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Design Document

FET Control Box Redesign 2002

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Abstract:

The power FET Control box is designed for general instructional and research laboratory use. It incorporates two electrically independent FET devices and control logic to achieve three switching modes whereby the two FETs can be made to switch with identical switching functions, complementary with dead-time switching functions, and alternating switching functions. A multitude of dc-dc, dc-ac, and ac-ac converters can be realized by using either one FET Control Box or ganging two FET Control Boxes in a master-slave configuration.

Document Revision History

Issue	Date	Comments
000	3/4/2004	Released after revision and review
001	9/15/2004	Added troubled shooting section

Contents

1. Introduction

This project provides advanced Power MOSFET systems capable of being used in a plurality of projects. Robert S. Balog was the project manager as well as performed all of the mechanical and electrical design. Jonathan Kimball provided helpful insight as well as a design review forum. Professor Philip T. Krein provided overall guidance. Construction assistance was provided by Andrew Niemerg (BSEE '02), Brian Raczkowski (BSEE '03), and Nathan Brown (BSEE '04), the ECE Electronics Shop and the ECE Machine Shop.

1.1 Scope

The primary end use of the FET boxes is for ECE469 use. Therefore, it must be rugged and reliable in an undergraduate lab setting. It must also be easy to debug and repair.

In addition, it is desirable to provide advanced performance sufficient for use in a research setting.

The box contains two electrically independent and isolated pairs of Power MOSFETs and Power Diodes and the control logic to internally generate three switching modes based on PWM control.

1.2 Definitions

BOM: Bill of Material. The parts list that contains part numbers and reference designators.

Control Mode: The two electrically independent FET devices can be made to switch in one of three modes – 1) identically, 2) complementary with dead time, 3) alternately.

Master / Slave: Two or more FET boxes can be connected such that one acts as the master clock and the rest act as slaves. In this manner bridge topologies can be achieved.

Switching function: The signal that governs the frequency and duty ratio of switching. The FET boxes have an internal PWM generator, or they can be supplied with an external switching function.

1.3 References

Schematics:	SK0003 Rev 4
PCB Layout:	PB0003 Rev C
Drawings:	PJ0008 Rev A

2. Specification

POWER SUPPLY:

1. Grounded AC line cord with universal IEC style (computer) receptacle with integrate fuse and an ac power switch.
2. External DC input power jack 0.100” barrel jack.
3. OFF-line **isolated** switching power supply using a flyback design and galvanically isolated step-down transformer.
4. Power ON indicator (LED) on secondary of flyback converter.
5. 180 kHz switching frequency.
6. Pot core flyback inductor to limit EMI
7. Three flyback secondary circuits: two FET gate drive circuits and a control circuit.
8. Each gate drive supply is electrically isolated.
9. Control circuit referenced to earth ground for safety.

POWER SEMICONDUCTORS:

- Power diode (MUR3040PT) and FET (IRFP360) with lossy snubber designed for 200V, 10A.

POWER SEMICONDUCTOR CONNECTIONS:

- Multi-hookup binding posts with 0.750” center layout.

CONTROL INPUTS: (BNC jacks)

- D input for direct modulation of q(t). Example: PWM generation.
- q(t) w/ switch (DPDT):

  int: ouput q(t) to BNC as master control
  ext: input q(t) from BNC as slave control
- Switch to select mode for FET 2 (DPTT):
  1. q(t)
  2. invert q(t) with dead time (internal adjustment via multi-turn pot)
  3. Alternate FET 1 and FET 2 for push-pull
- ESD protection: series resistance and zener clamp.

CONTROLS:

- Duty Ratio:
  - Multi-turn precision POT
  - 5% to 95% range.
- Frequency:
  - Single turn POT with indicator.
  - 1 kHz to 300 kHz in two ranges

CONSTRUCTION:
- PCB based design
- Front panel mounted controls and connections
- Rear panel ac line cord, dc aux input, fuse, power switch.

3. User Interface

The user interfaces for the FET Control Box resides on the front and rear panels. The rear panel contains the ac and dc supply connections and power switch. The front panel contains the uncommitted FET and Diode connections and controls and inputs for the switching function.

3.1 Back Panel

The back panel contains the AC input and fuse, the DC input, and the power switch. The FET Control Box accepts 120V AC via a standard IEC style line cord. The AC inlet has an integral fuse and spare fuse holder. The power switch turns off the AC power. Alternatively, a 12 VDC source can be used. Polarity is +12 on the "tip" and ground reference common on the "ring." The power switch has no effect when using the DC input.

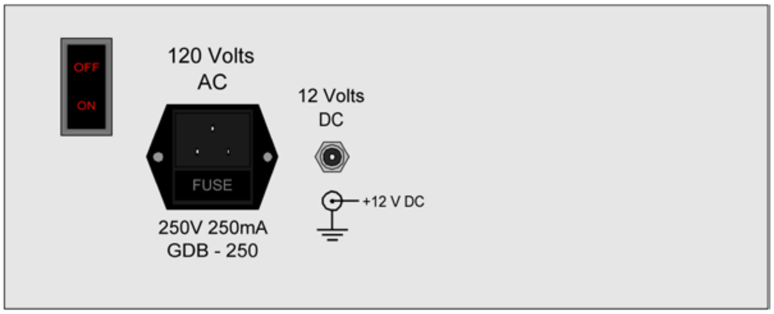

Figure 1: Rear Panel

3.2 Front Panel

The front panel contains the frequency and duty ratio controls for the FET Control Box, external control input and outputs, the source and drain terminals for each of the FETs, and the anode and cathode terminals for each of the auxiliary diodes. The two FETs and two auxiliary diodes are completely isolated for configuration in a wide variety of topologies. There is a switch for selecting the switching functions for the two FETs. Another switch selects between the internally generated switching function and an externally supplied switching function. For internal switching function operation, "int," the Frequency and Duty Ratio knob set their respective parameters and the q(t) BNC jack operates as an output. A second BNC, D, allows the user to override the Duty Ratio control knob with an external signal. For externally generated switching function, "ext," the q(t) BNC is the input for a TTL compatible signal. The green LED indicates that the internal power supply of the FET Control Box is operating.

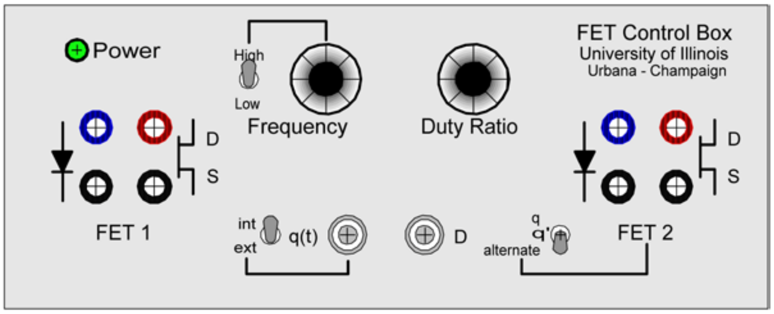

Figure 2: Front Panel

4. Theory of Operation

4.1 Power Supply

The FET box is designed to be powered primarily from a 120 V_{ac} earth grounded main connection. A fuse and power switch are located on the rear panel and act to prevent high voltage from reaching the PCB. The input front end of the power supply is shown on page 1 “Input Rectifier” of the schematic.

A step-down transformer (T1) with center-tapped secondary is used to achieve galvanic isolation. A MOV (MOV1) across the primary and necked down traces on the PCB offer protection and clamping in the case of a line voltage transient.

The secondary circuit of the transformer is earth grounded thru a ferrite bead. The ferrite bead (L1) is necessary to prevent common mode noise coupled to the chassis ground via the FETs and grounded heatsinks from coupling into the control circuit. A half-bridge rectifier (D2,D3) and capacitors (C1,C2,C40) provide a dc bus voltage. A linear regulator (U13) provides tightly regulated 12V for the power supply PWM ic.

Page 2 of the schematic “Isolated Flyback Power Supply” contains the control and power stages for the flyback converter. The PWM ic (U2) operates in open loop mode with frequency set by C12 and R4 and duty ratio set by trim pot R19. A gate driver ic (U3) provide low impedance current drive for the flyback FET (Q1). The snubber circuit is not entirely necessary as the ratings of the FET are more than adequate to maintain a safe operating area (SOA).

The flyback inductor (T2) is wound on a P3622 bobbin and a P36/22 pot core with one gapped and one ungapped 3B7 ferrite piece. Two secondary circuits provide the isolated 12V nominal voltage for the gate drive of each power FET. The actual voltage is set to about 14V with no power FET current and drops to about 12V with high switching frequency or large drain currents on the power FET devices. A linear regulator provides 5V from the unregulated 7V winding for the logic ics.

4.2 Internal Generation of Switching Function

Another PWM ic (U4) operates open loop to generate a primary PWM signal used to derive the switching function for each of the power FETs as shown on page 3 “FET Drive PWM Circuit” of the schematic. The front panel mounted “Duty Ratio” control (R8) adjusts the duty ratio while pront panel mounted “Frequency” control (R11) adjusts the oscillator frequency. The duty ratio control is trimmed at high and low end to minimize dead-travel by R7 and R10. The frequency range selector switch (S2) switches a second capacitor (C20) in parallel with the primary timing capacitor (C19).

The dual outputs of the PWM ic open collector and wire-or’ed together with a pull-up resistor. The PWM signal is buffered by U14 before the front panel mounted BNC (J4). A series resistor (R28) provides current limiting in the event of a short circuit on the BNC or elsewhere external to the control box.

The PWM ic can be synchronized externally by providing a TTL compatible signal on the q(t) BNC (J4) and selecting “ext” on the front panel mounted switch (S1). An external duty ratio can be programmed via the “D” front panel mounted BNC (J3) connector. The external signal is setup with an inverting function so that a higher signal at “D” will drive a lower duty ratio. This enable easy feedback connection without an external inverting op-amp.

4.3 Dead-Time and switching function control logic

The switching function for each power FET is derived by the logic circuit on page 4 “Deadtime Circuit w/ Second FET Logic” in the schematic. The front panel mounted switch (S3) selects the switching function for each of the power FETs. Dead time is generated for the “complement with deadtime” configuration by R12 and C23. Nominal deadtime is set for 150nS. It is critical that the correct family of logic be used (U6) because of the different threshold voltage levels inherent between TTL and CMOS. Use only the logic families called out on the BOM.

The isolated gate drive is provided by the circuit on page 5 of the schematic. Speed-up capacitors C32 and C33 help increase the switching speeds of Q2 and Q4. U8 and U10 prvide optical isolation. Low impedance gate drive is provided from each isoltaled gate drive voltage buss by U9 and U11.

4.4 Power Output Stage

The main power devices (M1, M2, D13,D14,D15,D16) are mounted on heatsinks using electrically isolating material. Speed-up capacitors C52, C53 help with commutation. Gate-source resistors R26,R27 help to prevent dv/dt turn on via the miller capacitance. Due to the wide operating range of the FET control box, the snubber is not optimized but instead designed to protect the FET under worste case conditions to maintain operation within the SOA.

5. Assembly Instructions

5.1 Rear panel wire harness make-ready

NOTE: Observe pin numbers on MTA connectors begin with #1 on right and increase to the left. All assemblies use stranded wire.

5.1.1 AC Power Wire Harness Assembly make-ready

Terminal	Wire	MTA 156 (3 pos)
Neutral	6.75″ white #18 AWG for Neutral	#1
Earth GND	7″ green #18 AWG for GND	#2
Hot	8.25″ black #18 AWG for Hot	#3

Over the wire harness, add 4″ of 0.25″ dia. clear heat shrink tubing centered between the ends. Crimp 90^{O} fast-on “flag” connectors on other ends of the harness. Use a vise to crimp.

One (1) 4″ black #18 AWG wire with 90^{O} fast-on “flag” connectors on both ends.

5.1.2 DC Power wire harness assembly make-ready

Barrel connector Terminal	Wire	MTA 156 (3 pos)
Ring (GND)	3.75″ white #18 AWG	#1
Tip (POWER)	3.75″ black #18 AWG	#2

5.2 Front Panel Wire Harness make-ready

NOTE: Observe pin numbers on MTA connectors begin with #1 on right and increase to the left. All assemblies use stranded wire. First solder wires to terminals, and then cut all wires to same length and crimp into connector. Twist all wires within a harness together.

5.2.1 Freq switch assembly (SPDT switch)

Terminal	Wire	MTA 100 (2 pos)
On	5″ orange #24 AWG	#1
Center	5″ purple #24 AWG	#2
On	No Connect	No Connect

5.2.2 M/S switch (SPDT switch)

Terminal	Wire	MTA 100 (3 pos)
On	4″ yellow #24 AWG	#1
Center	4″ purple #24 AWG	#2
On	4″ orange #24 AWG	#3

5.2.3 Mode switch (DP3T)

Mode switch has three rows of four terminals. ⇒ one color per row, three colors.

Terminal	Wire	Flying leads
Bottom row	2″ yellow #24	tinned
Middle row	2.5″ purple #24	tinned
Top row	3″ orange #24	tinned

5.2.4 Duty ratio POT (Multi-turn pot)

Terminal	Wire	MTA 100 (3 pos)
#1	6″ yellow #24 AWG	#1
#2 wiper (center)	6″ purple #24 AWG	#2
#3	6″ orange #24 AWG	#3

5.2.5 Frequency POT (Single-turn pot)

Terminal	Wire	MTA 100 (2 pos)
#1	No Connect	No Connect
#2 wiper (center)	4″ purple #24 AWG	#2
#3	4″ orange #24 AWG	#1

5.2.6 BNC jacks (Qnt=2)

Terminal	Wire
Center	2″ red #24 AWG
Ring	2″ black #24 AWG

Tin ends of wires and twist together.

5.2.7 Green LED

Terminal	Wire	MTA 100 (2 pos)
Anode (longer lead)	6″ #24 AWG red wire	#1
Cathode (shorter lead)	6″ #24 AWG black wire	#2

Cut LED leads to approx 0.75″ keeping the anode longer. Solder wires to LED, staggering solder joint. Slide 1″ of 3/32″ clear heat shrink each wire all the way to the LED body. Shrink with heatgun. Slide 1″ of 3/16″ clear heat shrink around both leads and shrink with heatgun.

5.3 Back Panel Assembly

NOTE: Use tools called out in instructions. Do-not use adjustable wrenches as they slip and may mar the finish. Use only parts called out in the BOM – no substitutions.

1. Wipe all metal surfaces with rag and Windex to remove any grease or residue before assembly.
2. Insert AC switch by pressing firmly into panel as shown in Figure 3.
3. Insert AC inlet. Secure with two (2) 6-32 x ⅜″ flat head Phillips head screw with 6-32 backing nuts as shown in Figure 3 and Figure 4. Tighten with appropriate size screwdriver and 5/16” wrench to hold nut. (slot heads ok if Phillips not available)
4. Install one (1) 250mA fuse into fuse holder and one (1) into spare holder.

5. Insert DC coaxial barrel jack with a backing nut and a front nut. Adjust so jack sits flush on panel as shown in Figure 3. Use ¼” washer as a spacer on inside panel if needed as shown in Figure 4. Tighten using a ⅜″ wrench.

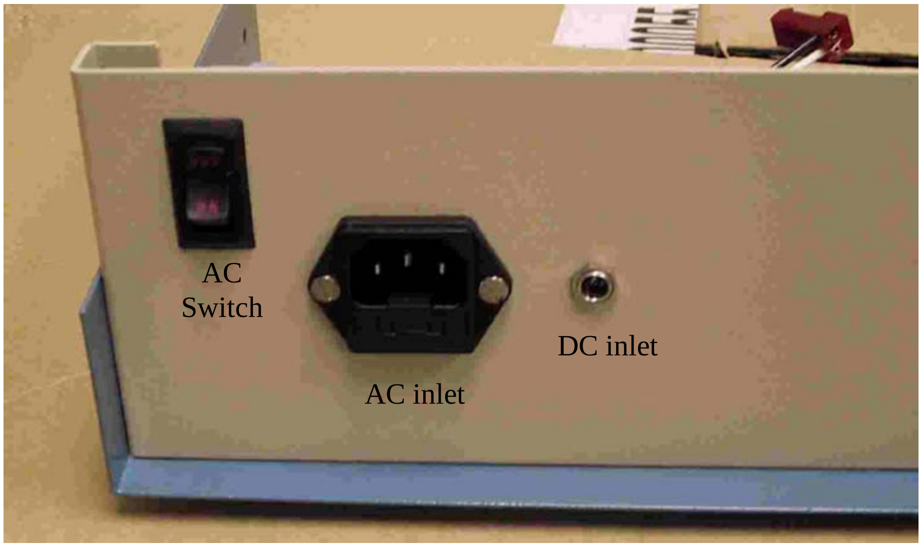

Figure 3: Back Panel Assembly - outside

Figure 4: Back Panel Assembly – inside

5.4 Front Panel Assembly

NOTE: All devices mount flush to front of panel. Adjust rear nut to achieve proper mounting depth. When given the choice, use the thinner nuts on the output of the panel and the thicker ones for the inside (hidden).

1. Wipe all metal surfaces with rag and Windex to remove any grease or residue before assembly.
2. Install binding posts in correct color order. Tighten nut with ⅜″ wrench.
3. Install BNC jacks with solder washer, star washer, then nut on inside of panel. Tighten with a 7/16” wrench.

4. Install M/S and freq selector switches. Be sure to orient in straight up/down manner. Use a front nut and back nut with star washer and round washer to flush mount the switch to the front of the panel. Star washer goes against panel, then round washer followed by nut. Reverse the locator notch on the round washer since no hole exists for it. Frequency selector switch (S2) mounts with yellow wire up. M/S switch (S1) mounts with orange wire up. Tighten using ⅜″ wrench and channel lock pliers to hold switch body in vertical orientation.
5. Install pots. Use a front nut and back nut with star washer to flush mount the shaft threads to the front of the panel. Tighten using ½” wrench.
6. Turn the pot shafts fully CCW. Install knobs for pots with screws at 10 o’clock and 2 o’clock. Tighten with 0.050” allen wrench. Freq knob indicator should point to 7 o’clock when fully CCW and 5 o’clock when fully clockwise. Duty ratio knob is without indicator line.
7. Place retaining ring over LED and push past LED. Insert LED holder from the front of panel. Push LED into holder from rear of panel. Push holder and LED to front, compressing ear-tabs so that the retainer ring can slide on. Hold retainer from back and push LED holder from front until flush with panel and assembly is tight.

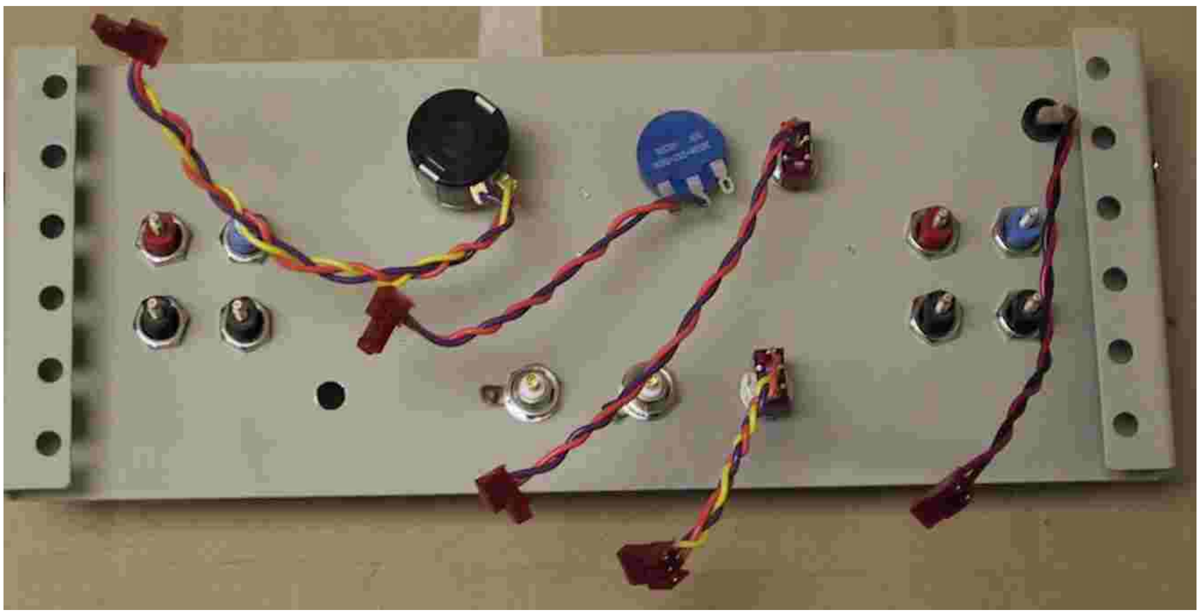

Figure 5: Front Panel Assembly - inside

5.5 Bottom Assembly

1. Wipe all metal surfaces with rag and Windex to remove any grease or residue before assembly.
2. Attach rubber feet (4) with 6-32 x ¼″ Phillips pan head screws to the 6-32 x 3/8″ stand-offs on the inside of box. Do not over tighten.
3. Attach the fifth 6-32 x 3/8″ stand-off to the bottom enclosure with a 6-32 x ¼″ Phillips pan head screw. Use a ¼″ hex nut driver to hold the standoff while tightening.

5.6 PCB Make-Ready

5.6.1 U13 heat-sink

Wipe all metal surfaces with rag and Windex to remove any grease or residue before assembly. Attached heat-sink to U13 with 6-32x¼″ Phillips pan head screw and 6-32 using a 5/16” socket driver.

5.6.2 Heatsink ground wire

8.00″ green #18 AWG for M1 heatsink
10.00″ green #18 AWG for M2 heatsink

Strip and tin one end using solder pot, crimp #8 ring terminal to other.

5.6.3 L2, L3 snubber inductor

3.00″ #14 AWG magnetic wire

Cut magnetic wire to length. Remove 0.25” of varnish from both ends of wire. Pass wire through ferrite bead and align at mid-point. Bend each wire under ferrite bead as shown in Figure 6. Tin ends of wire using a solder pot to ensure uniform coating.

Figure 6: 1 turn ferrite bead for snubber inductor

5.6.4 L1 inductor

Put 11 turns of #16 AWG magnetic wire on a L1 ferrite inductor. Strip insulation ½” from end and tin using solder pot.

Figure 7: L1 inductor

5.6.5 T2 flyback inductor

The flyback inductor consists of a total of four (4) electrically isolated windings placed on a pinned 36/22 pot core bobbin as per Table 1. Pins are numbered consistent with DIP package. All windings MUST be wound in counter-clockwise as viewed from above starting with the dot-winding as in Figure 8.

1. Wind Isolated-A and Isolated-B simultaneously by using two spools of wire.
2. Use yellow polyester tape to separate the two windings.
3. Solder to pins.
4. Wind Control winding.
5. Tape using yellow polyester tape.
6. Solder to pins.
7. Wind primary coil.
8. Tape using yellow polyester tape.
9. Solder to pins.
10. Test for continuity of each coil and for shorts between coils.

Table 1: Flyback inductor windings

Winding Order	Wire	# of turns	Nominal Inductance	Pins on bobbin (dot-first)
1) Isolated-A	#24 AWG magnetic wire	38	577µH	2-5
1) Isolated-B	#24 AWG magnetic wire	38	577µH	3-6
2) Control	#24 AWG magnetic wire	29	336µH	9-10
3) Primary	#24 AWG magnetic wire	50	1000µH	8-11

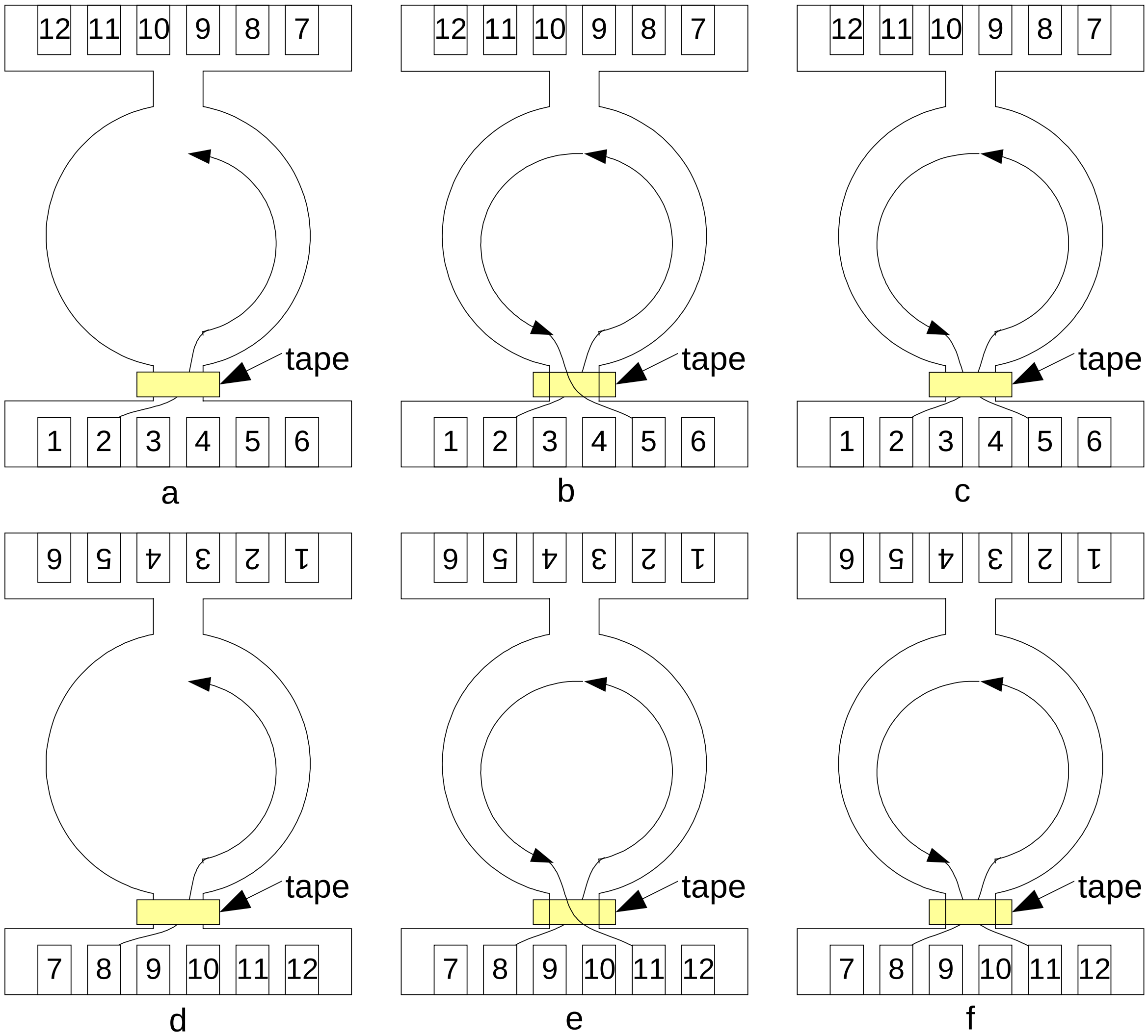

Figure 8: Winding direction and taping (viewed from the top)

5.6.6 Heat-sink with power diodes and FETs

1. Wipe all metal surfaces with rag and Windex to remove any grease or residue before assembly. Pay particular attention to the flat back of the heatsink.
2. Use the heatsink assembly fixture shown in Figure 9. Note that the left and right side heatsinks are mirror images. Only one heatsink can be assembled at a time. Orient the heatsink assembly fixture with the writing in the normal orientation (shown in Figure 9)

Figure 9: Heatsink assembly fixture

3. Cut plastic shoulder washer to fit thickness of metal tab on D13, D14.
4. Insert M1 face down in the slot labeled *FET* on the *Left* side.
5. Insert D13 and D14 face down in the slot labeled *Diode* on the *Left* side.
6. Cover the tab of M1, D13, and D14 with thermal isolation pads, aligning the hole in the pad with the hole in the device. Do NOT use thermal grease.
7. Slide the *Left* heatsink into the fixture with the end-side hole facing to the left. Use the alignment pins on the fixture to properly locate the heatsink.
8. Flip the fixture and heatsink over. Attach M1, D13 and D14 to the heatsink using fasteners and shoulder washers specified in Table 2. Hand-tighten.

Table 2: Heatsink assembly fasteners

Part	Fastener	Shoulder washer
M1, M2	4-40x½" Phillips pan head	Un-modified
D13, D14, D15, D16	4-40x⅜" Phillips pan head	Cut to size

9. Remove the heatsink from the fixture.
10. Verify no electrical shorts exist to heatsink: use a multi-meter in continuity mode to check for shorts between each pin of M1, D13, D14 and the heatsink. If a short exists, remove the screw for that device, Repeat the assembly of that part using the fixture. Note the position of the thermal pad. Check again for shorts.
11. Attach the ground wire to the heatsink as per Table 3 using a star washer and 6-32x⅜" Phillips pan head screw.

Table 3: Heatsink ground wire

Heatsink	Wire
Left	8.00″ green #18 AWG for M1 heatsink
Right	10.00″ green #18 AWG for M2 heatsink

12. Repeat assembly steps 3 through 11for *Right* heatsink.
13. Fully assembled heatsinks are shown in Figure 10 and Figure 11.

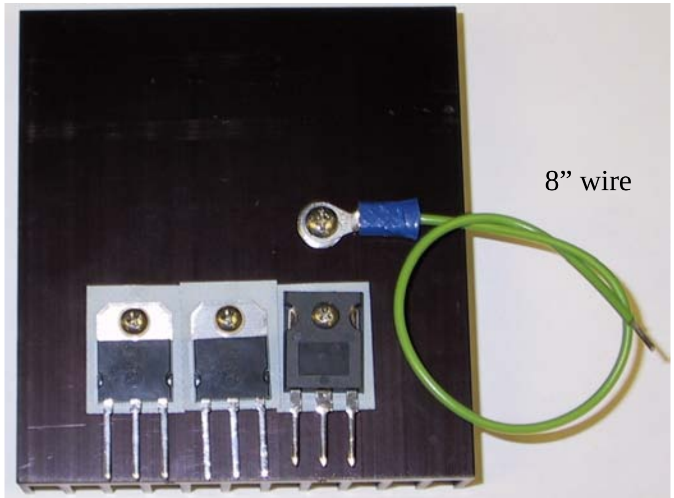

Figure 10: Left side heatsink

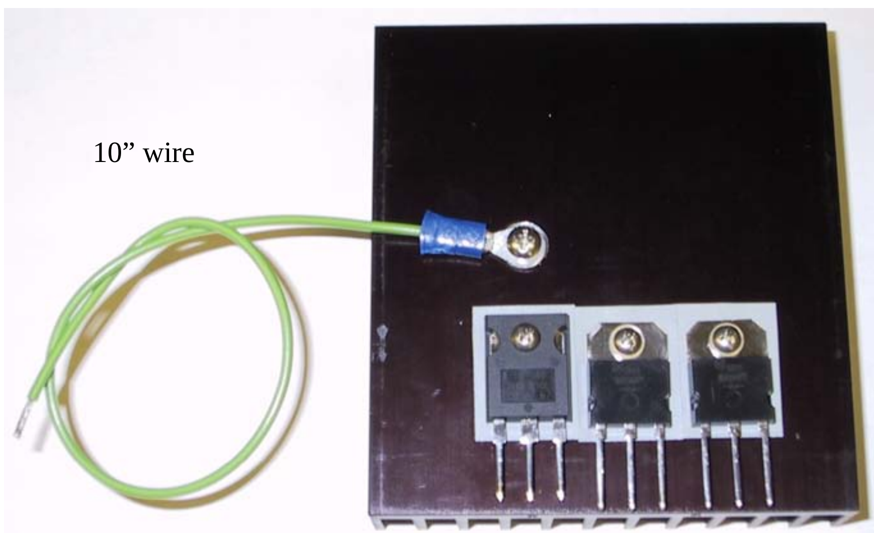

Figure 11: Right side heatsink

5.7 PCB assembly

1. Insert IC sockets only (no chips).
2. Insert and solder IC sockets with a fine tip iron.
3. Insert and solder 1μF and 0.1μF capacitors as in Figure 12.

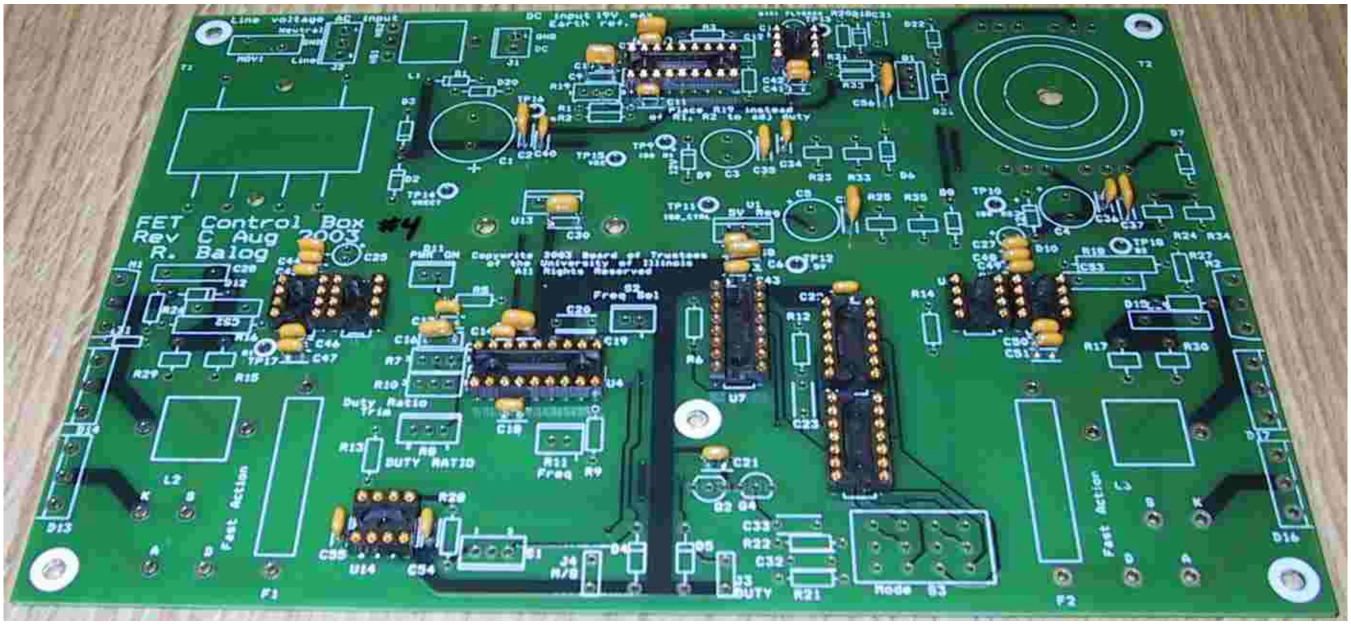

Figure 12: Sockets, 1μF and 0.1μF capacitors

4. Insert and solder test points.
5. Insert and solder ¼W resistors. Bend leads at 0.400”.
6. Insert and solder Q2 and Q4.
7. Insert and solder pot R7, R10.
8. Insert and solder R19.
9. DO NOT insert R1, R2, or C31.
10. Insert remaining capacitors.
11. R16, R18 bend leads at 0.700”
12. Bend D1-D12, D18-D22 diodes at 0.400”.
13. Insert and solder MTA headers.
14. 1W and 2W resistors placed as “hairpins” per Figure 13 and Figure 14.
15. Insert a 0.300” jumper at location 171 near M1.
16. Insert the fuse into the fuse holders before inserting the holder into the PCB. This helps retain the fuse holder during soldering.
17. Solder L2 and L3 onto PCB ensuring that the ferrite stands above the PCB for air circulation.
18. Insert and solder L1.
19. Insert heatsink and U13 assembly into PCB. Solder heatsink pins BEFORE TO-220 pins.

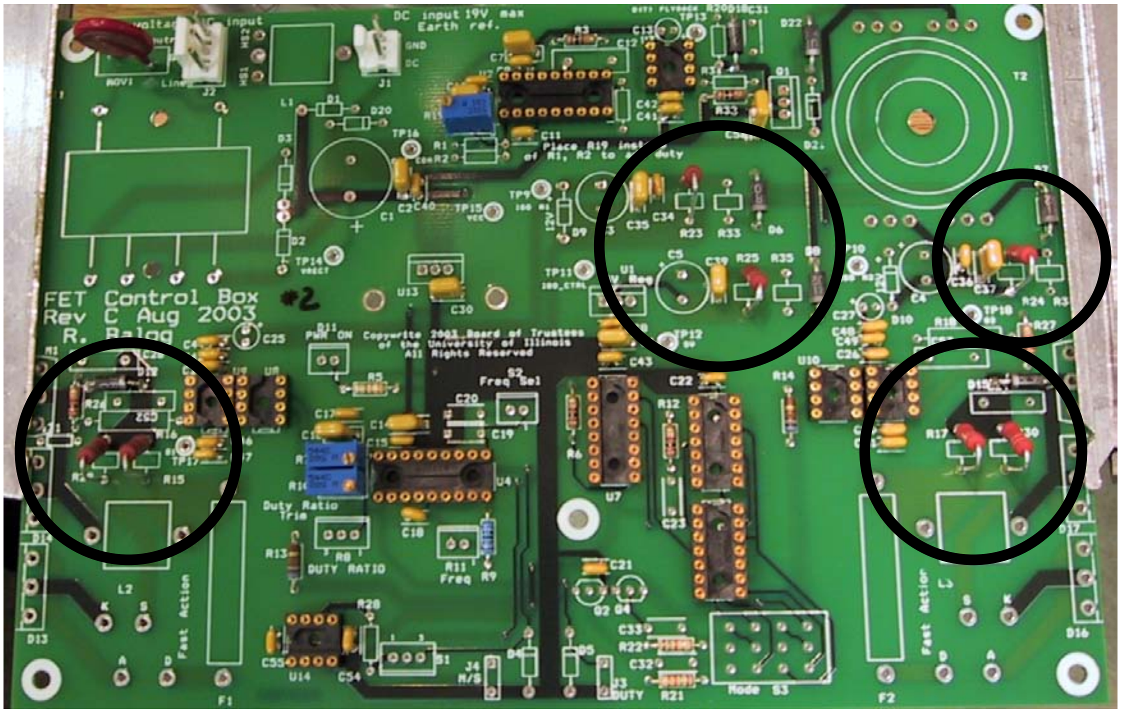

Figure 13: Hairpin 2W resistors

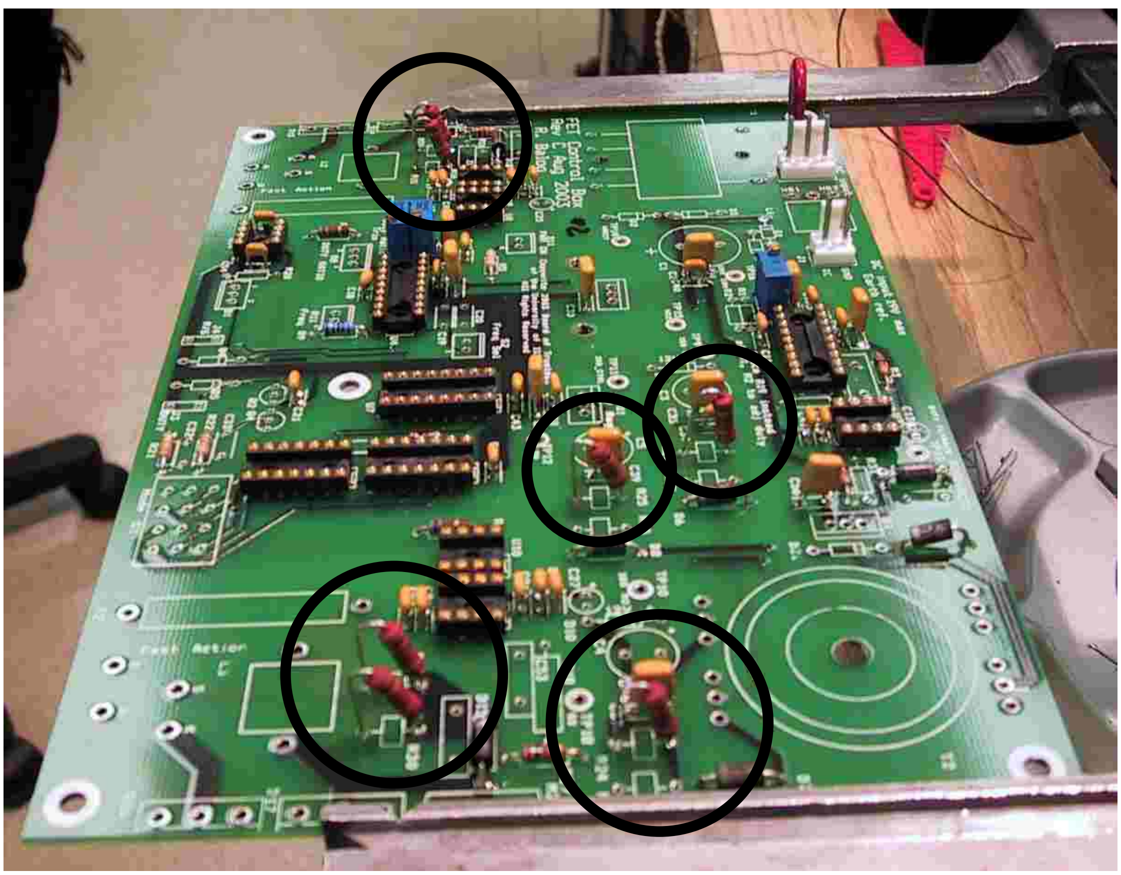

Figure 14: Orientation of Hairpin resistors

20. Secure the transformer (T1) to the PCB with the long 4-40 screws inserted from the bottom so that the nut is on the transformer and the head against the PCB.
21. Assemble the flyback inductor (T2) as in Figure 15 with the ungapped (no marking) 36/22 pot core half on the bottom, then the pinned bobbin, followed by the gapped (with markings) core piece. Secure the flyback inductor (T2) with the nylon screw inserted from the bottom of the PCB and a nylon washer. Hand tighten with a 11/32" nut driver. Solder pins after tightening screw.

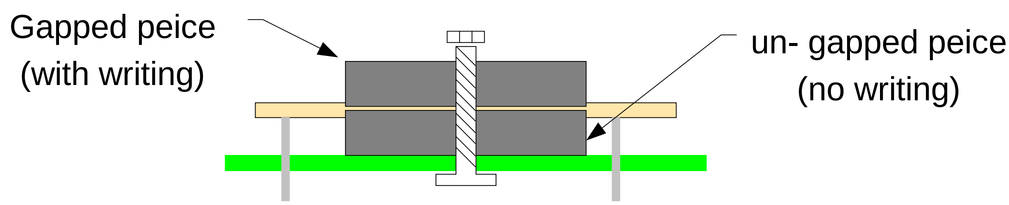

Figure 15: Flyback transformer mounting to PCB

5.8 Final Assembly

1. Ensure that PCB has been tested according to 6.1 Power supply and 6.2 PWM section
2. Solder all wires from front panel assembly to PCB according to Table 4, Table 5, Figure 16, and Figure 17.

NOTE: Wire to binding posts is 16 AWG.

NOTE: For placement of panel wires to the PCB, assume a top view with writing right side up.

NOTE: Left and Right cluster of binding posts NOT identical.

Table 4: Front Panel BNC connection

BNC terminal	Wire	PCB pad
Center	Red	Top
Ring	Black	Bottom

Table 5: Front panel binding post connection

Binding post		PCB pad	wire
Blue	Top right	A	cut to 3.25” strip ¼” ea. end Side, tin one end
Black	Bottom right	K	cut to 2.25” strip ¼” ea. end Side, tin one end
Red	Top left	D	cut to 3.25” strip ¼” ea. end Side, tin one end
Black	Bottom left	S	cut to 2.25” strip ¼” ea. end Side, tin one end

Figure 16: Solder wires from PCB to binding posts

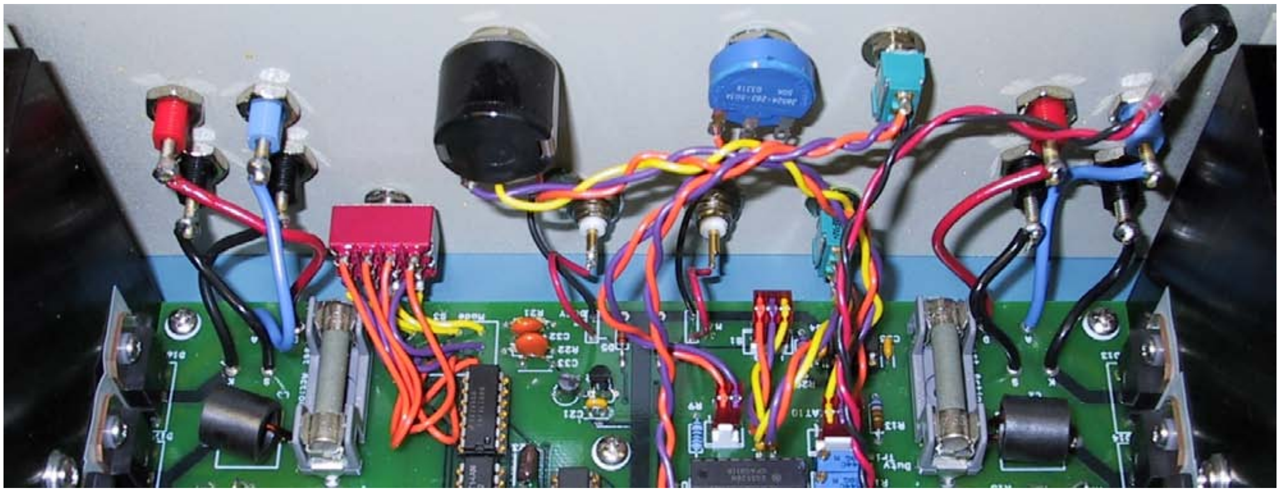

Figure 17: Inside of front panel fully assembled

3. Use solder jig to hold pieces together as shown in Figure 18. NOTE: JIG holds everything upside down. Position right heatsink subassemblies on left side with green wire pointing to back. As shown in Figure 19. Position left heatsink subassemblies on right side with green wire pointing to back as shown in Figure 20.

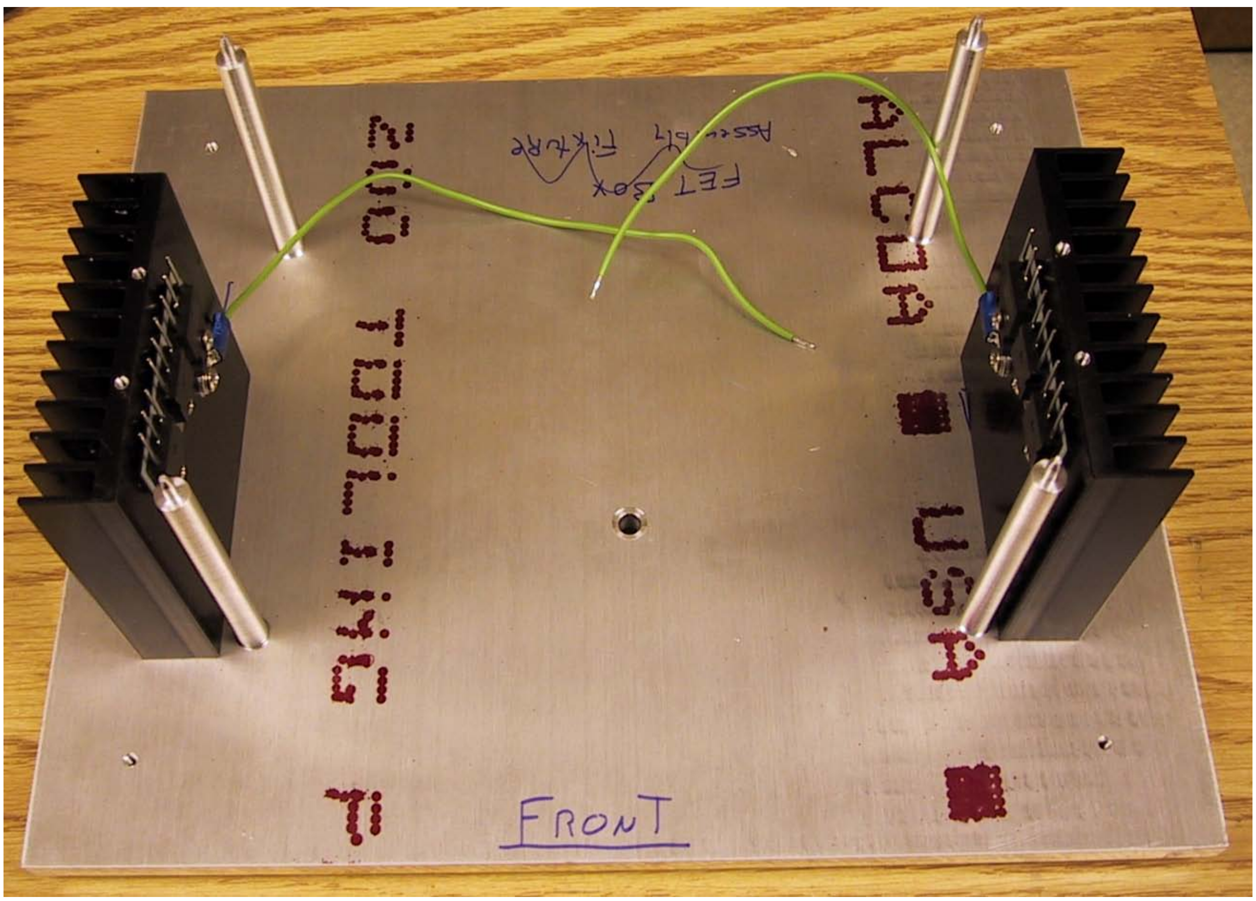

Figure 18: Heatsink assembly fixture

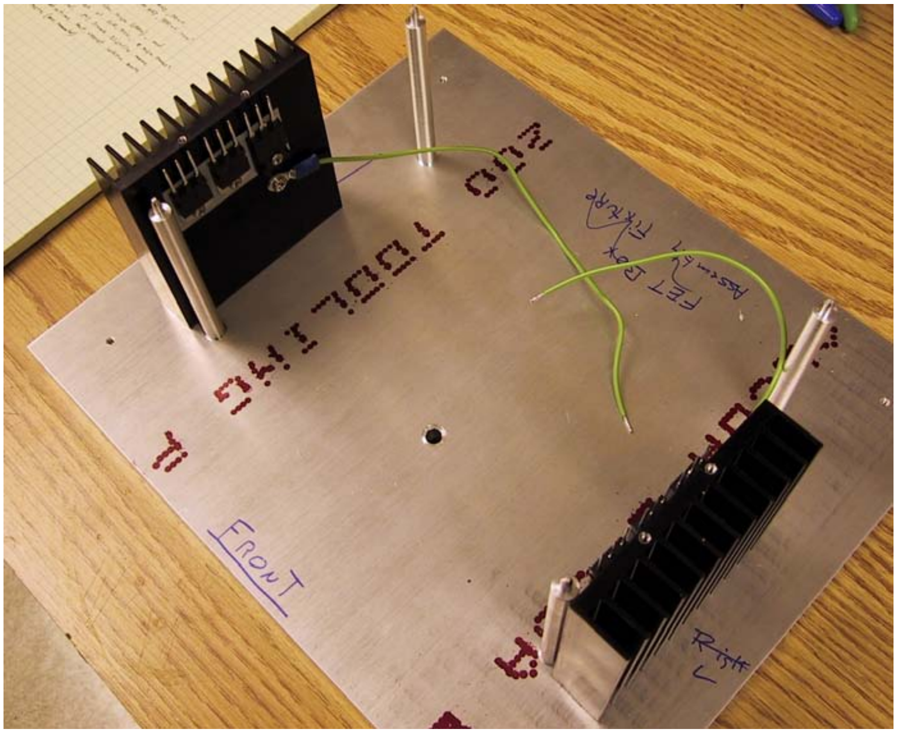

Figure 19: Heatsink assembly fixture - left side

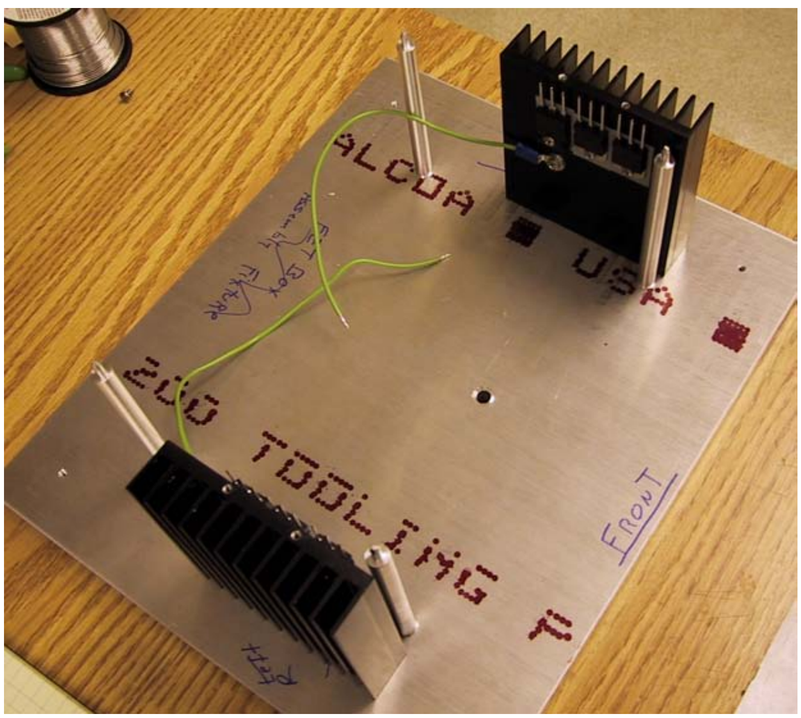

Figure 20: Heatsink assembly fixture -right side

4. Turn PCB upside down and aligned with power component pins.
5. Lower the PCB to rest on the stand-off locator pins as in Figure 21 (NOTE: front panel not shown for illustration purposes).

6. Ensure that the PCB fully seated and resting on the stand-off pins for proper alignment. Solder the power devices to the PCB. Trim off leads.
7. Inserted the green ground wires from the heatsinks HS1 and HS2 from the bottom of the PCB and solder from the top.

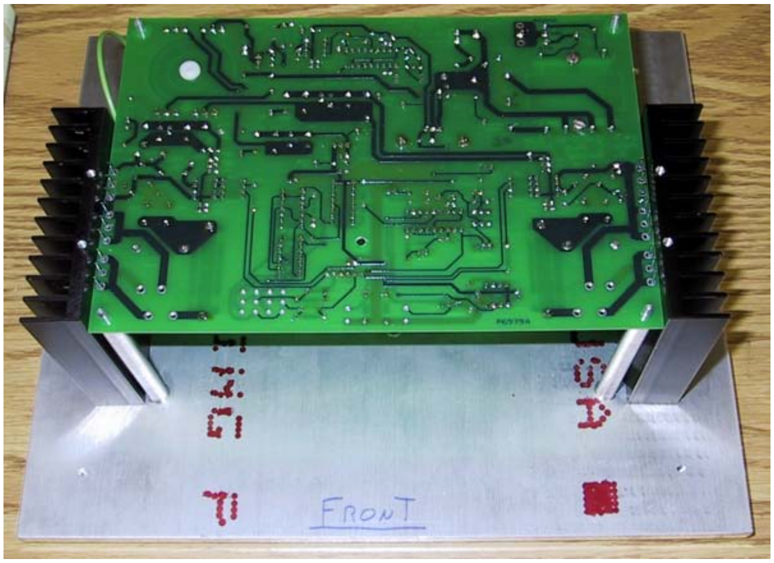

Figure 21: Heatsink assembly fixture with PCB

8. Turn a bottom enclosure piece upside down and place over PCB-heatsink assembly.
9. Attach the heatsinks to the bottom enclosure with 4-40x⅜” (4) Phillips pan head screw.
10. Remove assembly from fixture.
11. Attached PCB to stand-offs using 6-32x3/16” (5) Phillips pan head screws. Hand tighten only.
12. Attach front panel to bottom enclosure using 6-32 screws provided with enclosure.
13. Attached rear panel to bottom enclosure using 6-32 screws provided with enclosure.
14. Attach all wire harness from front and rear panel as shown in Figure 22.

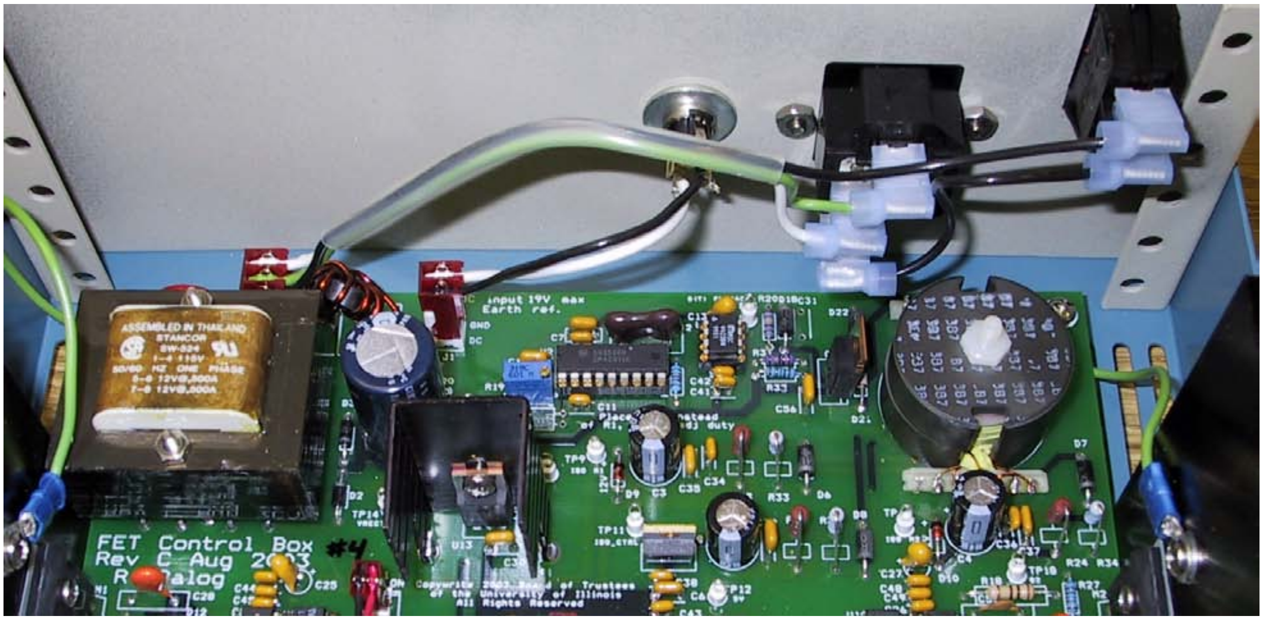

Figure 22: Rear panel wire harness

15. Attach top enclosure piece using 6-32 screws provided with enclosure.
16. Test as per section 6.3.

6. FET Control Box Assembly Electrical Testing

NOTE: All ICs initially removed from sockets. Always use the variac to ramp up the ac voltage – never switch on 120V directly.

6.1 Power supply (requires a test ac harness)

1. With U2 and U3 removed from socket, connect 120V thru a variac to the PCB via J2 using test ac harness shown in Figure 23. Slowly increase AC voltage via variac to 120Vac . If at any point the input ac line current exceeds 125mA, turn off the power. Measure voltage at TP14 (Vrect) with respect to TP16 (ckt com). It should be 19V – 20 Vdc.

Figure 23: Ac test harness

2. Verify TP15 (VCC) is at 12Vdc ± 0.010 V with respect to TP16.
3. Turn off AC power. Insert IC U2.
4. Adjust R19 to approximately mid-point (10 turn pot , clockwise lowers voltage).
5. Ramp up AC voltage. Verify that pin2 of U3 is a square wave, has frequency of 180kHz ± 10kHz. Adjust R19 for an approximately 50% duty ratio (wiper voltage will be about 3V).
6. Turn off AC power. Insert IC U3.
7. Ramp up AC voltage. Measure voltages across D9 (TP9 to anode) and D10 (TP10 to anode). Adjust R19 such that these voltages are about 13.5Vdc ± 0.050 V. (final duty ratio ~55%, record the actual value with the PCB serial number)
8. Measure voltage at TP12. It should be 5Vdc ± 0.010 V.
9. Verify that "Power" LED on the front panel turns on.
10. Turn off AC power.

6.2 PWM section (requires a front panel)

6.2.1 Procedure

1. Insert U4.
2. Attach R8 (duty ratio), R11 (frequency), and S2 (freq sel) from the front panel. Adjust pot R7 and pot R10 to approximately the mid-point. Position S2 (freq sel) in the up or “high” position.
3. Connect Oscilloscope to the lead of R6 by the silk screen (toward front of box). Turn on AC power. Verify that the Duty Ratio and Freq knobs work for both freq ranges (high and low).
4. Turn off AC power.
5. Insert U5, U6, U7, U8, U9, U10, U11, U14. OBSERVE ORIENTATION!
6. Connect Oscilloscope probes (2) from TP17 to the top pad of M1 and from TP18 to the bottom pad of M2. Adjust freq and duty ratio control knobs to about mid-point.
7. Put Mode switch into up position [q,q]. Ensure that both pins have exactly the same signal.
8. Put Mode switch into middle position [q,q’]. Ensure that both pins have complementary signals. Verify dead-time between two signals (both stay low for time.)
9. Put Mode switch into down position [Alt q, Alt q]. Ensure that both the signals alternate with half the frequency.
10. Set the Mode switch in the “up” position [q,q], and the frequency select switch to “high” and the freq knob full CCW. Adjust the Duty ratio trim potentiometers as per Table 6.

Table 6: Duty Ratio trim

Position of Duty ratio knob	Adjust
CW	R10 to minimize dead travel
CCW	R7 to minimize dead travel

6.2.2 Trouble Shooting Guide

Symptom	Correction
V_{gs} of M1, M2 not identical when MODE is [q,q]	Verify Q2 and Q4 part number and insertion orientation.
No signal on V_{gs} as either M1 or M2	Check proper placement of U8, U9 and U10, U11 for each FET respectively.
No dead-time for one or both switching transitions when MODE is [q,q’]	Verify proper logic family is used for dead-time circuit U5 and U6. Excessive propagation delay through the opto-couplers will require a larger time-constant in the dead-time control logic.
V_{gs} of M1, M2 not alternating when MODE is [Alt q, Alt q]	Verify U7 part number and insertion orientation.

6.3 Final test

6.3.1 Procedure

1. Connect a buck converter shown in Figure 24 to each FET.

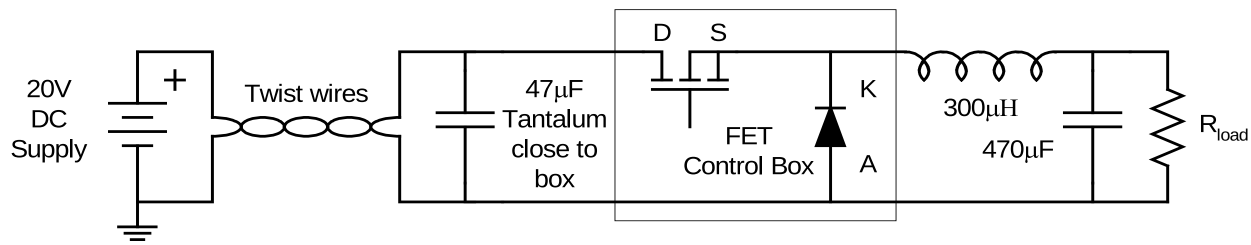

Figure 24: Buck converter test circuit

2. Wire the tantalum capacitor or equivalent quality low ESR electrolytic as close to the banana posts as possible and to make the connection between the FET source terminal and the diode cathode terminal as short as possible. Observe polarity and voltage ratings of the tantalum capacitor. The positive lead is connected to the DRAIN banana jack. Twist the leads of the supply wires to minimize inductance.
3. Use a 3.6Ω, 38W or equivalent load resistor. Set the input voltage to 20V and current limit to 4A. Set duty ratio to 50% and a frequency of approximately 30kHz.
4. Connect an oscilloscope probe across the diode and another across the load resistor. Attach a clamp style current probe to the wire connecting the source banana jack to the inductor. Observe current polarity.
5. Switch on power to the FET Control Box. Verify expected results shown in Table 7 and waveforms as shown in Figure 25. Verify that the diode voltage is in-phase with the $q(t)$ signal and dips negative while $q(t)$ is low. The output voltage is "ac" coupled and is in-phase with the inductor current. The inductor current is rising for positive diode voltage and falling for negative diode voltage. All traces are stable and do not jitter or jump.
6. Increase the current limit to 6A. Sweep the frequency and duty ratio to verify operation. Check both "high" and "low" frequency ranges.

Table 7: Typical operation of buck converter test circuit

V_{IN}	20V
I_{IN}	1.2A – 1.5A
V_{OUT}[1]	DC: 8.8V – 9.9V AC: 20mV – 50mV[2]
Duty Ratio	47% – 53%
Frequency	28kHz – 32 kHz

[1]Measured with a multi-meter at the load
[2]Actual ac component will vary depending on ESR of output capacitor

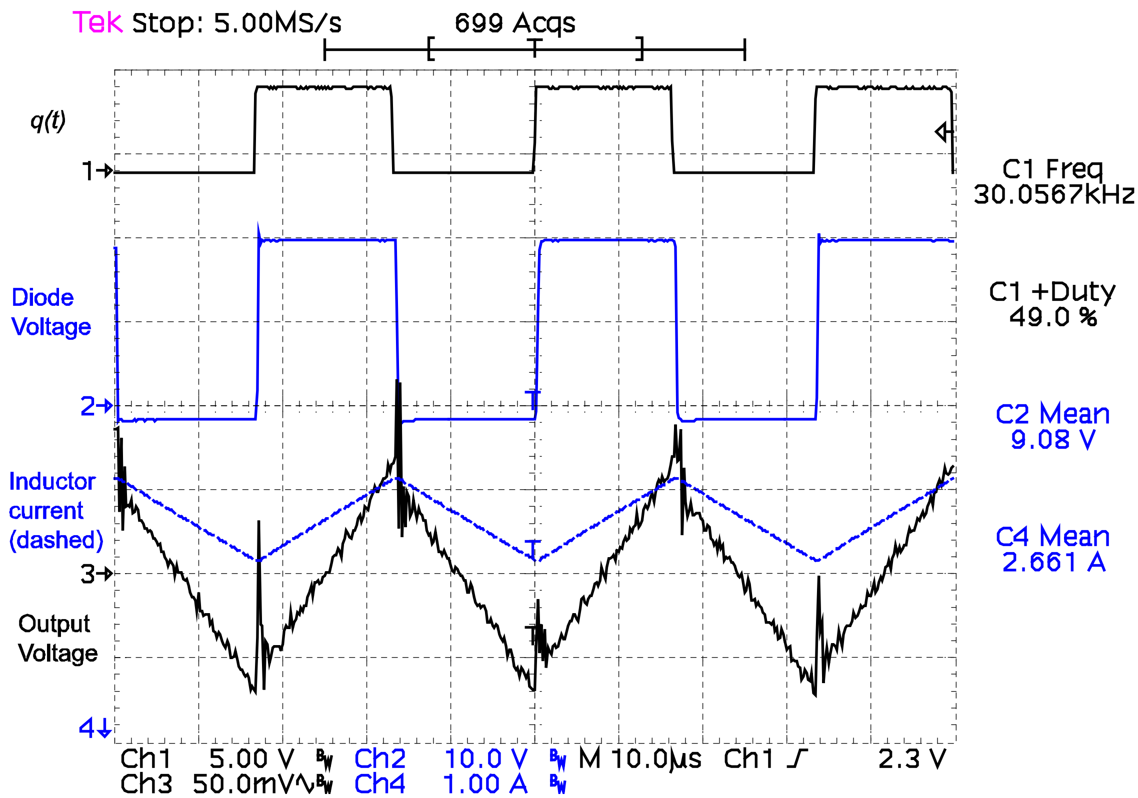

Figure 25: Buck Converter typical waveforms

6.3.2 Trouble Shooting Guide

Symptom	Correction
Duty Ratio control changes signal at $q(t)$ but has no effect on output voltage. The output voltage is approximately the supply voltage.	Check FET for possible short
The inductor makes a popping or hissing sound	Converter is likely running in discontinuous current mode. Verify if the inductor current drops to zero for any portion of the switching period. If so, increase the switching frequency to elliminate the condition.

7. Verification of Operation: "Calibration"

1. Use a multi-meter with diode checking capability. Connect the positive lead of the meter to the Source "S" banana jack of the left FET and the negative lead of the meter to the Drain "D" banana jack and verify approximately 0.5V. Reverse the multi-meter leads and verify an "open" condition. If a short exists in either configuration, then the FET is likely short circuited. Replace the FET.
2. Repeat for the right FET.
3. Verify that the front panel "POWER" led lights when the power switch is turned on. If not, open the top cover and perform the steps in section 6.1.
4. Connect a BNC cable from the $q(t)$ jack to an oscilloscope. Set the Mode switch in the "up" position [q,q], and the frequency select switch to "high" and the freq knob full CCW. Verify that the switching frequency is approximately 26kHz. Sweep the Duty Ratio control knob through the entire range of motion and observe the duty ratio of $q(t)$. Verify that there is no appreciable "dead-travel". If a problem exists, open the top cover and perform the steps in section 6.2.
5. Set the frequency range selection to "low" and the frequency control knob to CCW. Verify that the frequency is less than 1kHz. Turn the Duty Ratio Control knob to CCW and verify that minimum duty ratio is achieved. Turn the Duty Ratio Control knob to CW and verify that maximum duty ratio is achieved.
6. Repeat for frequency range selection to "low" and the frequency control knob to CW.
7. Repeat for frequency range selection to "high" and the frequency control knob to CCW.
8. Repeat for frequency range selection to "high" and the frequency control knob to CCW.

8. PCB Bill of Materials

Quantity	Reference	Part
1	C1	1000uF, 63V
11	C2,C6,C7,C9,C14,C16,C30,C35,C37,C39,C56	1uF
3	C3,C4,C5	470uF
27	C8,C10,C11,C15,C17,C18, C21,C22,C24,C26,C34, C36,C38,C40,C41,C42,C43,C44,C45,C46,C47,C48, C49,C50,C51,C54,C55	0.1uF
1	C12	1500 pF
3	C13,C25,C27	22uF Tant
3	C19,C32,C33	1000 pF
1	C20	0.047uF
1	C23	500pF
2	C29,C28	0.001uF, HV
2	C52,C53	1000pF
3	D1,D2,D3	1N4004
1	D4	1N4733
1	D5	1N4742
7	D6,D7,D8,D12,D15,D18,D22	MUR160
2	D9,D10	1N4744
2	D21,D20	1N4747
2	F1,F2	10A Fast Blow
1	J1	2 POS MTA156
1	J2	3 POS MTA156
1	L1	FT50-43
2	L2,L3	1Turn FT50B-43
1	MOV1	V130LA10A
1	Q1	IRF540
2	Q2,Q4	2N3904
6	R3,R6,R12,R26,R27,R32	1k
1	R4	5.1k
1	R5	330, 1/4W
2	R10,R7	5k POT
1	R9	2k

2	R14,R13	680
7	R15,R17,R23,R24,R25,R29,R30	330, 2W
2	R16,R18	10, 1/2W
1	R19	10k POT
1	R20	27k, 1/4W
2	R22,R21	1.5k
1	R28	47
1	R31	10, 1/4W
3	R33,R34,R35	4.7, 1W
1	TP9 - TP18	WHITE Test-Point
1	T1	SW-524
1	T2	P36-22 – custom transformer
1	U1	MC7805C / TO220
2	U4,U2	SG3526
1	U3	MIC4423
1	U5	SN74LS08
1	U6	SN74HC14
1	U7	SN74LS175
2	U8,U10	HP2211
3	U9,U11,U14	MIC4420
1	U13	MC7812C / TO220