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A NEW CATHODE HEATING FOR THE PROTON SOURCE OF LINAC 2

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Abstract

A new cathode heating system for the proton source of linac 2 was developed to make operation of the source easier. It uses a precise closed loop current controller that controls the power by means of phase-shifting control using a triac. It is housed in a plug-in euro chassis module. It replaces the old system that was awkward in operation especially after a power failure and had to be adjusted to the correct current manually.

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A new cathode heating system for the proton source of linac 2 was developed to make operation of the source easier. It uses a precise closed loop current controller that controls the power by means of phase-shifting control using a triac. It is housed in a plug-in euro chassis module. It replaces the old system that was awkward in operation especially after a power failure and had to be adjusted to the correct current manually.

1. SYSTEM REQUIREMENTS

- The current through the cathode filament should be controlled and kept constant.
- Soft start when power is switched on. The old system used a motor driven variable transformer (variac) with a voltage controller. This caused problems especially after powercuts because the variac was still at a high output voltage and had to be turned back to zero manually before a restart.
- The filament should be protected against overcurrent.
- the cathode control should provide auxiliary signals. A 0 to 5 V output that is proportional to the rms value of the filament current from 0 to 60 A.
  A 5 V signal to indicate that the cathode power is above a pre-set value.
- Reliability in a hazardous environment. All in- and outputs must be protected against overvoltage and short circuit. This is necessary because of occasional breakdowns of the 92 kV in the Faraday cage.

2. THE CATHODE

Mixed oxide thermionic, hairpin 16 mm by 92 mm.
Filament current approximately 50 A.
Filament resistance hot 70 - 80 mΩ; cold <10 mΩ.
Power approximately 150 W.

The cathode is powered via an isolation transformer primary 220 V secondary 5 V, 70 A and an isolation voltage of at least 1.5 kV. The arc voltage is applied to the secondary.

3. THEORY OF OPERATION

3.1 The Principle of Controlling the Power

The output power is controlled by triggering the triac in every sine half-wave with a delay that is called the firing angle α. (Fig. 1) This cuts off part of the sine wave.

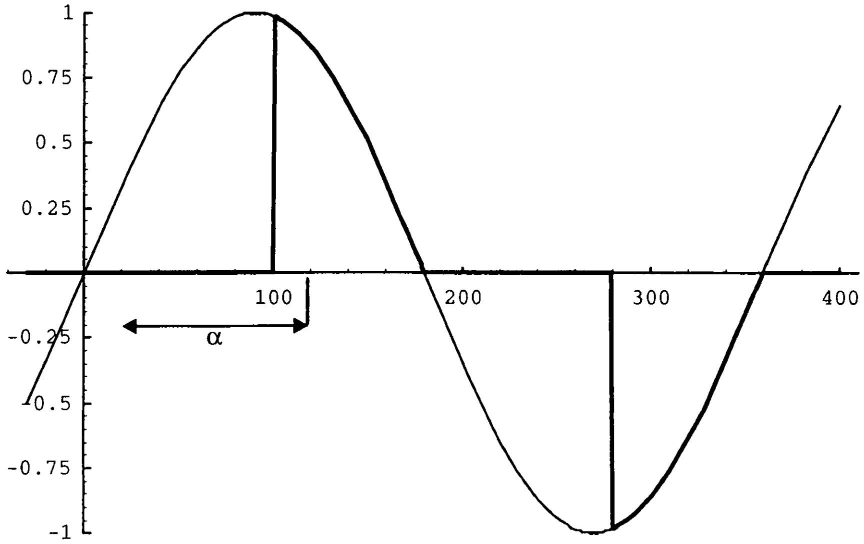


Figure 1

In order to build a controller it is necessary to know how the rms value of the current or voltage in Figure 1 depends on the firing angle α.

The general formula for the rms value of a periodic waveform is the following:

$$V_{RMS} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} \tag{1}$$

If the wave form is a cut-off sine as in Fig. 1 the formula becomes with $V(t) = V_0 \sin \omega t$:

$$V_{rms} = V_0\sqrt{\frac{1}{\pi}\int_\alpha^\pi \sin^2 \omega t d\omega t} \tag{2}$$

The integration is only done over the first half of the sine wave because the second is symmetric.

The solution of this integral is:

$$V_{rms} = V_0\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{1}{4\pi}\sin 2\alpha} \qquad 0 \le \alpha \le \pi \tag{3}$$

With α in degrees: $V_{rms} = V_0\sqrt{\frac{1}{2} - \frac{\alpha}{360} + \frac{1}{4\pi}\sin 2\alpha} \qquad 0 \le \alpha \le 180$ (4)

The graph of this function is shown in Fig. 2 with a peak value $V_0 = 311$ V. This corresponds to the mains voltage of 220 V.

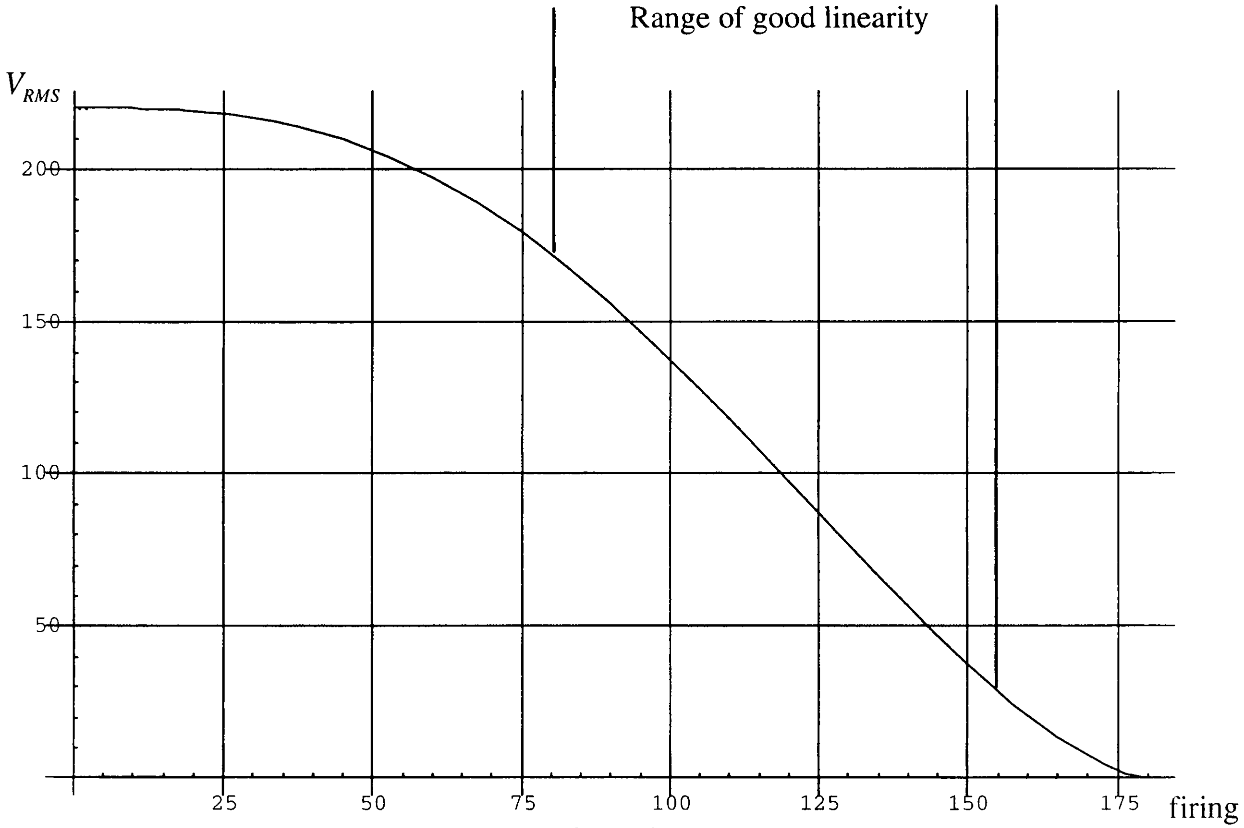


Figure 2

The graph shows that between approximately 80 and 155 degrees the function is fairly linear. This corresponds to voltages of approximately 175V to 35V, which is the range in which the controller must work under normal conditions. Outside this range the slope of the function is smaller. This will reduce the loop gain of the controller thus making the controller slower. Stability, however, will be maintained. The slope is obtained by differentiating (3) Fig. 3.

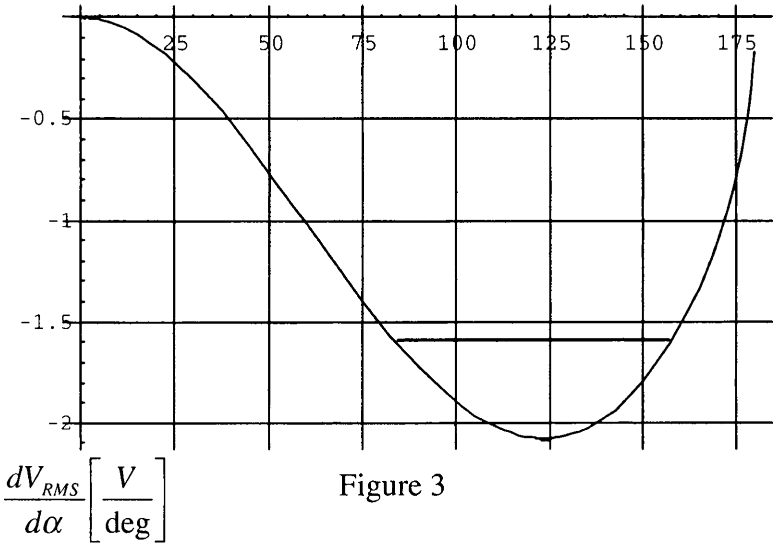


Figure 3

The graph shows Vrms differentiated with respect to α.
α in degrees.
In the range of good linearity the slope varies between approximately 1.6 and 2.1. This is tolerable as controller performance will not change significantly.

3.2 The rms Converter

The rms converter that is used is the AD536AJD of Analog Devices. It has an error of less than 0.5%. The converter produces a dc output voltage that is proportional to the rms value of the input voltage. The block diagram in Fig. 4 shows the principle of operation of the rms converter:

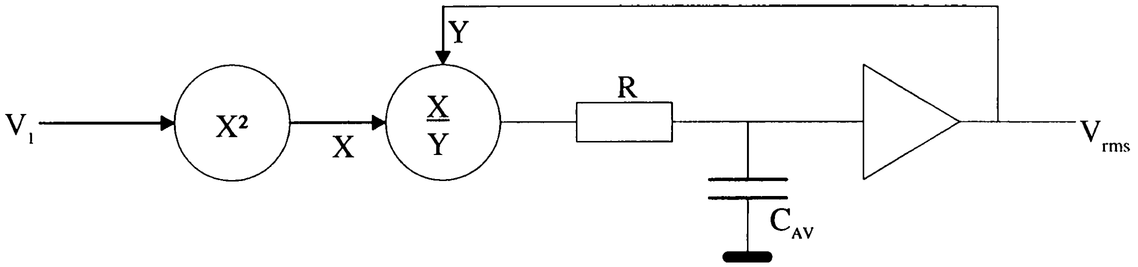


Figure 4

The transfer function is a nonlinear differential equation:

$$\sqrt{RC_{AV}V_{rms}\left(\overset{\bullet}{V}_{rms}+\frac{1}{RC_{AV}}V_{rms}\right)}=|V_1| \tag{5}$$

In order calculate the dynamic behavior, Eq. (5) has to be linearized around an operating point in which dV_{rms}/dt is assumed to be 0. Linearization is done with the following equation:

$$\Delta V_1=\left.\frac{\partial V_1}{\partial V_{rms}}\right|_{OP}\Delta V_{rms}+\left.\frac{\partial V_1}{\partial \overset{\bullet}{V}_{rms}}\right|_{OP}\Delta\overset{\bullet}{V}_{rms} \tag{6}$$

the index OP means operating point $\overset{\bullet}{V}_{rms}=0$

The result of Eq. (6) applied to Eq. (5) is the following:

$$\Delta V_1=\Delta V_{rms}+\frac{1}{2}RC_{AV}\Delta\overset{\bullet}{V}_{rms} \tag{7}$$

This is the differential equation of a first-order RC low pass. The time constant is $RC_{AV}/2$.

Figure 5 shows the block diagram of the linearized rms converter. It is used to calculate the dynamic behavior (with second-order filter to reduce ripple).

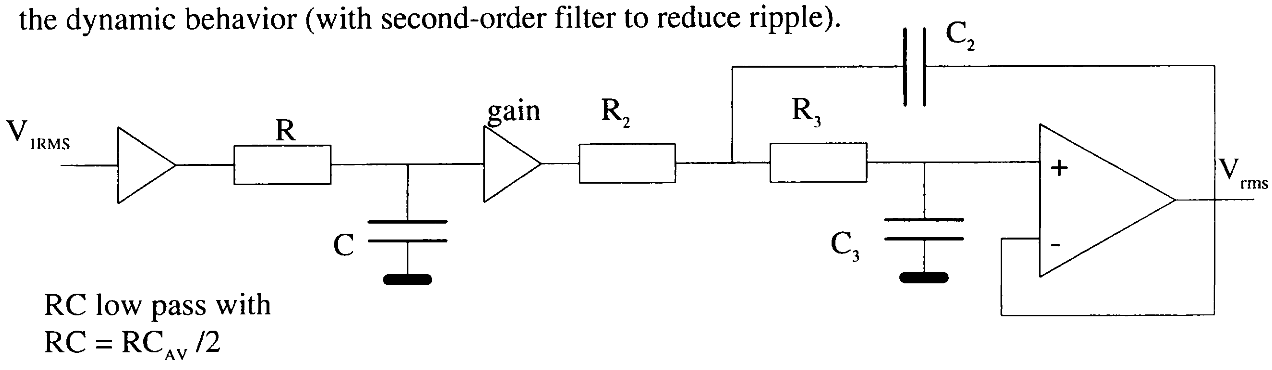


Figure 5

Both the real converter and the linearized one were simulated with PSpice. The step response and the bode plots were sufficiently similar.

Now it is possible to calculate the transfer function of the converter; Eq. (8). The rms converter is the only part of the system that contains time constants.

$$\frac{V_{rms}}{V_{1rms}} = \frac{1/RC}{s+\left(1/RC\right)} \cdot \frac{1/R_2R_3C_2C_3}{s^2+\left(R_2+R_3/R_2R_3C_2\right)s+\left(1/R_2R_3C_2C_3\right)} \cdot gain \tag{8}$$

The first part of the right-hand side of equation (8) describes the RC low pass, the second part the second-order filter.

The resistor R is an internal resistor on the chip. The values of the other resistors and the capacitors were chosen according to the data book and optimized by simulation with PSpice.

$$R = 25\ \mathrm{k\Omega},\ R_2 = 51.1\ \mathrm{k\Omega},\ R_3 = 31.6\ \mathrm{k\Omega},\ C_{AV} = C_2 = C_3 = 1\ \mu\mathrm{F}$$

The gain of the converter is determined by $R_2/25\ k\Omega = 2.044$

Equation (8) becomes with $C = C_{AV}/2$

$$\frac{V_{rms}}{V_{1rms}} = \frac{49543}{(s+19.569)(s+31.645)(s+80)} \cdot 2.044 \tag{9}$$

3.3 The Gain Control

Since the controller loop gain is proportional to $1/R_{filament}$ it is necessary to compensate this by a gain control that has a gain proportional to $R_{filament}$. Otherwise a low $R_{filament}$ would cause the controller to oscillate. The gain control is a one quadrant multiplier-divider that is made with 4 transistors and 4 op-amps as shown in Fig. 6.

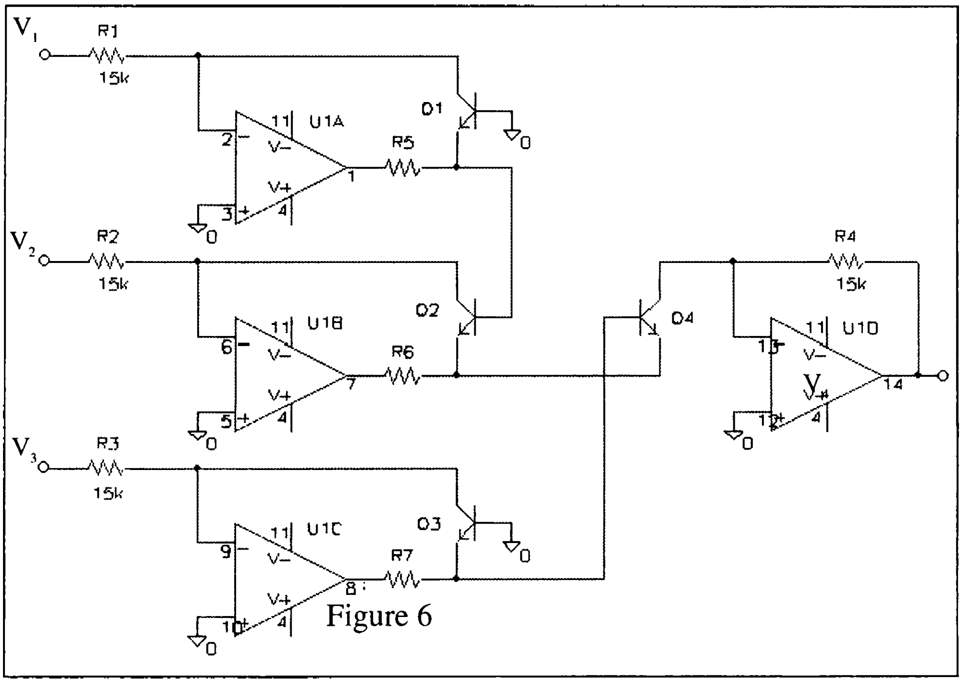


Figure 6

The collector current depends on the base emitter voltage as follows:

$$I_C = I_S e^{V_{BE}/V_T} \tag{10}$$

V_T is the "thermal voltage" kT/q.

Equation (10) solved for V_{BE} is:

$$V_{BE} = V_T \ln I_C / I_S \tag{11}$$

The collector currents of Q_1, Q_2, Q_3 in Fig. 6 are proportional to the input voltages V_1, V_2, V_3. The base emitter voltage of Q_4 is: $V_{BE4} = V_{BE1} + V_{BE2} - V_{BE3}$.

Expressing the base emitter voltages with equation (11):

$$V_{BE4} = V_T \left(\ln \frac{I_{C1}}{I_{S1}} + \ln \frac{I_{C2}}{I_{S2}} - \ln \frac{I_{C3}}{I_{S3}} \right) = V_T \ln \left(\frac{I_{S3}}{I_{S1} I_{S2}} . \frac{I_{C1} I_{C2}}{I_{C3}} \right) \tag{12}$$

Finally the collector current of Q_4 can be expressed with Eq. (10) using Eq. (12):

$$I_{C4} = \frac{I_{S4} I_{S3}}{I_{S1} I_{S2}} \cdot \frac{I_{C1} I_{C2}}{I_{C3}} \tag{13}$$

The output voltage V_4 is proportional to the collector current of Q_4. Assuming that all transistors have the same I_S the output voltage of the multiplier-divider is:

$$V_4 = \frac{V_1 V_2}{V_3} \tag{14}$$

For accuracy it is important that all transistors have the same temperature and dissipate only very little power to avoid self-heating. The collector base voltage should be small and constant. With the transistor BC337-25 the collector current should be between 10µA and 1 mA for best accuracy. The circuit only works with positive input voltages.

In order to control the gain two auxiliary voltages are generated by means of precision rectifiers. One is proportional to the mean value of the filament voltage V_{AV}, the other is proportional to the mean value of the filament current I_{AV}. The ratio V_{AV}/I_{AV} is proportional to the filament resistance.

V_{AV} is connected to V_2 in Fig. 6 and I_{AV} to V_3. V_1 is the output voltage of the PI-controller.

3.4 The Closed Loop Controller

The diagram in Fig. 7 shows the process to be controlled.

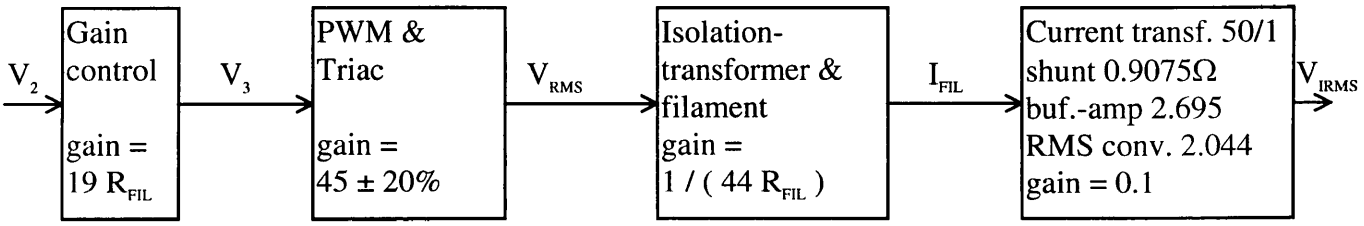


Figure 7

With all four gains in Fig. 7 multiplied and the transfer function of the rms converter the closed loop controller becomes (Fig. 8):

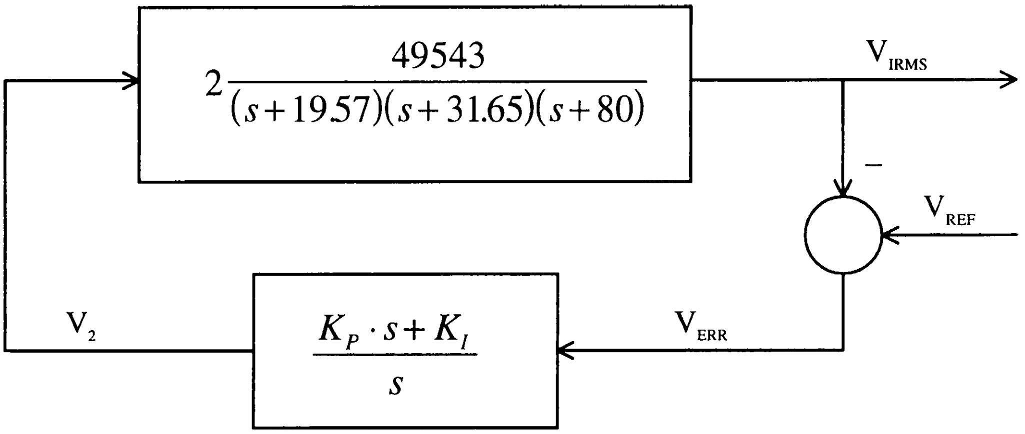


Figure 8

The reference voltage V_{REF} is 0 to 10 V which corresponds to 0 to 60 A filament current. The parameters K_I and K_P of the controller were determined with the root locus method.

Best performance is obtained for $K_I = 3.3$ and $K_P = 0.17$. However, these values are not critical. K_I may vary from 2 to 3.5 and K_P can be adjusted correspondingly between 0.1 and 0.18 without any significant deterioration of performance. With these values the settling time constant is 62 ms to 75 ms that means the settling time of the controller is always below approximately 300ms.

3.5 The Cathode Hot Detection

The proton source uses an interlock system to ensure that the source only works if all conditions for safe operation are met. One condition is that the cathode has to be hot. Therefore the cathode control provides a signal that indicates a hot cathode. The signal is a +5 V voltage that switches a relay in the interlock system.

The cathode hot detection uses the resistance of the filament which rises with temperature to determine when the cathode is hot. If the cathode is cold the voltage is low and rises with increasing temperature. When the ratio of filament voltage to current exceeds a certain adjustable value the cathode is sufficiently hot.

The cathode hot signal is generated by a comparator that monitors the signals V_{AV} and I_{AV}. If the ratio is over a preset threshold the comparator gives the cathode hot signal.

3.6 The Acquisition Output

For the source acquisition system the controller provides a signal that is proportional to the rms value of the filament current. The output is 0 to +5 V which corresponds to 0 to 60 A filament current.

3.7 The Overload Protection

In order to protect the cathode from overheating a current monitoring circuit measures the filament current and switches the current off if it gets too high. The current is switched off in two ways: First the PI-controller output is turned to a negative voltage and secondly a relay in series with the triac switches the load current off.

The protection circuit measures the primary current of the isolation transformer and computes the rms value by means of a simple converter that consists of three OP amps and some transistors. A self holding comparator compares the rms-value with a threshold voltage and switches the controller off if the current is too high.

The controller can be switched on again by pressing the reset button or by turning the power off and on

4. THE REALIZATION OF THE CONTROLLER

Figure 9 gives an overview of the whole system.

The controller is a plug in module for eurochassis. It consists of two 100 mm * 160 mm circuit boards in a metal box. It is 44 units wide and single height.

One of the boards is the controller-board. Figure 10 shows the block diagram.

All signals are connected via a 32 pin D-Type DIN 41612 connector.

The other board is the power-board. Figure 11.

Because it operates at mains voltage a 15 pin H-Type DIN 41612 connector is used.

On the front panel of the controller there are two panelmeters. One shows the output voltage to the isolation transformer. The other shows the filament current.

The controller works with mains voltages between 205 and 240 volts. It can be adapted to any cathode with a power up to 1000 W.

It has now worked for one year in the proton source and proved to be reliable and resistant to flashovers.

Figure 9 - Cathode control for proton source linac 2: System overview

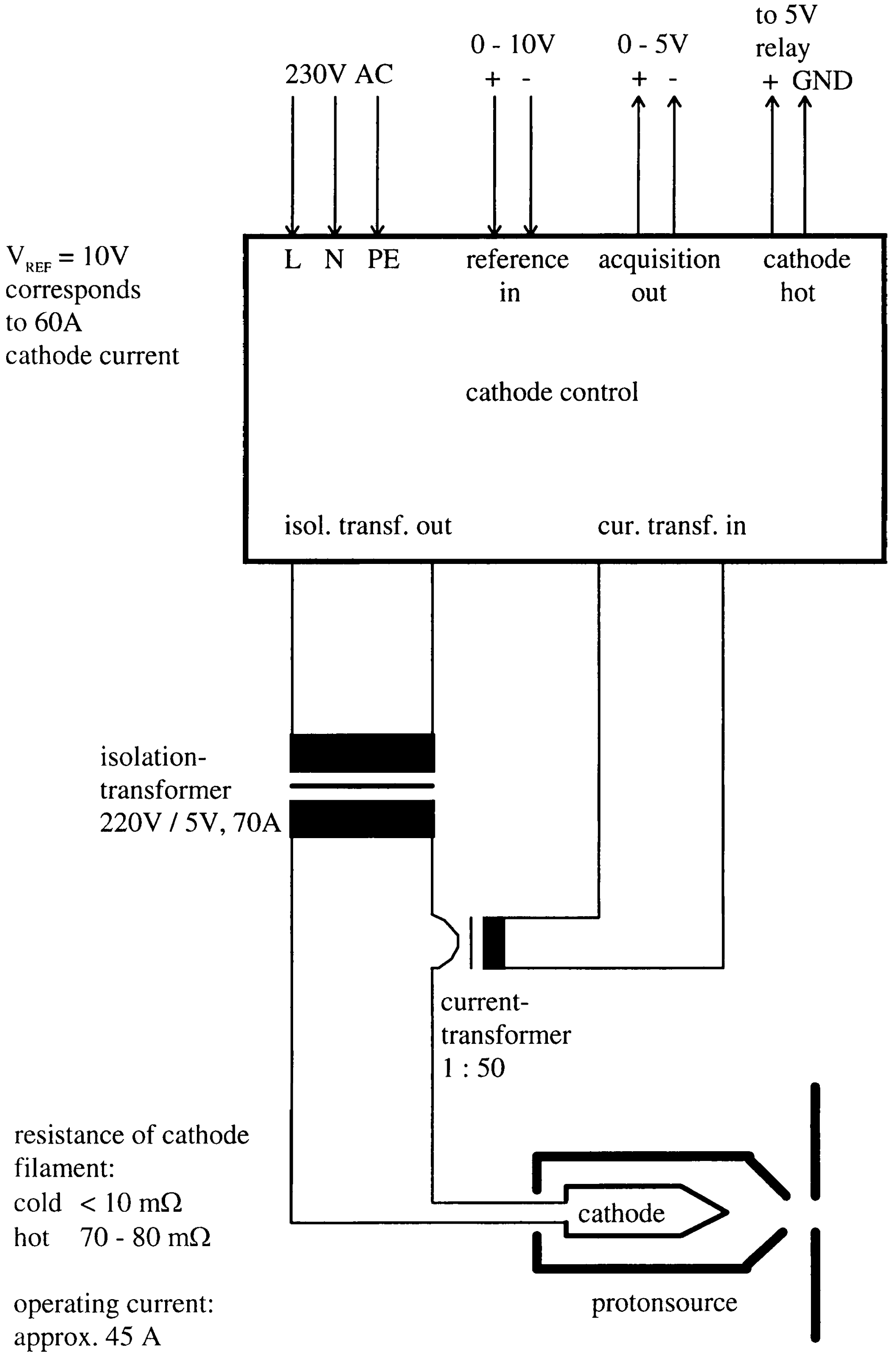


Figure 10; Cathode heating for proton source linac 2:   controller board

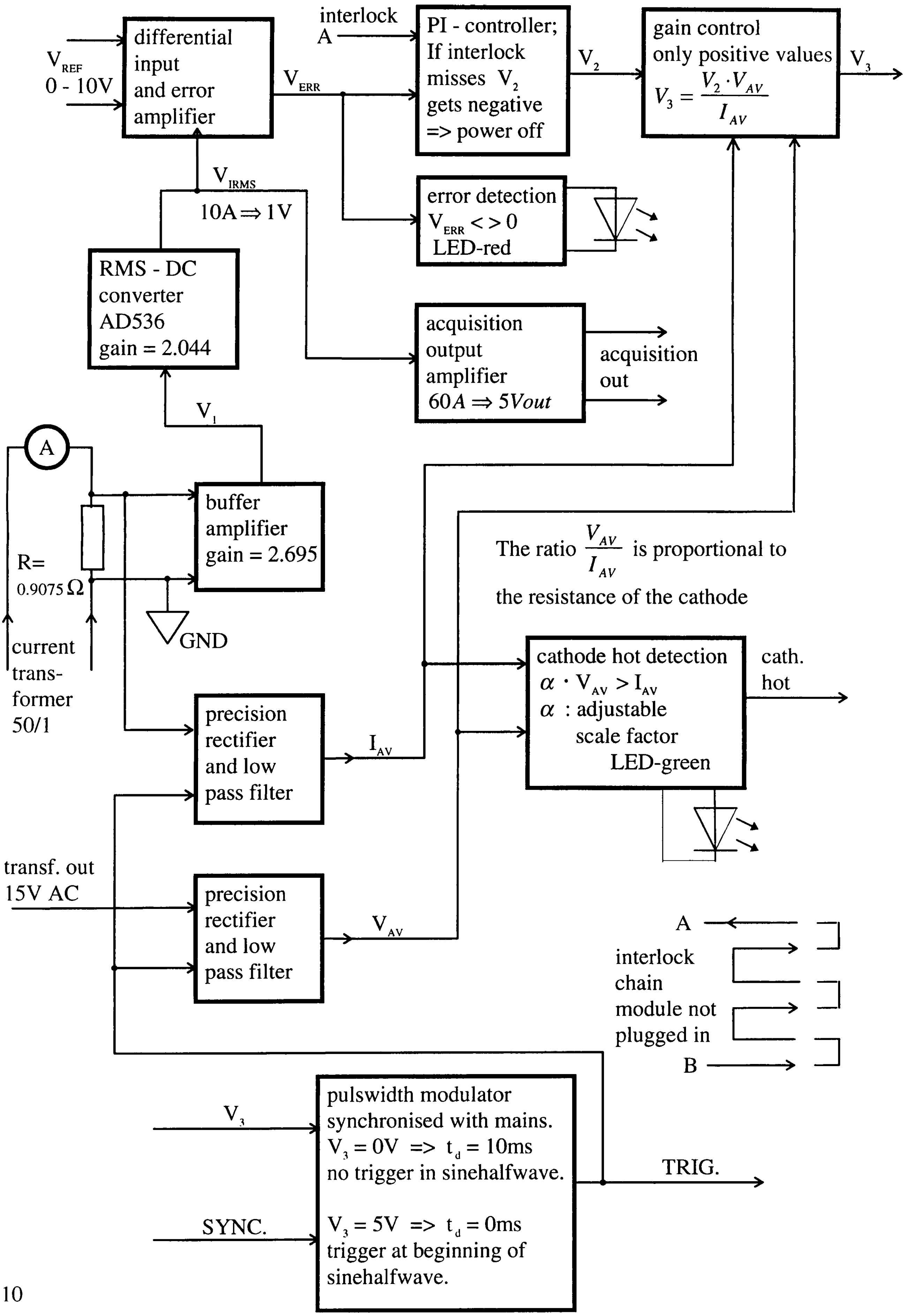
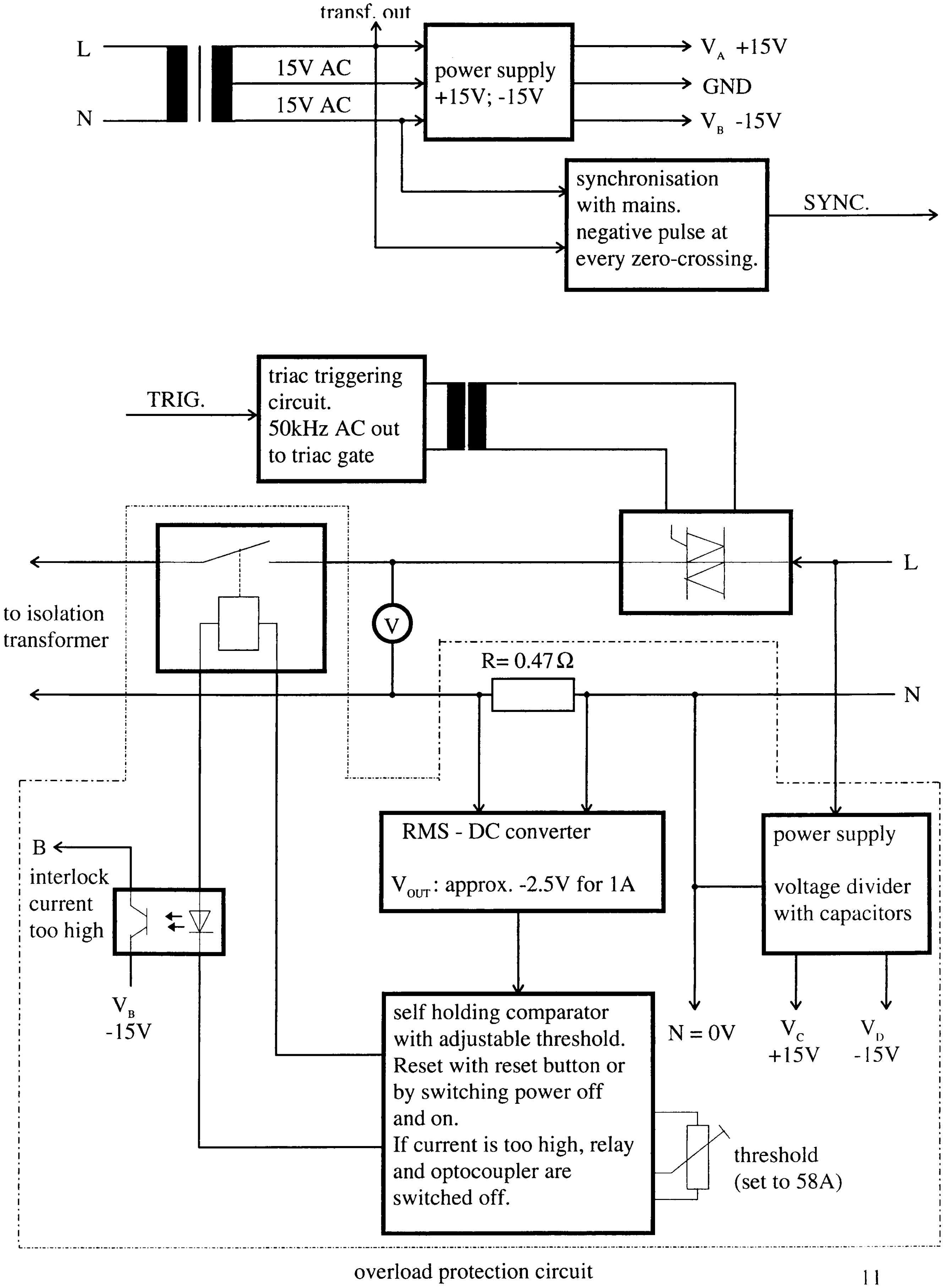
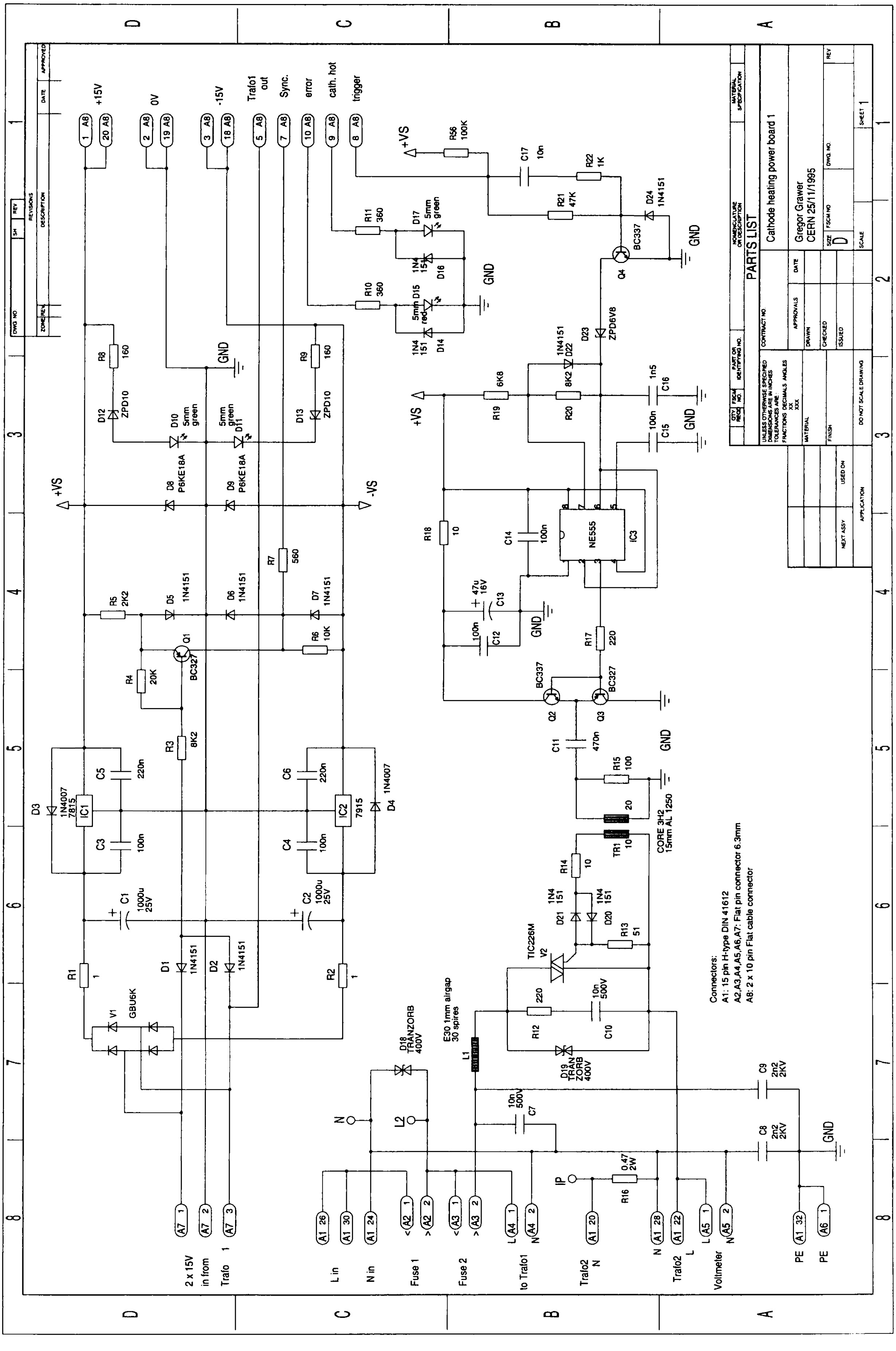


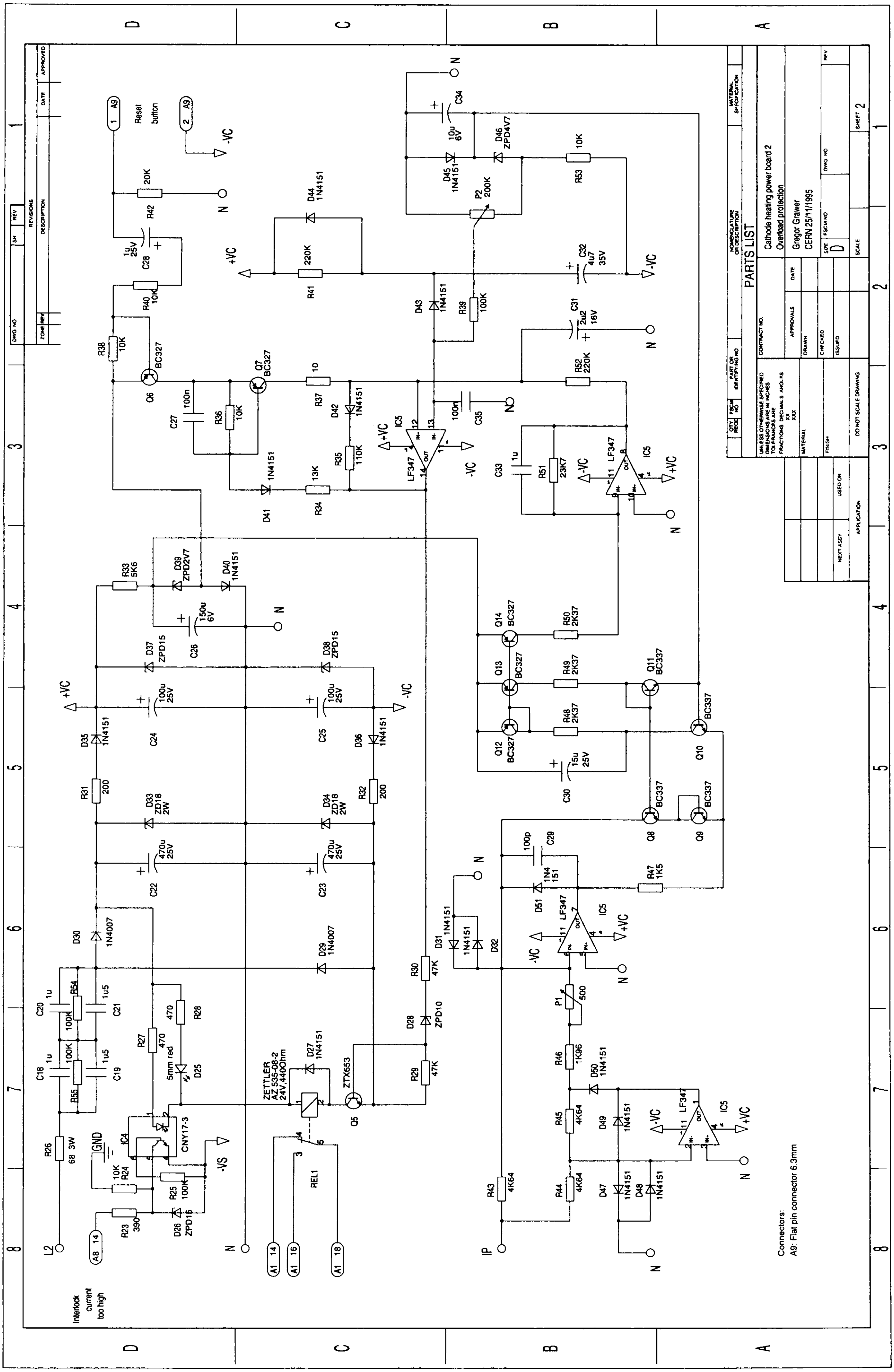
Figure 11; Cathode control for proton source linac 2: power board



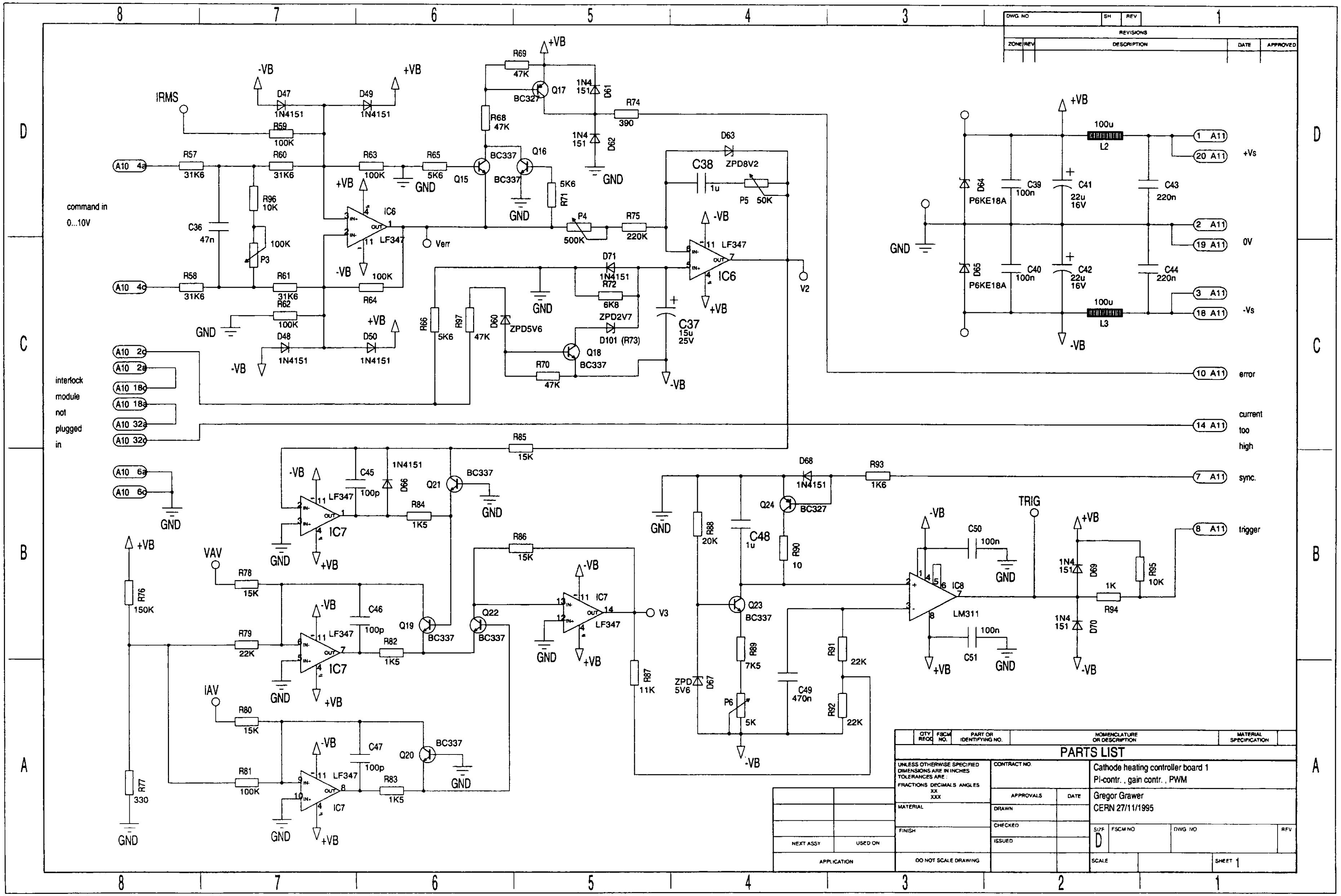
Schematic 1: power supply, mains synchronisation, triac driver circuit



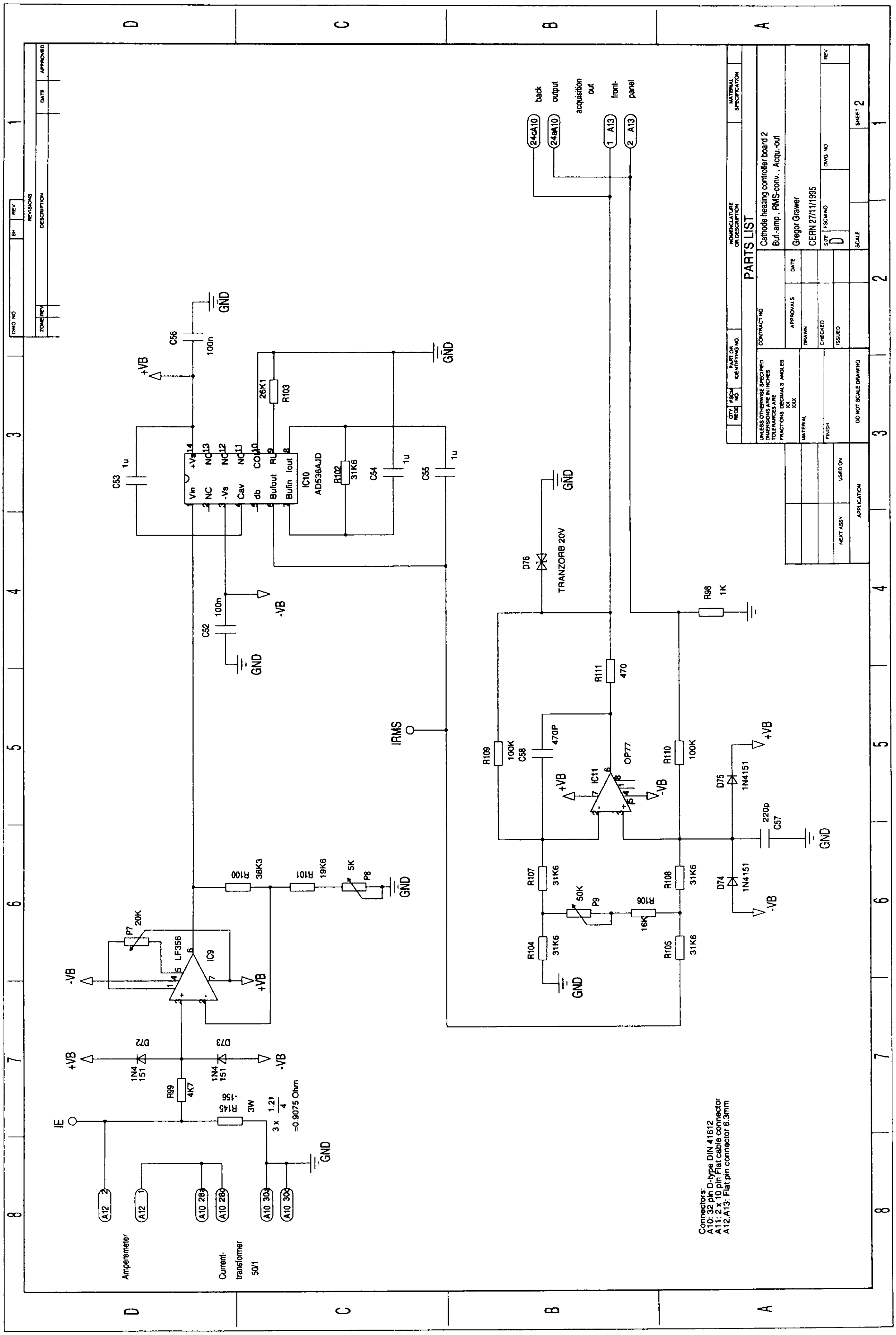
Schematic 2: overload protection circuit



Schematic 3: differential input, PI-controller, gain-control, PWM synchronised with mains



Schematic 4: buffer amp. , RMS-converter, acquisition output



Schematic 5: 2 precision rectifiers for current and voltage, cathode hot detection