

APPENDIX A. INSTRUMENTING THE FN ACCELERATOR

A.1 Passive, Fail-Safe, Retrofit Interface Techniques

The McMaster Tandem Accelerator first went "on-line" in 1968. Its control system design dates from that era, and, unlike a modern accelerator, few of its instruments have been designed for attachment to computers. Since it would not be feasible to replace all of the control hardware for this project, some means to "retrofit" a computer interface to the existing electronics is needed. These retrofits must be:

a) *Optional*. It must always be possible to run the accelerator manually, in the accustomed fashion.

The interfaces must be removable by computer command or the throw of a switch.

b) *Passive*. Even when the computer is controlling the accelerator, the human operator must be able to monitor its function. The interfaces must not interfere with the existing displays.

c) *Fail-Safe*. If the computer system should fail -- even if power to the interfaces is lost -- the interfaces must fail to a "safe" state, e.g., blocking the accelerator beam. Ideally they should fail to the "manual operation" state.

d) *Economical*. The interfaces should cost little; implying a minimum of new hardware, and the fewest number of changes to the existing hardware. Economies of scale should be exploited where possible.

Four circuits have been devised to meet these goals.

A.2 Isolated Meter Repeater

Sixty different analog quantities must be observed by the operator of the accelerator -- be it computer or human. These range from terminal megavolts to corona points position to vacuum pressure. The wide variety of sensors and metering circuits share no common design, and would have to be redesigned individually.

But there is one commonality: all sixty quantities are displayed for the operator on ordinary panel

meters. Thus a single circuit which could monitor the indication on a panel meter could interface all sixty measuring devices. Panel meters are frequently installed at high-voltage points within vacuum-tube circuits, so the "repeater" output must be electrically isolated from the meter.

Circuit Description

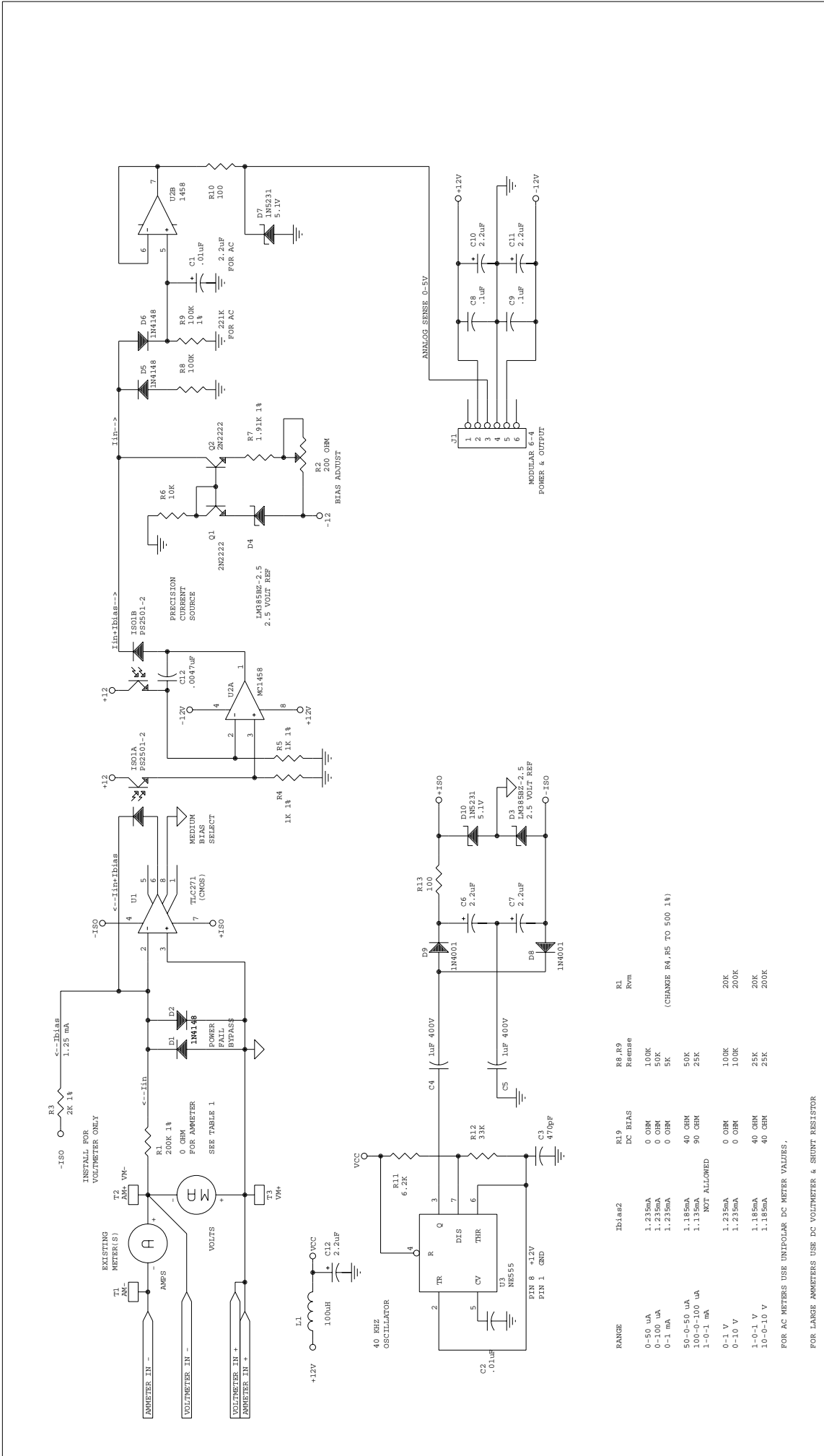
The Isolated Meter Repeater, Figure A-1, is a multi-range voltmeter/ammeter. The core of this circuit is an analog optoisolator, ISO1. The feedback of op amp U2A acts to make the ISO1B diode current equal to that of the ISO1A.¹ Thus a variable current can be measured with no electrical connection. The "primary" diode is biased into its approximately-linear region (Hewlett-Packard, 1985) by adding 1.25 mA, derived from an inexpensive precision voltage regulator D3. An equal current is subtracted in the "secondary" stage by the current mirror Q1-Q2.

A "current follower" op amp U1 provides drive for the optoisolator and buffers the input signal. This device may operate at a circuit potential of several hundred volts, so it must be provided with an isolated power source. Oscillator U3 generates 40 kHz AC, which is *capacitively* coupled to a voltage doubler. This scheme was thought to be less expensive than the more common transformer coupling. Suitable transformers are hard to find, whereas capacitors blocking 600 volts are readily available. The rectified signal is filtered and regulated to provide +5V for the TLC271 "micropower" op amp, and -2.5V for the bias.

Currents of plus or minus 1 mA can be measured. The bias current limits the negative input range, since I_{bias} must exceed $-I_{in}$. The isolated power source limits the positive range, since $I_{bias} + I_{in}$ must not exceed the available current. This current is converted to a 0-5V output by U2B; R9 can be selected to provide a full-scale "movement" of 50 μ A, 1 mA, or any current in between. Half-wave rectifier D5-D6 allows measurement of AC current and voltage; in this application R9 is scaled by 2.21 to convert half-wave average to RMS voltage (assuming a sine wave input).

Use of a "multiplier" resistor R1 converts the ammeter to a voltmeter. With a 50 μ A movement,

1. C12 compensates for the propagation delay through the isolator; without it the circuit will oscillate.



RANGE	Ibias2	R19	DC BIAS	R8,R9	R1	Rvm
0-50 uA	1.235mA	0 OHM	100K	100K		
0-100 uA	1.235mA	0 OHM	50K	50K		
0-1 mA	1.235mA	0 OHM	5K	5K		(CHANGE R4,R5 TO 500 1%)
50-0-50 uA	1.185mA	40 OHM	50K	50K		
100-0-100 uA	1.135mA	90 OHM	25K	25K		
1-0-1 V	NOT ALLOWED					
0-10 V	1.235mA	0 OHM	100K	100K	20K	
10-0-10 V	1.185mA	40 OHM	25K	25K	20K	
	1.185mA	40 OHM	25K	25K	20K	

FOR AC METERS USE UNIPOLAR DC METER VALUES.

FOR LARGE AMPMETERS USE DC VOLTMETER & SHUNT RESISTOR

Figure A-1. Isolated Meter Repeater

the input impedance is 20,000 ohms per volt.

When inserted as an ammeter, the circuit should not interfere with the measured current flow. When powered, op amp U1 will be a "virtual short" (maintaining 0 volts across its input). When unpowered, D1-D2 provide a path for current to flow, ensuring a maximum voltage drop of 0.7 volts. These also protect the op amp input, without interfering with its operation.

The completed circuit is fabricated on a 2.25" x 2.25" printed circuit board, which can be mounted directly on the back of a standard panel meter.

Experience and Recommendations

Experience with the circuit has been generally good; it is reliable, responsive, and sufficiently linear. The board is versatile enough to be used unmodified for most of the AC and DC meters in the FN accelerator. It has proven easy to modify and customize in the field.

One customization deserves note. The FN Terminal Voltmeter requires a 2 volt DC meter with a high (megohms) input impedance. It was possible to cut and jumper the board to convert U1 to a voltage follower, with a 5 megohm input resistor. In retrospect, it would have been better to design the primary with a dual CMOS op amp (TLC272), allowing a stage for isolation and gain.

Experience has shown that the bias adjustment R2 needs a range of several hundred uA. (Even then, R7 or R3 must occasionally be replaced to match the bias currents). This presents no problem with a 1 mA movement, but when the full scale deflection is 50 uA, it is difficult to "zero" the output. A current gain stage in the primary would also solve this problem.

Optoisolators have a temperature-sensitive transfer characteristic. Using a matched dual isolator in a single package (NEC PS2501-2) is essential, but if one side of the package is warmed (even with a fingertip), the output begins to drift.² The zero adjustment (R2) should be made when the circuit has stabilized at operating temperature.

Some FN panel milliammeters show a significant drop when the power is removed from the

2. In private communication, Alan McIlwain of Atomic Energy of Canada Ltd. reports that adding a heat sink to the optoisolator improves this problem.

meter repeater. The 0.7 volt drop across D1-D2 is excessive in some applications. An earlier design used a relay to bypass the meter repeater when unpowered; either this more expensive alternative, or a more sophisticated electronic bypass, will be needed for a "mature" board design.

The greatest problems occurred with the capacitively isolated power supply. If the measured circuit and the computer system are truly isolated, there is no problem; but if they have any common ground (as is frequently the case), a "ground loop" can be created between the output and the input. The end result is that 40 kHz AC is coupled into the secondary amplifier. It was possible to correct this in most cases by judiciously inserting input resistors, but it is clear that capacitive coupling is inadequate, and it should be abandoned in favor of transformer coupling.

In a few cases, the meter repeater picked up 60 Hz AC from the FN electronics. The resultant ripple on the output appears as noise on the measured quantity. This was generally solved by putting bypass capacitors on the repeater input, and by increasing C1 (e.g., to 10 uF) to create a long time-constant RC filter. A redesign of the output stage would allow a more effective filter.

A.3 Solid State Variac

The principal control device used in the FN accelerator is a "Variac" autotransformer, adjustable from 0 to 120 VAC and providing a few amps of current. This device is not readily adapted to computer control. Although it is possible to turn a Variac shaft with a microprocessor-controlled stepper motor (Lind and Poehlman 1992), a non-mechanical solution is preferable. This involves replacing the Variac with an electronic device which can be controlled either manually or by computer.

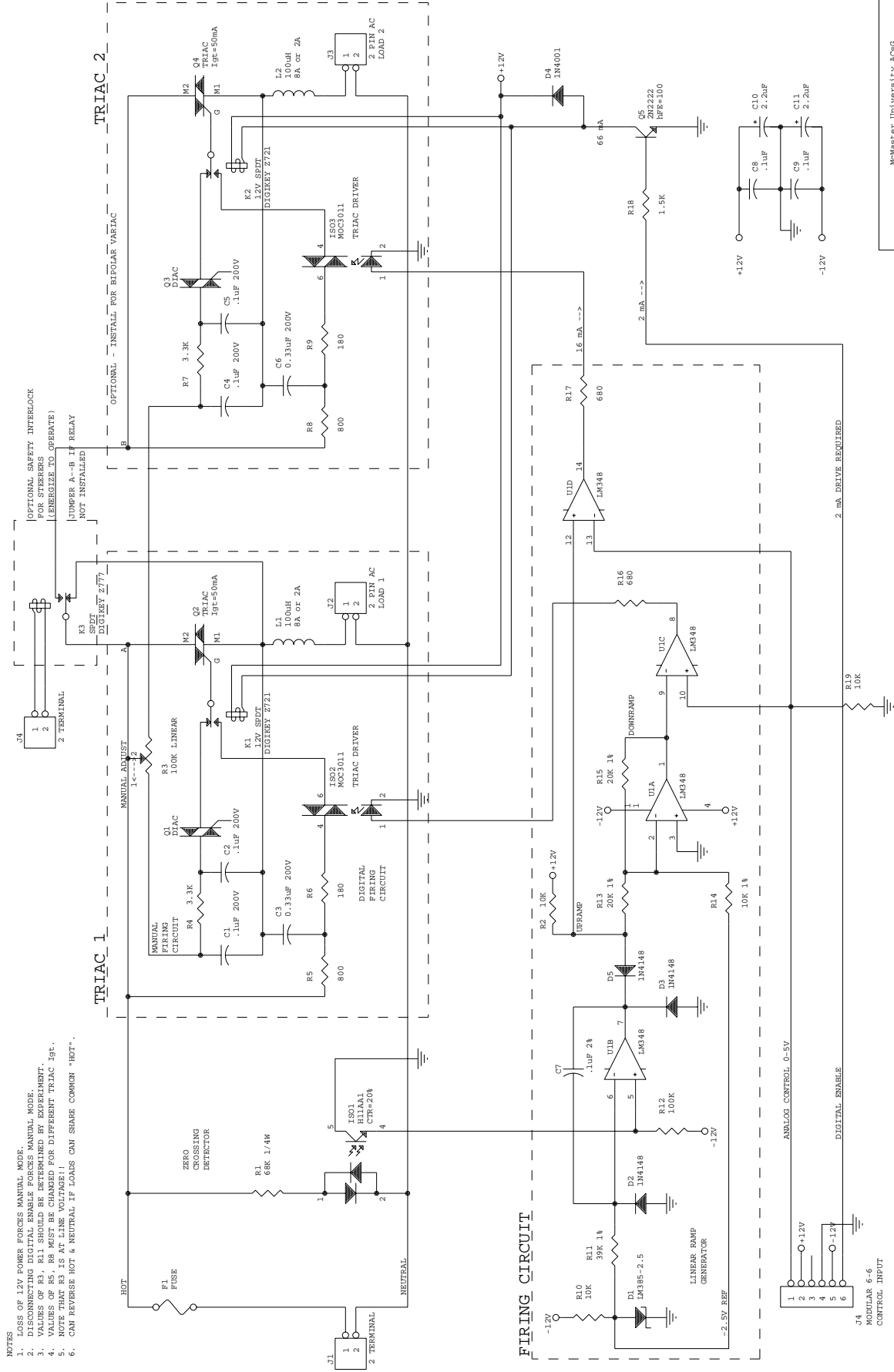
Circuit Description

The "solid state Variac," Figure A-2, uses a Triac device to provide a variable AC output. By switching the Triac on partway through the AC half-cycle, the effective (RMS) voltage can be reduced from 120 VAC.³

The Triac Q2 must be "fired" (triggered) at some point from 0 to 180 degrees into each half cycle

3. The peak output voltage remains unaffected over half of the adjustment range.

- NOTES
- LOSS OF 12V POWER FORCES MANUAL MODE.
 - ON CONNECTING THE WIRE TO THE MANUAL MODE.
 - VALUES OF R5, R8 SHOULD BE DETERMINED BY EXPERIMENT.
 - VALUES OF R5, R8 MUST BE CHANGED FOR DIFFERENT TRIAC IS't.
 - NOTE THAT R3 IS AT LINE VOLTAGE!!
 - CAN REVERSE HOT & NEUTRAL IF LOADS CAN SHARE COMMON "HOT".



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Figure A-2. Solid State Variac

of the AC line. If fired at 0 degrees (the start of the half cycle), the Triac is continuously on, producing full output. If fired at 180 degrees (the end of the half cycle), the Triac is continuously off, for zero output. This firing signal is generated as in the conventional lamp dimmer (ARRL, 1992), by a variable resistor and "Diac" trigger diode (R3 and Q1 in the figure). This provides a manual control.

The computer's control signal is a DC voltage from 0 to 5 volts. This is compared with a sawtooth wave synchronized with the AC half-cycle. U1B generates a positive-going ramp; it is reset to 0 volts when the AC wave crosses zero and ISO1 turns off. U1A produces a negative going ramp, reset to +5V at the zero crossing, as shown in Figure A-3. When this ramp falls lower than the input voltage, comparator U1C fires the Triac optocoupler ISO2, which in turn fires the Triac Q2 (Motorola 1982). If the control voltage is raised, the Triac fires earlier, yielding a larger AC output.

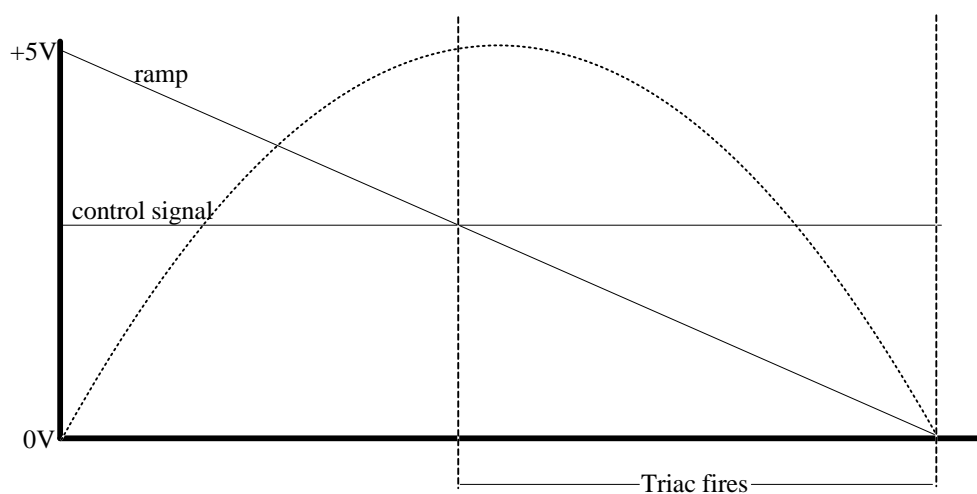


Figure A-3. Generation of Triac Firing Signal

When a Variac is used to control beam steerers, it can be connected so that when one steerer is adjusted to maximum voltage, the other is at minimum, and vice versa. In the solid state Variac, a second Triac is required. The same control signal is compared with the *positive*-going ramp to provide the firing signal for Triac Q4. When the control voltage is raised, the Triac fires later, yielding a smaller AC

output. Likewise, the manual control R3 operates in opposite directions for the two Triacs. When only a "unipolar" control is required, these components may be omitted.

Relays K1 and K2 are actuated by a digital output from the computer to transfer from the manual control R3 to the computer-controlled firing circuit. If the computer is disconnected or loses power, the relays select the manual control, which requires only the AC line for operating power. Relay K3 is an optional safety interlock; if installed, it must be energized for the steerers to operate. If de-energized, the steerers will be powered to full deflection (one switched off, the other at full voltage).

Experience and Recommendations

Aside from a few heater elements (e.g. in the cesium boiler), the most common use of the Variac is to adjust the output of a high-voltage power supply. A typical supply is an encapsulated module containing a transformer, a rectifier, and a filter capacitor. The output voltage of this supply, when lightly loaded, will follow the peak (and not the RMS average) of the AC input voltage. Early experimentation indicated that good control of the output could be achieved with a Triac circuit. Upon installation in the FN, however, two difficulties were encountered.

First, many of the high voltage supplies are normally operated with a low AC input, i.e., at the low end of the control range. The manual control circuit requires a minimum voltage (typically 35V) to fire the Diac; below this voltage the Triac will be cut off. Second, a hysteresis effect was frequently observed with the manual control circuit: the control had to be advanced excessively to fire the Triac, but then could be reduced below the firing level. Both of these problems were solved when they occurred by putting a resistance⁴ in series with the load, such that the usual high-voltage settings corresponded to the middle of the Triac control range. This problem would not be expected with the computer firing circuit, which has exact control of phase angle, but the requirement for "fail-safe" manual control takes precedence.

Another difficulty was encountered with the "bipolar" Triacs used to control the steerers. The

4. A 40 watt incandescent lamp was found to be quite effective in many cases.

effective steerer voltage is the difference between two HV power supplies, controlled by two Triacs acting in opposition. The effective response curve of a Triac is nonlinear, especially when controlled by a variable resistance and Diac. The difference output of two opposed Triacs⁵ exhibits a reversal near zero, i.e., a control reversal at the middle of the control range (the most common setting). This problem was not observed with the computer firing circuit. Time constraints precluded more experimentation with the manual firing circuit, but it should be possible to alter the response curve such that this control reversal no longer occurs.

A.4 Repeating Picoammeter

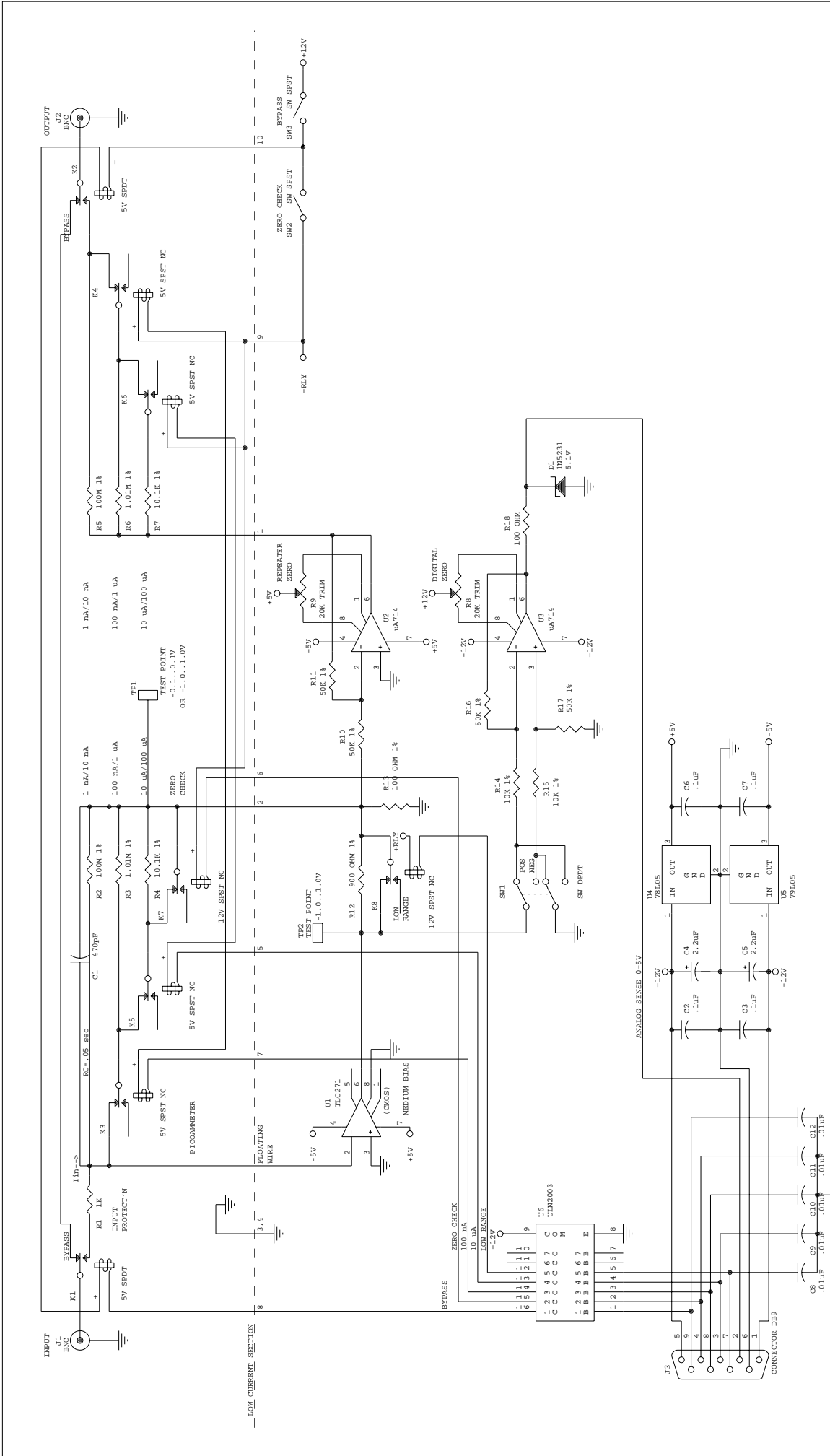
Many of the adjustments of the FN accelerator are made with reference to beam current, as measured at an inserted Faraday cup. The interface must perform two functions: first, convert an input current (in the range of tens of picoamperes to tens of microamperes) to a DC voltage that can be measured by the computer. Second, while doing so, permit the current to be measured with the existing panel meter. This could have been done with a meter repeater (section A.2), except that there is no way for the computer to read or change the range switch of the Keithley Model 414 picoammeter.

Circuit Description

Two electronic picoammeters cannot be simply connected in series to read the same current. Instead, the circuit of Figure A-4 operates by measuring the input current, and then generating an equal (but independent) output current. This output current can then be measured with the existing Model 414 meter.

U1 is a TLC271, a low-cost CMOS op amp, with a 1 pA input bias current. Relays K3 and K5 select feedback resistors of 100, 1, or .01 megohm, which respectively will convert 10 nA, 1 uA, or 100 uA to an output voltage of 1.0 V. Resistor K8 switches a 1/10 voltage divider into the feedback loop, multiplying the output of U1 by 10. In this case a current of 1 nA, 100 nA, or 10 uA will cause a "full scale" output of 1.0V from U1. This voltage will have the opposite polarity from the input current. Op

5. Two Triacs on an imperfect AC feed can also interact, since each can distort the AC wave.



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- NOTES
1. LOSS OF POWER FORCES ALL RELAYS OFF (BYPASS).
 2. LOSS OF DIGITAL INPUT FORCES ALL RELAYS OFF.

Figure A-4. Inline Picoammeter

amp U2 buffers this voltage and re-inverts the polarity. This voltage is then applied to a 100, 1, or .01 megohm resistance, selected by K4 and K6, to produce an output current equal to the input current.⁶

Meanwhile, op amp U3 amplifies the 1.0V DC to 5 volts DC, the full scale input of the A/D converter. The polarity can be made switch selectable (SW1) because each installation of this meter will only encounter one polarity of current (negative in the low energy section of the accelerator, positive in the high energy section).

In addition to reading this 5V analog signal, the computer has five TTL control outputs. Three select the range, controlling relays K2-K6 and K8 as described above. Another causes K7 to short the feedback resistor of U1, forcing an output of zero. This can be used by the computer to determine the zero offset of its analog input subsystem. The final control activates K1 and K2 to completely bypass the repeating picoammeter, connecting the output directly to the input. This is the "fail safe" default if the computer is disconnected or loses power. The zero check and the bypass can also be manually operated, by SW2 and SW3.

Experience and Recommendations

Unfortunately, accelerator operations were terminated before this unit could be put into service. Both the input (U1) and output (U2) circuits were tested in the laboratory, and both worked well.⁷ There are two areas of potential concern.

First is current leakage, the curse of picoammeters. To minimize this, the low current section was isolated on a separate PC board, with only one low-current connection (U1 input) to the main electronics board. All other connections to the low-current board (relay control and U1 output) were far removed from the low-current traces. The effectiveness of these measures remains to be seen.

Second, it is likely that relay switching will induce transient currents into the input. Relays are unavoidable, since electronic switches cannot match the relays' 10^{10} ohm "off" resistance. The relays are

6. This takes advantage of the fact that the input resistance of the Model 414 picoammeter is effectively zero (much smaller than R5-R7).

7. Tests were conducted with a 10 megohm feedback resistor, as 100 megohm resistors were not on hand.

controlled with DC, so current should only be induced briefly when a relay is switched on or off. The computer can allow for this on the infrequent occasions when the meter range must be changed.

A.5 Beam Profile Monitor Tap

The other principal beam measurement uses a "beam profile monitor." This is a mechanism which moves a thin wire through the beam horizontally and vertically.⁸ As the wire passes through the beam, a current proportional to the intersected beam is induced. On an oscilloscope this current appears as two "cross-sections" of the beam.

Circuit Description

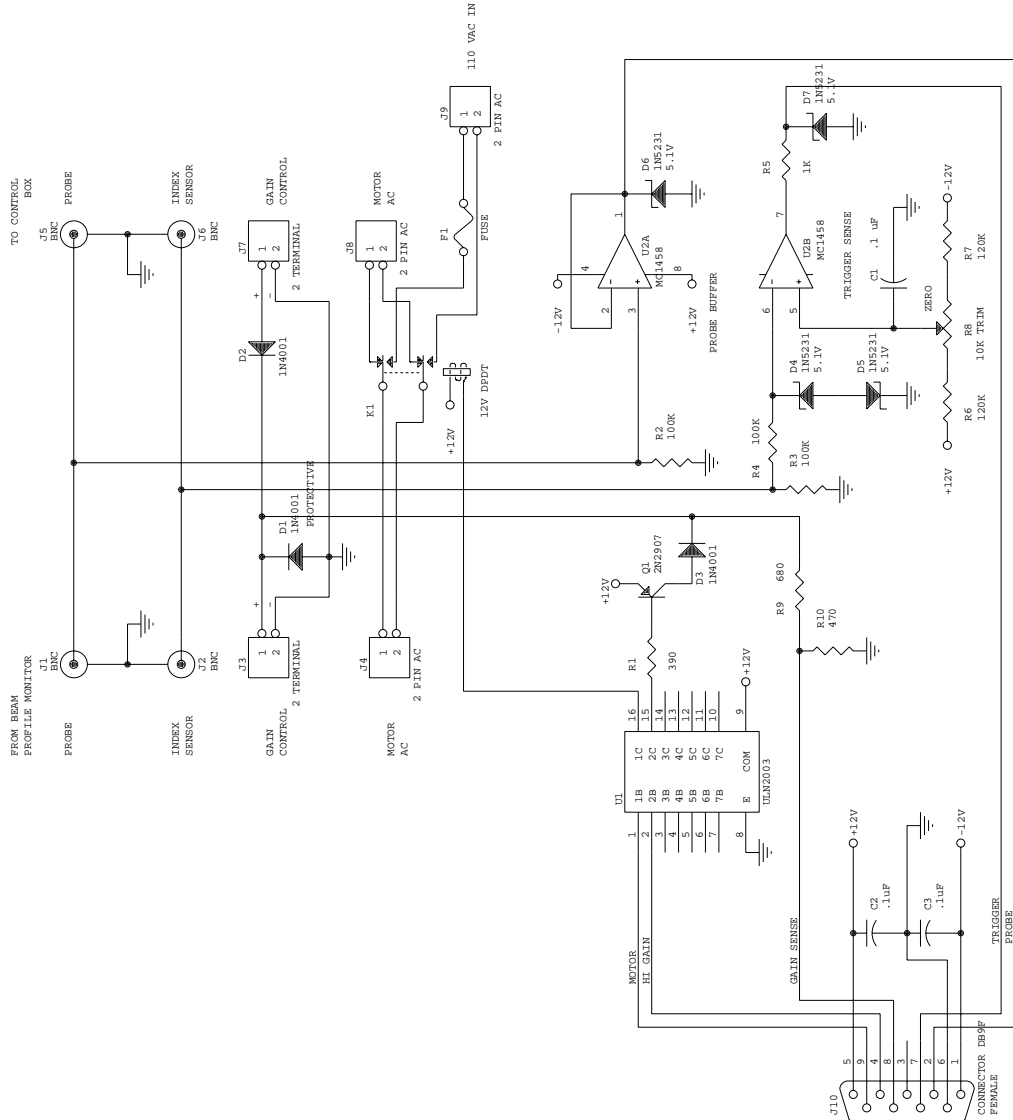
The beam profile monitor (BPM) is controlled by two switch inputs, one to turn on the beam scanning process (by turning on a motor), and the other to switch in an optional x10 amplifier at the sensor head. The primary output is a voltage proportional to intersected current. A second output provides a synchronization pulse at the start of the scan. Scanning is continuous at about 17 scans per second.

The computer interface for this is quite simple, as shown in Figure A-5. The "probe" signal is simply buffered. The "index" signal is converted to a digital pulse by a comparator; using a circuit similar to that of the BPM control unit. These are noninvasive "taps" which do not affect the normal display operation.

The "motor" control output actuates a relay driver in U1, turning on K1, which switches the motor power on and disables the manual control. The "gain" control output actuates Q1, outputting 12 volts to turn on a relay in the BPM sensor head. Thus, both of the output controls are a "logical OR" with the manual controls: either unit can turn on the BPM; both must agree to turn it off. Since the x10 amplifier will affect the observed signal, the computer is provided with a "gain sense" input to detect when it is manually activated.

The project was terminated before this unit could be field tested.

8. A single cleverly bent wire, rotated by a motor, traverses the beam in both directions.



- NOTES
1. LOSS OF POWER IS "SAFE".
 2. INPUT DISCONNECT IS "SAFE".

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Figure A-5. Beam Profile Monitor Tap

A.6 Programmable Resistor

The FN accelerator employs a few "resistively programmed" power supplies. The output voltage (or current) of such a supply is set by an external resistance. Either a fixed or variable resistor may be used. This resistor is usually in the feedback loop of an amplifier, so it must be isolated from ground.

Circuit Description

Figure A-7 illustrates an optoisolated, voltage-controlled resistor. The key component in this circuit is an H11F1 optoisolated FET, which, like a conventional FET, acts as a variable resistance. The response curve of this device is decidedly nonlinear; however, experimentation has revealed that an H11F1 in parallel with a fixed resistor has a quite linear characteristic. Figure A-6 shows two examples: a 10K ohm resistor in parallel with the FET, and a 680 ohm parallel resistor. In each case the response "saturates" at 100 ohms resistance, with an input current of about 9 mA.

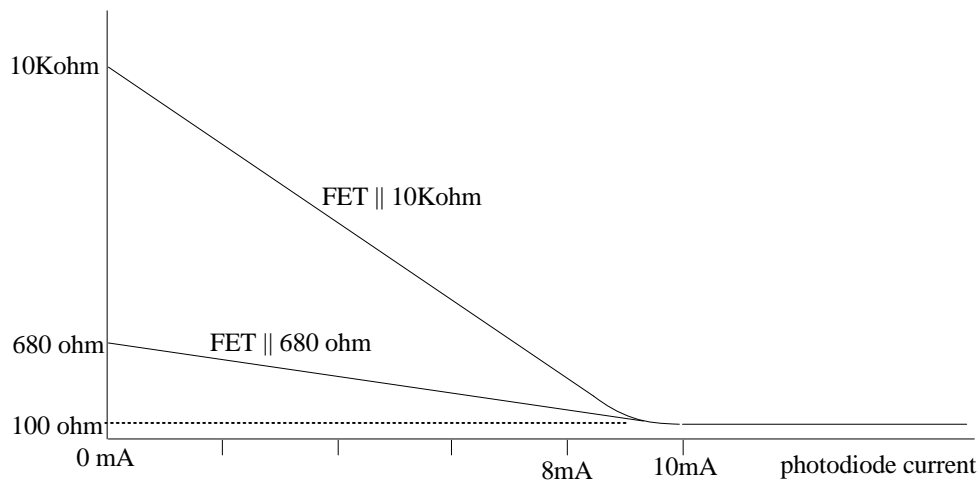


Figure A-6. Programmable Resistor Characteristic

U1 converts the 0 to 5V DC control signal from the computer, to a 0-10 mA current (the useful range) through optoisolator ISO1. Relay K1 transfers control from the existing manual potentiometer to the opto-FET. If the computer is disconnected or switched off, manual control is the default.

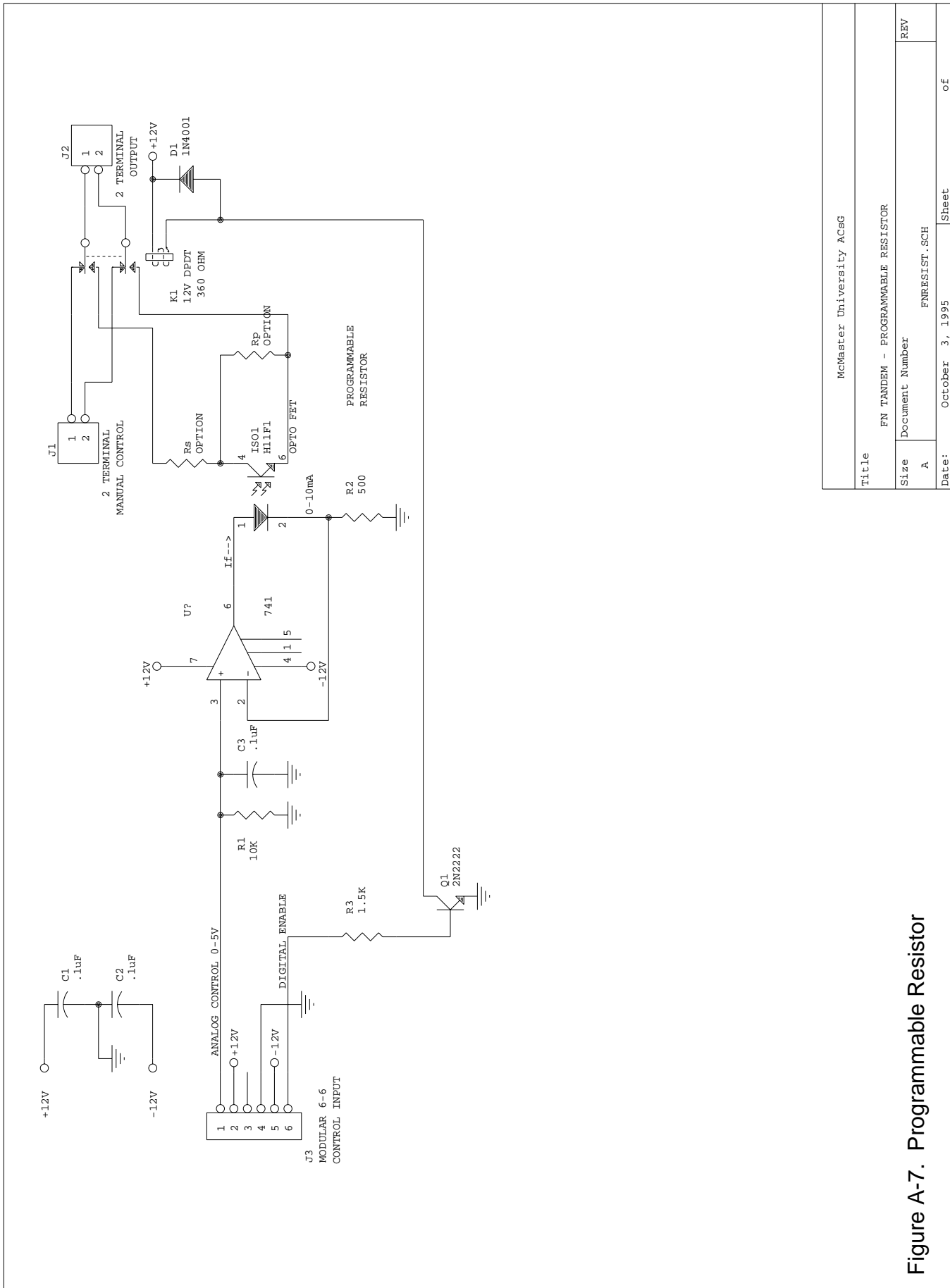


Figure A-7. Programmable Resistor

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