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FAIRCHILD SEMICONDUCTOR™

Application Note 42002

ML4831 277 Volt Electronic Ballast Controller

GENERAL DESCRIPTION

This application note describes a low cost dimmable ballast design using the ML4831 electronic ballast controller IC. The design can be evaluated by assembling the parts listed in this document. This design is a version of Micro Linear's ML4831 220V ballast EVAL board. The ML4831EVAL-220V is designed to be modified for 277V operation by following the recommended changes in the parts list.

Operating over the range of 249 to 305 V_{RMS}, this power factor corrected 60 W electronic ballast, with a dimming range capable of a 10:1 intensity change, was optimized to power two series-connected F32T8 fluorescent lamps, and displays all the features of Micro Linear's ML4831 ballast controller IC. The mode of operation used for pre-heat, striking and dimming of the lamps is the widely accepted variable frequency, non-overlapping inverter topology.

Figure 1 displays the block diagram of this 277V ballast design.

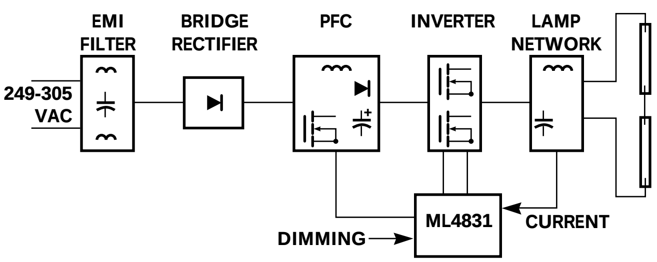


Figure 1

Applying AC line voltage to the ballast will supply start-up power to the ML4831 enabling gate drive for the PFC boost MOSFET Q1 and the inverter FETs Q2 & Q3. PFC action generates a well regulated 450 VDC supply for the lamp inverter circuit and a low DC supply voltage for the ML4831. The inverter stage consists of 2 totem pole configured N-channel power MOSFETs with their common node supplying the lamp network. The pair of MOSFETs are driven out of phase by the ML4831 at a 50% duty cycle.

The lamp network is single low pass LC section which when controlled from the ML4831 provides:

- Adjustable lamp power
- Required lamp starting voltage
- Controllable preheating filament and lamp voltages
- Near unity power factor
- High input impedance during starting or lamp-out-of-socket conditions
- Linear dimming with filament voltages increasing as lamp current is decreased

The series connected lamps are across the output of the LC network.

LAMP NETWORK DESIGN

The ML4831 allows the designer to select the filament preheating frequency and the lamp starting/minimum operating frequency.

The operation of the lamp network can be described by equations:

$$e_O = \frac{(e_{IN})(x_C)}{x_L + x_C} \quad (1)$$

and

$$Q = \sqrt{\frac{r_L}{r_{IN}} - 1} \quad (2)$$

Where:

e_{IN} = equivalent RMS network input voltage

e_O = Open circuit network output voltage

VB = PFC output voltage

x_C = Reactance of shunt capacitor

x_L = Reactance of series inductor

Q = Transformation Q of network

r_L = Equivalent lamp resistance at P_O

r_{IN} = Transformed value of r_L needed to produce P_O

P_O = Desired lamp power (arc and filament)

High frequency measurements using reference lamps and ballasts as described in ANSI Standards C82.3-1983 and C78.375-1991, must be performed to determine lamp current and voltage at the desired ballast factor. These values are used to determine P_O and r_L.

Since the PFC uses a boost type converter:

$VB > \sqrt{2} \times V_{RMS}$ line (max);

VB > (1.414) (1.1) (277), and thus

VB > 431VDC (450VDC is used).

The RMS amplitude of a square wave's fundamental is $\sqrt{2}/\pi$ times its peak to peak value.

So;

$e_{IN} = 0.45VB = 203\ V_{RMS}$

And by assuming negligible losses in the reactances;

$$r_{IN} = \frac{e_{IN}^2}{P_O} = \frac{203^2}{54} = 761\Omega \quad (3)$$

From high frequency reference ballast measurements, F32T8 lamps operating at an 0.86 ballast factor;

lamp current = $0.175A_{RMS}$

lamp voltage = $140V_{RMS}$

lamp arc power = 49W (total)

P_O (total) = 54W (allocating 5W to filaments)

$r_L = 1600\Omega$ (total),

and, from equation (2), Q = 0.986.

Values for x_C and x_L can be found from:

$$Q = \frac{x_L}{r_{IN}} = \frac{r_L}{x_C} \quad (4)$$

Thus $x_C = -1522\Omega$ and $x_L = 750\Omega$, and, from equation (1), $e_O = 400V_{RMS}$.

In this case there is insufficient voltage to reliably start the two lamps. A minimum starting voltage of $480V_{RMS}$ is required. Providing more starting voltage usually will require that a transformer be included in the network design. However, since the network nearly produces enough voltage, choosing a operating frequency (f_{MIN}), which is slightly higher than the unity power factor (resonant) frequency (f_{DES}), can provide the additional starting voltage.

CHOOSING THE STARTING/OPERATING FREQUENCY

The operating frequency, f_{MIN}, was found by:

a) finding a frequency — f_{DES} — to make the shunt network capacitor a standard value using the resonant values for x_C and x_L of -1522Ω and 750Ω, respectively. Using a 3.3nF capacitor makes f_{DES} = 30.8kHz and the inductor 3.88mH.

b) choosing a starting voltage, e_O (507V), then using equation 1) to find f_{MIN} from the capacitance and inductance values found in paragraph a).

$$f_{MIN} = 34\ \text{kHz}$$

For lamp rectification protection, line isolation, and Q enhancement, 33nF capacitors C9 and C22 (see figure 10) were added in series with the inductor on both the high and low sides of the line. The size of the inductor was increased to 5.5mH to compensate for the added capacitance. Since this increased the network Q at f_{MIN}, the starting voltage increased to $567V_{RMS}$. F_{MIN} can be reduced to 33.15kHz to keep the starting voltage at $507V_{RMS}$.

CHOOSING THE PREHEATING FREQUENCY

The lamp starting scenario is the ballast characteristic that has the greatest impact on lamp life. The ML4831, when used with a properly designed lamp network, allows a designer to select:

a) the filament preheating time interval, and

b) the voltage across the lamps and filaments during the preheating interval.

ANSI C82.11-1993 sets the minimum preheat time at 0.5 seconds. A time of 0.7 seconds was used in this design with $290V_{RMS}$ across the lamps, and filament voltages of $6.0V_{RMS}$ during preheating. This gives a good hot to cold filament resistance ratio, R_H/R_C, and low glow current. Equation (1) is used to find the preheat frequency of 51kHz using 290V for e_O.

SELECTING OSCILLATOR COMPONENTS

Inverter frequencies f_{MIN} and f_{PREHT} that were chosen to be 33kHz and 51kHz, respectively, are 1/2 of the corresponding oscillator frequency. Refer to the ML4831 Data Sheet for the equations and device parameters to calculate r_T and r_S. To get a discharge time near 1µs the value for C_T was chosen at 2.2nF.

NETWORK INDUCTOR DESIGN

Since maximum stress on the inductor occurs during preheating, those conditions were used for its design. At f_{PREHT}:

$x_L = 1760\Omega$

$x_C = -919\Omega$

$e_O = 290V_{RMS}$

$$V_{IND} = \left(\frac{290}{919}\right)1760$$
$$= 555V_{RMS} \qquad (5)$$

The E 25/7 (EF 25) core was selected because:

- low cost and availability
- high A_E (core) X A_W (bobbin)
- efficient size for 90VA at 30kHz and 2000 gauss

For 2 turn filament windings at $6V_{RMS}$ during preheating;

$$N = \frac{555}{3} = 185 \text{ turns} \qquad (6)$$

Operating at a induction level of 2523 gauss during the lamp preheating interval.

Voltage across the inductor during normal lamp operation;

$$V_{IND} = (X_L)\sqrt{\left(\frac{V_L}{r_L}\right)^2 + \left(\frac{V_L}{x_C}\right)^2}$$
$$= 1174\sqrt{\left(\frac{280}{1600}\right)^2 + \left(\frac{280}{-1379}\right)^2} = 315V_{RMS} \qquad (7)$$

Where;

x_L = reactance of series network inductor (T3) at f_{MIN}

V_L = voltage across lamps

x_C = reactance of shunt capacitor (C8)

The filament voltages during normal lamp operation;

$$V_{FIL} = \frac{(315)(2)}{185} = 3.4V_{RMS} \qquad (8)$$

LAMP OPERATION

The effect of the power delivered to the filaments (r_F = 2.5Ω total) must be considered in the determination of arc power and lamp current. If the network is operated at f_{DES} (30.8kHz) the transfromed series inductance, x_L in equation 4), is slightly reduced due to the reflected filament resistance; however, the addition of the transformed series filament resistance to the transformed series lamp resistance results in a total resistance of 815Ω. This is larger than r_{IN} (761Ω) thereby reducing the power delivered to the lamps. By operating at f_{MIN} (34kHz), the total series resistance is reduced to 749Ω with a Z_{IN} of 755Ω. So by operating slightly above the design frequency more starting voltage and power can be supplied to the lamps at a power factor near unity. Z_{IN} is found from the equation:

$$Z_{IN} = (r_{LS} + r_{FS}) + j(x_{LS} + x_{CN} + x_{CS}) \qquad (9)$$

Where:

r_{LS} = transformed series lamp resistance;

And;

r_{FS} = transformed series filament resistance;

x_{LS} = transformed series inductive reactance; and

x_{CS} = transformed series capacitive reactance (C8)

x_{CN}= total series reactance of C9 and C22

Expanded:

$$Z_{IN} = \left(\frac{r_L}{1+Q^2} + \frac{(r_F)(n^2)}{1+Q_F^2}\right) + j\left(\frac{(x_L)(Q_F^2)}{1+Q_F^2} + x_{CN} + \frac{(x_C)(Q^2)}{1+Q^2}\right) \qquad (10)$$

Where $n = \frac{\text{inductor turns}}{\text{filament turns}} = \frac{185}{2} = 92.5$

$$Q = \frac{r_L}{x_C} = 1.16$$

$$Q_F = \frac{(r_F)(n^2)}{x_L} = \frac{(2.5)(92.5^2)}{1174} = 18.2$$

$$= \left(\frac{1600}{1+1.16^2} + \frac{(2.5)(92.5^2)}{1+18.2^2}\right) +$$

$$j\left(\frac{(1174)(18.2^2)}{1+18.2^2} - 284 + \frac{(-1379)(1.16^2)}{1+1.16^2}\right)$$

Z_{IN} = (682 + 64) + j(1170 – 284 – 791) = 746 + j95 = 752Ω

So, P_O (new) = 54 watts

By operating slightly higher than the resonant frequency, f_{DES}, we obtained the desired starting voltage and power to the lamps with a small inductive phase angle of 7 degrees.

LAMP OUT PROTECTION

As with all resonant topology circuits, the highest component stress occurs at open load. This can be controlled by operating only close enough to resonance to produce adequate starting voltage. When we chose the starting voltage and derived f_{MIN}, the open circuit input impedance of the network was defined:

$$Z_{IN} = rfs + j\,(xln + xcn + xc)$$
$$= 67 + j(1170 - 284 - 1379) = 497\Omega \qquad (11)$$

Where:

r_{FS} = transformed series filament resistance;

x_{LN} = transformed series inductive reactance;

x_{CN} = reactance of series capacitors C9 and C22; and

x_C = reactance of shunt capacitor, C8.

At the resonant frequency of 40.4kHz, Z_{IN} is 67Ω. Operating at f_{MIN}, Z_{IN} is 497Ω capacitive. Although Z_{IN} is relatively high, switching losses would waste power and require additional heat sinking if not for the ML4831's duty cycle interruption feature.

The ML4831 uses duty cycle interruption of the inverter gate drive with the off time set by C13 and R15 (See figure 10). Refer to the ML4831 Data Sheet for information on value selection. Unloaded conditions are detected by comparing a voltage created by the sampled lamp current at pin 2 of the 393 dual comparator with a reference voltage. If, at the end of the lamp starting scenario, lamp current is not detected the interrupt circuit is activated. The other comparator output, pin 7, activates the lamp feedback amplifier when lamp current is detected.

DIMMING

The light output of a fluorescent lamp is very closely related to both lamp current and arc watts. Light output is controlled by sampling the lamp current with current sensing transformer T5. Its secondary current is converted to a voltage and fed to the ML4831's Lamp Feedback Amplifier. The Amplifier output voltage varies in accordance with the amount of lamp current required (set by potentiometer R20) by internally adjusting the inverter frequency. The impedance characteristic of the lamp network results in lower lamp current (light) as the inverter frequency is increased.

If dimming is not desired:

T5, IC2, D8, D11, D16, R2, R3, R16, R20, R22, R24, R26, R27, R28, R29 C4 and C21 can be removed. Lamp out protection can be reinstated by sampling the voltage across C22 with a small capacitor. This voltage can then be DC restored, rectified, filtered and applied to pin 9 (2 diodes, 2 capacitors and 2 resistors). A good interrupt signal can be obtained since the voltage across C22 is more than 50% higher with a lamp out. See Application Note 52. Pin 5 must be grounded.

PERFORMANCE DATA

To measure system performance across the range of permissible input voltages use a variable or adjustable AC source.

A typical ballast of this design will have the following performance characteristics when operated as shown in the test conditions:

BALLAST TEST RESULTS

INPUT	249	277	305	VOLTS
P_{IN}	58.8	58.8	58.6	Watts
THD	5.0	5.3	7.8	%
PF	0.99	0.99	0.99	
OUTPUT				
Lamp I_{RMS}	0.168	0.169	0.170	A_{RMS}
CCF	1.26	1.25	1.27	
V_{FIL}	3.7	3.7	3.7	V_{RMS}

Test Conditions: 2 series wired T8 lamps (full intensity); 22°C
Equipment Used: Voltech Digital AC Power Analyzer #PM1000
Tektronix TDS 460 Digitizing Scope; Fluke 8920A; Tektronix 6021 current probe.

Test points are provided at the following circuit nodes:

- TP1 Circuit GND
- TP2 V_{CC}
- TP3 Interrupt
- TP4 PFC Boost Voltage
- TP5 Output

TYPICAL WAVEFORMS

Figures 2 through 4 display typical oscilloscope waveforms taken at various points on the EVAL Board. A brief description precedes each figure. Test conditions and oscilloscope settings are given below each photo. The waveforms were taken with the ballast powering two series connected F32T8 lamps.

PFC BOOST VOLTAGE (FIG. 2, TP4)

The DC bus for the inverter stage is derived from the rectified AC line. Note the 120Hz (2x line frequency) ripple voltage superimposed on the DC voltage. This is the result of the power factor correction of the AC line voltage. The peak to peak amplitude of the ripple voltage increases as the lamp intensity increases.

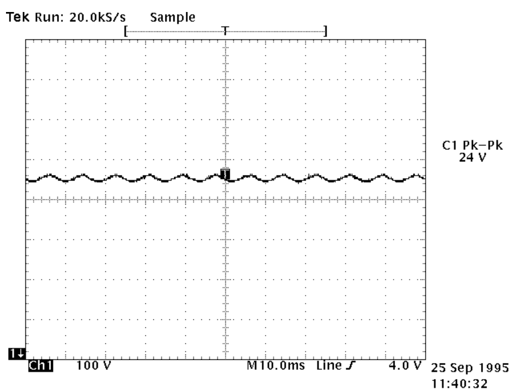


Figure 2. PFC Boost Voltage

Scope Setting: Vert. = 100V/div., Horiz. = 10ms/div.
Test Conditions: Lamps @ maximum intensity, 277VAC
Equipment Used: Tektronix TDS540 Digitizing Scope

INVERTER VOLTAGE/CURRENT (FIG. 3)

The boosted DC bus voltage is chopped by Q2 & Q3 resulting in the square wave appearing at the input to the lamp network (Q2/Q3/T4 node). The lamp network input current is sinusoidal due to the network Q. The current and voltage waveforms are nearly in phase which results in the minimum VA being supplied by the inverter to produce the required lamp watts. The small inductive phase ensures low switching losses.

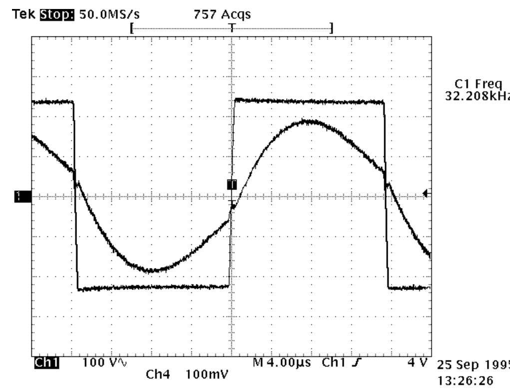


Figure 3. Inverter Output Voltage/Current

Scope Setting: Ch4 — 200mA/div, Ch1 — 100V/div, Horiz = 10µs/div
Test Conditions: Lamps @ maximum intensity, 277VAC
Equipment Used: Tektronix TDS540 Digitizing Scope, Tektronix 6021 Current Probe

LAMP CURRENT/VOLTAGE (FIG. 4)

A comparison of the lamp current and voltage is shown in Fig. 4. The small phase difference is typical when lamps are operated at high frequencies and is an indication of the increased lamp efficacy as compared to 60Hz operation. The lamp current crest factor (CCF) is approx. 1.3, well below the 1.7 limit. The user will note an increase in lamp voltage as the lamp is dimmed. This is a result of the negative resistance characteristic of a fluorescent lamp.

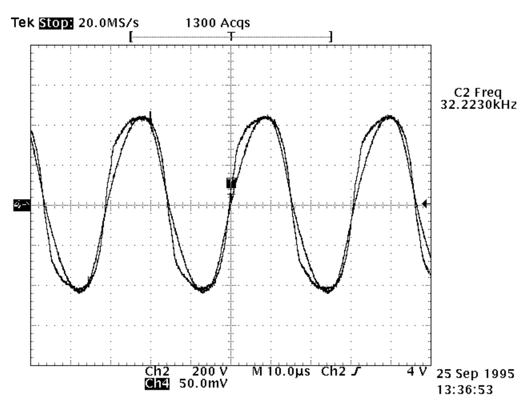


Figure 4. Lamp Current/Voltage

Scope Setting: Ch3 = 200V/div, Ch4 = 0.1 A/div, Horiz. = 10µs/div
Test Conditions: Lamps @ maximum intensity, 277 VAC
Equipement Used: Tektronix TDS540 Digitizing Scope, Tektronix 6021 Current Probe

277 VOLT ML4831 PARTS LIST

Item	Qty	Description	Vendor/Parts	Designation
Resistors				
1	1	1.0Ω, 1/2 W, 5% metal film	NTE/HW1DO	R1
2	1	4.3kΩ, 1/4 W, 5% carbon film	Yageo/4.3K-Q	R2
3	1	220kΩ, 1/4 W, 5% carbon film	Yageo/220K-Q	R3
4	1	12kΩ, 1/4 W, 5% carbon film	Yageo/12K-Q	R4
5	1	11.8kΩ, 1/4 W, 1% metal film	Dale/SMA4-11.8K-1	R5
6	2	422kΩ, 1/4 W, 1% metal film	Yageo/SMA4-422K-1	R6, 11
7	1	82kΩ, 1 W, 5% carbon film	Yageo/82KW-1ND	R7
8	3	22Ω, 1/4 W, 5% carbon film	Yageo/22-Q	R8, 9, 18
9	1	11.5kΩ, 1/4 W, 1% metal film	Dale/SMA4-11.5K-1	R10
10	2	442kΩ, 1/4 W, 1% metal film	Dale/442KXTR-ND	R12, 23
11	1	4.87kΩ, 1/4 W, 1% metal film	Dale/SMA4-4.87K-1	R13
12	1	470kΩ, 1/4 W, 5% carbon film	Yageo/470K-Q	R14
13	1	324kΩ, 1/4 W, 1% carbon film	Yageo/324K-Q	R15
14	1	10kΩ, 1/4 W, 1% metal film	Dale/SMA4-10K-1	R16
15	2	51Ω, 1/4 W, 5% carbon film	Yageo/51-Q	R17, 19
16	1	10kΩ potentiometer Not used (insert jumper)	Bourns/3386P-103-ND	R20 R21
17	1	11kΩ, 1/4 W, 1% metal film	Dale/SMA4-11K-1	R22
18	1	64.9kΩ, 1/4 W, 1% metal film	Dale/SMA4-64.9K-1	R24
19	1	5kΩ potentiometer	Bourns/3386P-502-ND	R25
20	1	20kΩ, 1/4 W, 5% carbon film	Yageo/20K-Q	R26, 28
21	1	200kΩ, 1/4 W, 5% carbon film	Yageo/200K-Q	R27
22	1	1.3kΩ, 1/4 W, 5% carbon film	Yageo/1.3K-Q	R29
Capacitors				
23	2	2.2nF, 250V, 10% “Y” Cap.	WIMA/MP3-Y	C1, 2
24	1	0.15µF, 300V, 10% “X” Cap.	WIMA/MP3-Y	C3
25	1	3.3µF, 50V, 20% electrolytic	Panasonic/ECE-A50U3R3	C4
26	1	0.47µF, 50 , 20% ceramic	AVX/SR215E474MAA	C5
27	1	2.2nF, 50V, 2.5% NPO ceramic	AVX/SR215E474MAA	C6
28	1	330pF, 50V, 10% ceramic	AVX/SR151A331JAA	C7
29	1	10nF, 630V, 5% polypropyl. Not used (insert jumper)	WIMA/MKP10	C8A, C8B
30	2	33nF, 250V, 5% polypropyl.	WIMA/MKP10	C9, 22
31	2	47µF, 250V, 20% electrolytic Not used Not used (insert jumper)	Panasonic/ECE-A2EU470	C10A, C10B C11 C12
32	1	10µF, 35V, 20% electrolytic	Panasonic/ECE-A35U100	C13
33	2	0.22µF, 50V, 10% ceramic	AVX/SR305C224KAA	C14, 15
34	1	100pF, 100V, 5% ceramic	AVX/SR211A101JAA	C16

Note: Shading denotes those items that must be changed on the ML4831EVAL board for 277 volt operation.

277 VOLT ML4831 PARTS LIST (continued)

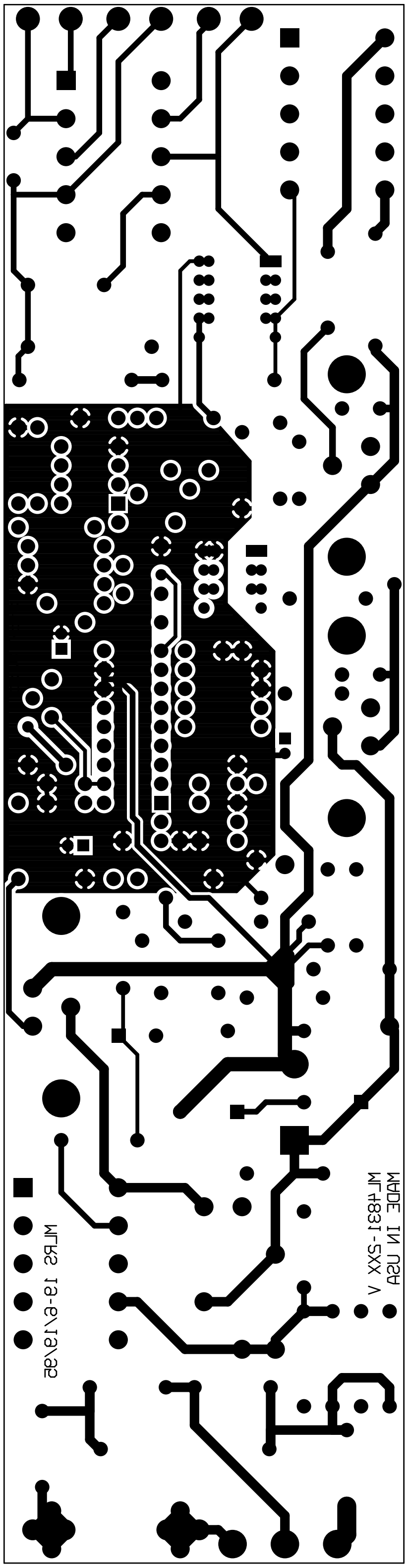
Item	Qty	Description	Vendor/Parts	Designation
Capacitors (Continued)				
35	1	1μF, 50V, +80/-20% ceramic Not used (insert jumper) Not used	AVX/SR305E105ZAA	C17 C18 C19
36	1	330μF, 25V, 20% electrolytic	Panasonic/ECE-A1EU331	C20
37	1	0.33μF, 50V, 20% ceramic Not used	AVX/SR251E334MAA	C21 C23
38	1	220μF, 16V, 20% electrolytic	Panasonic/ECE-A1CU221	C24
39	1	4.7nF, 50V, 10% ceramic	AVX/SR211C472KAA	C25
Diodes				
40	5	1A, 600V (1N4007 or 1N5061)	Motorola/1N4007TR	D1 – 4, 15
41	2	1A, 50V	Motorola/1N4001TR	D5, 6
42	1	1A, 600V ultrafast	GI/BYV26C	D7
43	3	0.1A, 75V	Motorola/1N4148TR	D8, 11, 13
44	1	1A, 50V fast	GI/1N4933	D9
45	1	15V, 1W 5% zener	ITT/1N4744A	D10
46	1	5.1V, 10% zener	Motorola/1N5231	D16
ICs				
47	1	Electronic Ballast Controller	ML4831	IC1
48	1	Dual Comparator	TI/TLC393	IC2
Transistors				
49	3	500V, 2.5 A power MOSFET	IR/IRF820	Q1 - 3
Inductors				
50	2	EMI/RFI, 600μH, DC res. = 0.45Ω	Prem Magnetics/SPE116A	L1, 2
Fuses				
51	1	1A, 5 × 20 mm., miniature	Littlefuse/F945-ND	F1
52		PC mount clips 5 × 20 mm.	Littlefuse/F058-ND	
Hardware				
53	3	TO-220 Heatsinks	Aavid Eng./PB1ST-69	
54	3	Mica Insulators	Keystone/4673K-ND	

Note: Shading denotes those items that must be changed on the ML4831EVAL board for 277 volt operation.

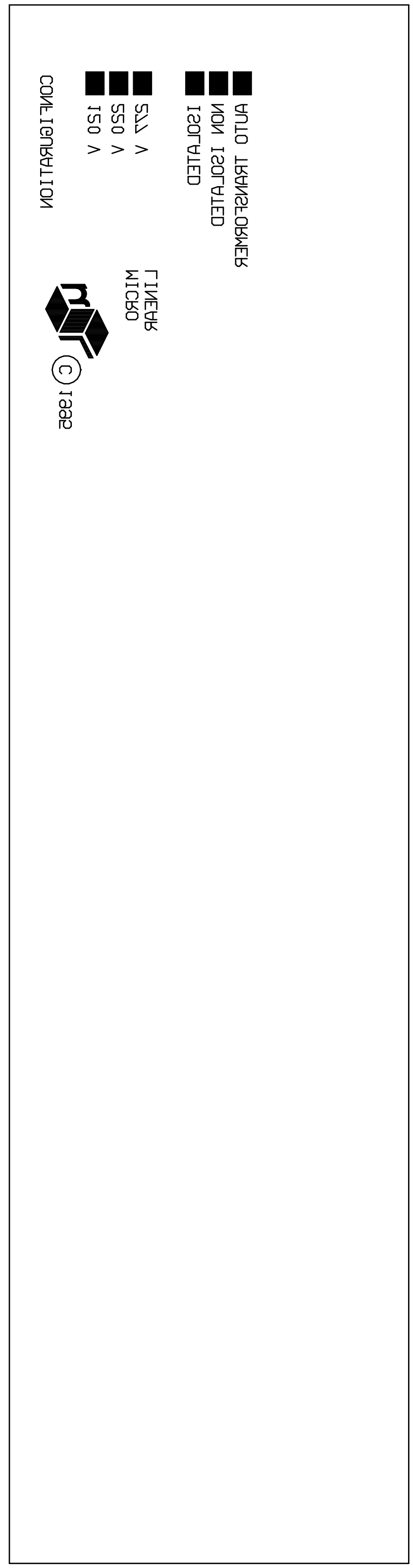
277 VOLT ML4831 PARTS LIST (continued)

Item	Qty	Description	Designation
Transformers			
55	1	Boost inductor: 5.0mH, Premier Magnetics P/N TSD-746; or EF25 core set, Seimens P/N B66317-G-X127, 10 pin vertical bobbin Seimens P/N B66208-J1110-T001. Wind as follows: 240 turns 27 AWG magnet wire - start pin 7, end pin 10; 1 layer mylar tape; 18 turns 30 AWG magnet wire-start pin 8, end pin 9. Note: Gap for 5.0mH ±3%. (Al = 87 ±3%) pins 7 to 10.	T1
56	1	Gate drive transformer, Lpri = 16 mH (min): Premier Magnetics P/N TSD-747; core Magnetics, Inc. P/N ZW-41407-TC; or Lodestone Pacific toroid mount P/N TM550-8. Wind as follows: 60 turns 36 AWG trifilar quadruple build magnet wire (red, green and clear). Connect flying leads as follows: red (start) pin 6, red (end) pin 7; green (start) pin 2, green (end) pin 3; clear (start) pin 1, clear (end) pin 8.	T2
		Not used Assembly note: Install jumpers from pin 10 to pin 4 and from pin 5 to pin 6.	T3
57	1	Inductor, Lpri = 5.5 mH: Premier Magnetics P/N TSD-780; or EF25 core set, or Seimens P/N B66317-G-X127; 10 pin vertical bobbin Seimens P/N B66208-J1110-T001. Wind as follows: 181 turns 28 AWG QPN magnet wire-start pin 6, end pin 7; 1 layer mylar tape; 2 turns 28 AWG QPN magnet wire - start pin 2, end pin 1; 2 turns 28 AWG QPN magnet wire-start pin 4, end pin 3; 2 turns 28 AWG QPN magnet wire-start pin 8, end pin 9; Note: Gap for 5.5 mH ±3%. (Al = 76 ±3%) pins 6 to 7.	T4
58	1	Current sense inductor: Premier Magnetics P/N TSD-749; or core Magnetics, Inc. P/N ZW-41407-TC (or equiv.); Lodestone Pacific toroid mount P/N TM550-6. Wind as follows: Primary = 4 turns 30 AWG kynar wire - start pin 1, end pin 5; Secondary = 400 turns 32 AWG magnet wire - start pin 10, end pin 6.	T5

Note: Shading denotes those items that must be changed on the ML4831EVAL board for 277 volt operation.

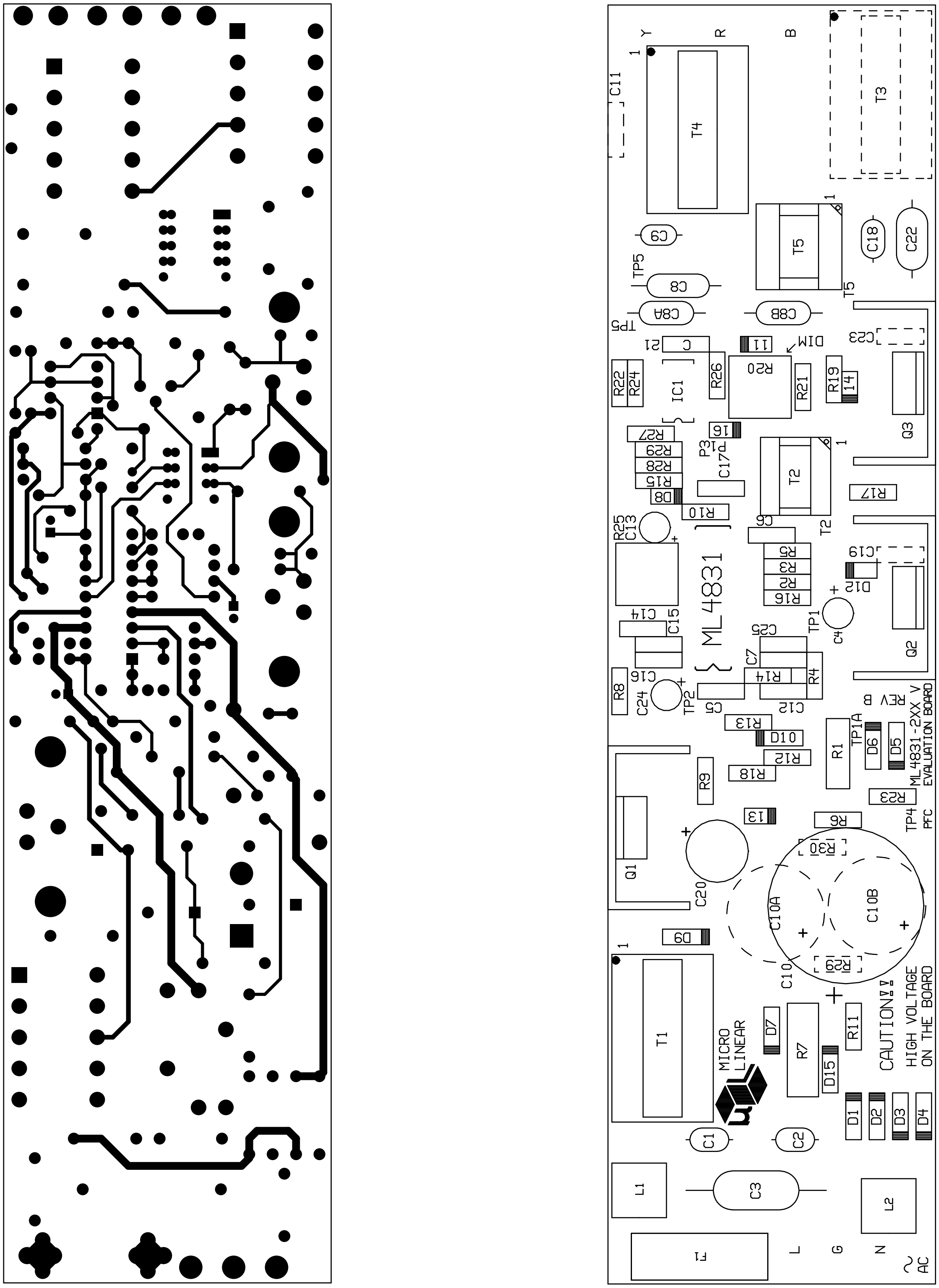


BOTTOM LAYER



BOTTOM SILK SCREEN

Figure 5. ML4831 Board Layout



TOP LAYER

TOP SILK SCREEN

Figure 6. ML4831 Board Layout

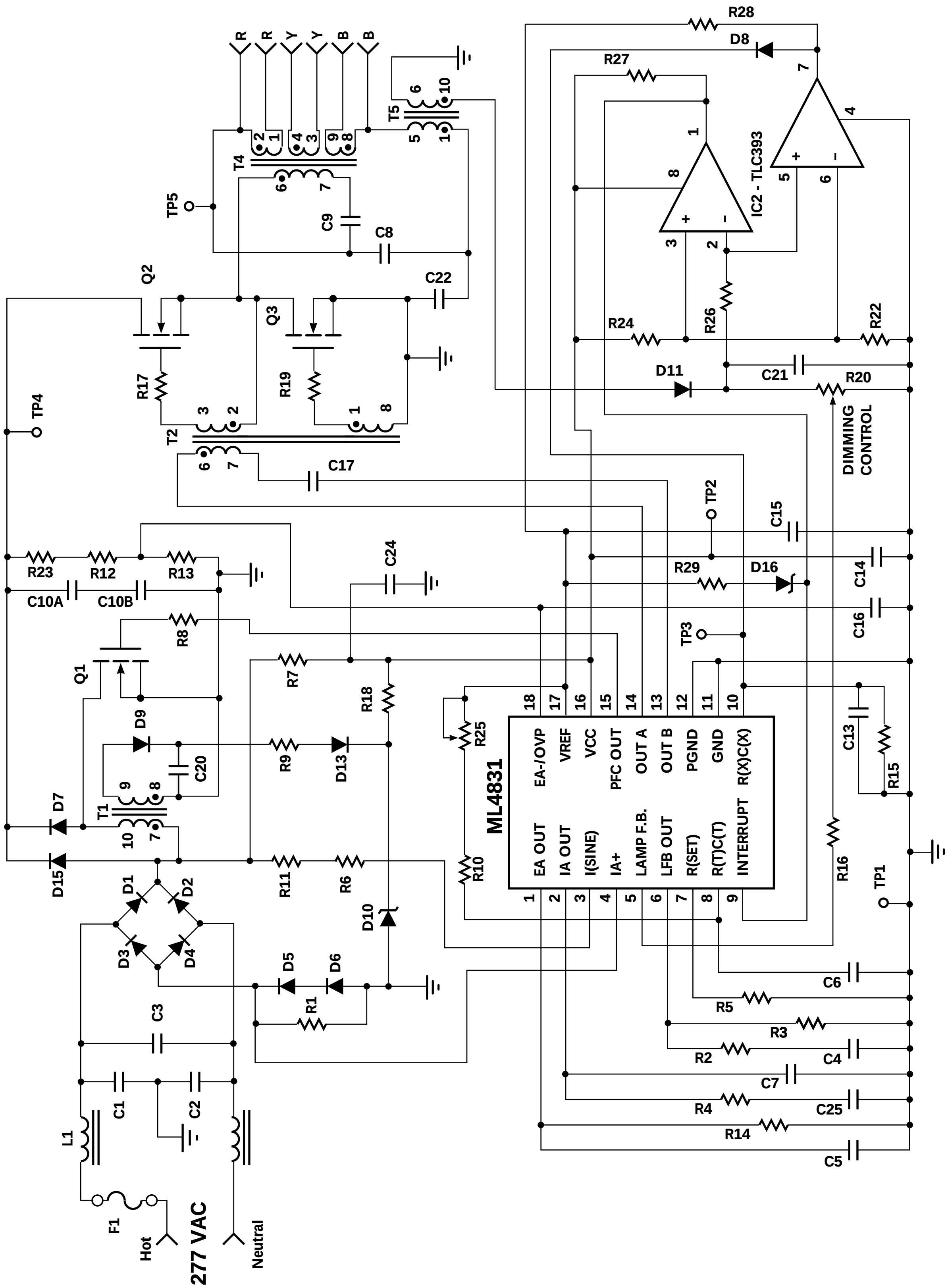


Figure 7. Schematic of the 277 Volt Version of the 4831EVAL-220V Circuit