hz).
*Sinusoidal symmetric Ua_{peak} = 0.017 * 803 mV_{peak} =* ***13.7 mV_{peak}***
For details see the chapter on ripple analysis.

Measuring gm adds max. 73%*100 mV_{mean} giving 87 mV_{peak} on the meter terminals. This is well within the range of the meter, so the "kissing point" can be set to slightly above the 97.5 mV full deflection == meter needle just touching the right end stop.
The amplifier feedback is formed by the meter rectifier with the shunted meter as a load. The meter rectifier is a standard component for power applications. Because the rectifier is part of the feedback loop, the forward voltage of its conducting diode pair is entirely compensated by the amplifier's open loop gain. The 6.8 nF feedback capacitor prevents oscillations when the meter current approaches zero.

Alignment

- Set the 1 K trimpot (V) to max. resistance. Set the Lim trimpot to min. resistance. Adjust the Vgnd trimpot to 1.95 V on pin 7. This level divides the total output span into a positive range above Vgnd (where meter goes to 100 %) and approx. 70 % of that range negative below Vgnd (where meter stops at 70 %).
- Apply +100 mV DC to input and adjust V to full meter deflection ("100"). This is the final setting. Do not touch the V trimpot any more.
- Increase input to +150 mV and adjust Lim so that the needle just touches the right end stop (kissing point).
- Reverse input polarity to -150 mV. Panel meter should go to approx. 70 % f.s. (not critical). Adjust Vgnd if necessary. If Vgnd is changed, apply +150 mV again and readjust Lim to the kissing point.

  This difference between full positive and limited max. negative deflection aids in distinguishing the direction to which to adjust the controls when nulling the anode current.

Analysis: Shunt Amplifier and Meter Amplifier Output Ripple

Output ripple of the shunt and meter amplifiers were measured with the test setup in Fig. 1.

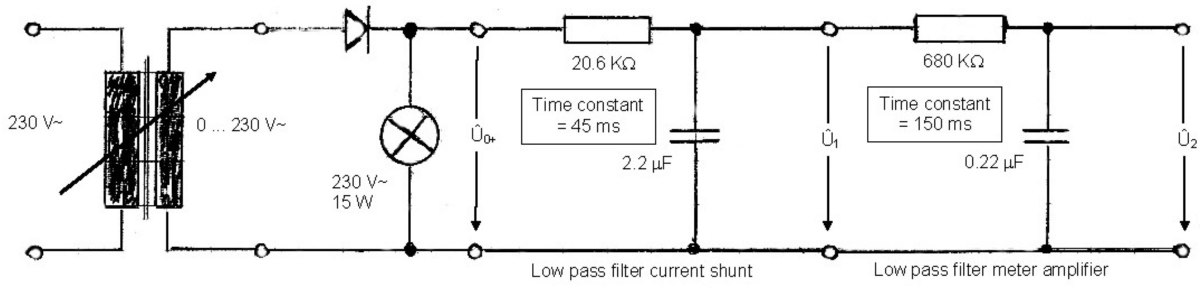


Fig. 1 Test setup

The input voltage curve U_0 is generated across a low power light bulb which creates a negligibly low source resistance for the first low pass filter. Time constants are as in the original circuits. To minimize load of the first filter the second low pass filter is reproduced by a high impedance RC combination with the same time constant.

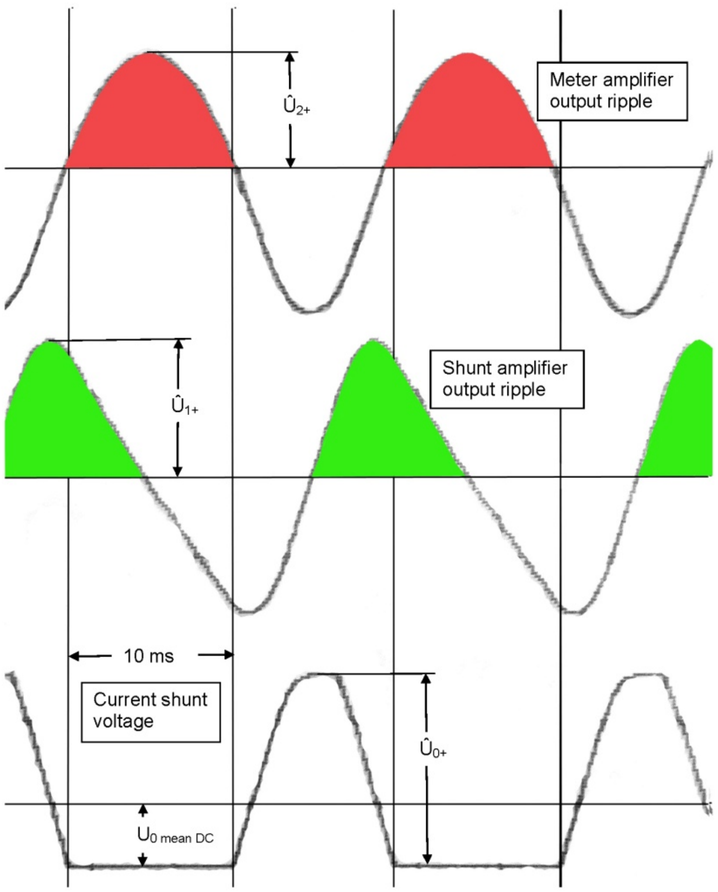


Fig. 2 Output ripple

The designated voltages were oscillographed and measured. Fig. 2 shows the traces.

The green peaks are the ripple amplitudes of the shunt amplifier output. During anode current measurement these peaks are fed to the meter amplifier where they appear at the output as the red peaks.

Neither green nor red ripple peaks must be clipped by insufficient amplifier output swing, otherwise the meter reading will be too low.

The following ripple amplitude ratios have been measured (RC = filter time constant, f = 50 Hz):

$$\hat{U}_{1+}/\hat{U}_{0+} = 0.5/(2\pi fRC)$$

$$\hat{U}_{2+}/\hat{U}_{1+} = 0.8/(2\pi fRC)$$

Overload Relay and Red Lamp LP2

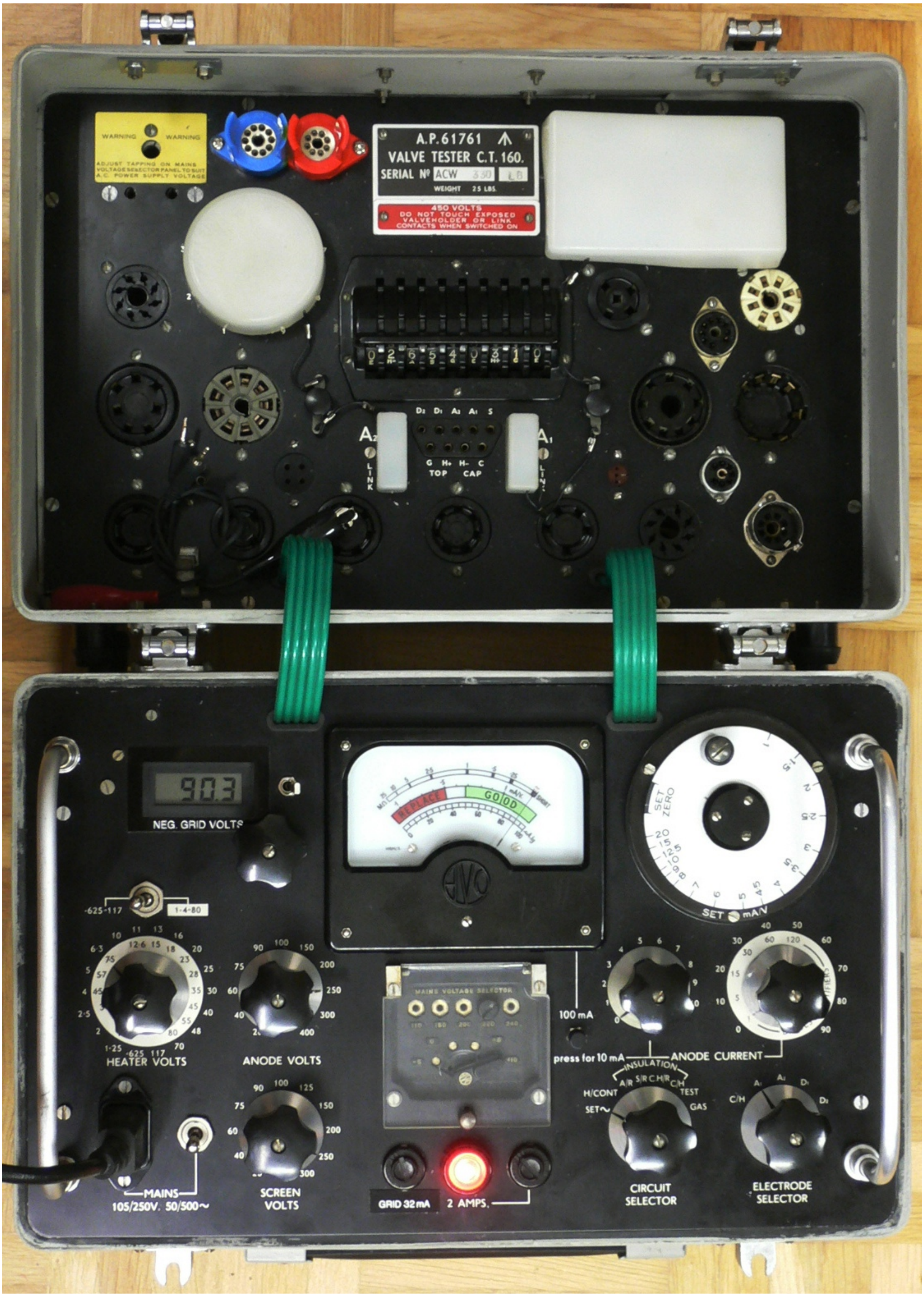
The open relay coil RL1 was rewound by a professional electric motor repair shop. The lamp was replaced by a Paulmann type 800.11.

A W08M bridge rectifier was inserted between the relay contact and the RL1 – LP2 series circuit. This greatly reduces contact arcing. The now DC current increases the magnetic force of RL1 which is compensated by a parallel 100 Ω resistor. Arcing is further reduced by the Zener diode. All this also makes relay action rather quiet. However, whenever the relay contact jitters the digital display begins to flicker and show irregular values. This catches immediate attention and is a good alternative to the former loud relay chatter.

Due to isolating corrosion between the moving arm and the magnetic yoke the spring sometimes carries the full lamp current when the contact opens. This can cause the spring wire to heat up and completely loose its elasticity rendering the spring useless. To keep destructive current away from the spring a highly flexible litz wire was soldered from the connection on the relay socket to the moving arm. Make the connection to the arm close to its tilting line in order to minimize motion of the cable.

Construction Details

Tester Panel and Valve Holder Panel



Modified tester panel and valve holder panel

The digital meter has been mounted at the position of the original Vg dial. The surrounding anodized aluminum frame covers the hole in the panel behind the scale. The new Vg potentiometer is mounted in place of the bushing for the original dial drive knob.

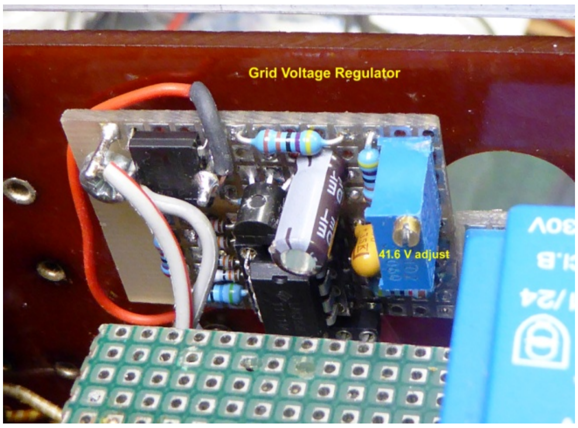
The display selector switch is mounted in the existing bore to the right of the former dial. It is toggled horizontally: left pos. = Ug display, right pos. = analogue meter display.

The pictured original green connection cables to the valve holder panel have been replaced by two pieces of black flat cable (Helukabel 26982 6G0.75).

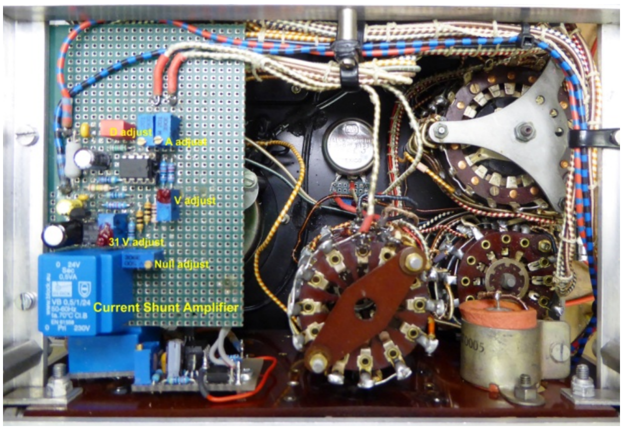
A set of pin straighteners (Dieter Waechter) has been mounted on the valve holder panel in the free space above the covered flying lead valve holder.

A Schuko socket insert has been mounted on the valve holder panel behind the two holes for the mains plug prongs. This will hold the power cord plug when the tester is folded up and stored away.

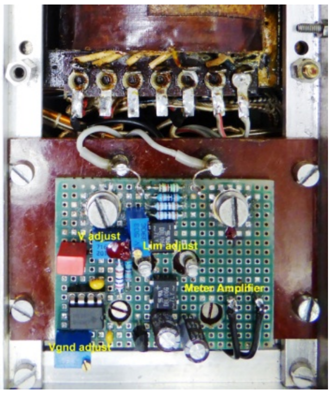
Underneath the Hood



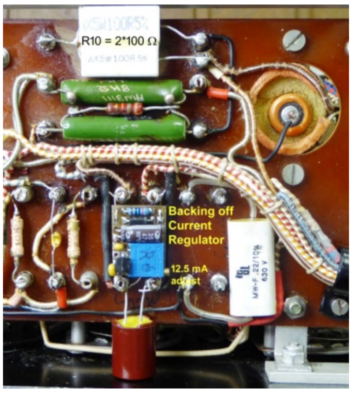
Grid Voltage Regulator



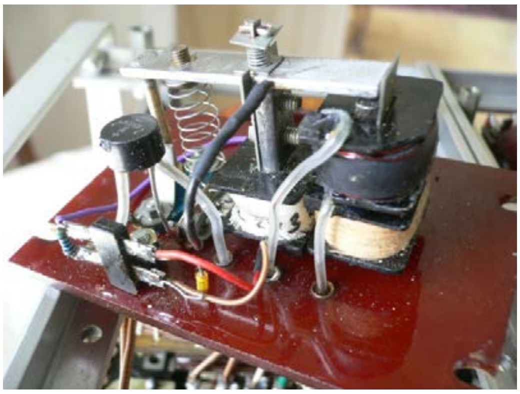
Anode Current Shunt Amplifier



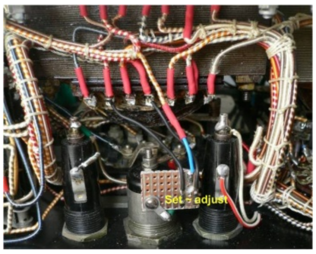
Meter Protection Amplifier



Backing off Current Regulator



Overload Relay



"Set ~" trimpot