YLFC700 Fan Speed Controller Product Failure & Solutions

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Introduction

The TRIAC-based fan speed controller used in an Xtrordinair Apex 42 fireplace has the model number: YLFC700. This unit is likely sourced by Travis Industries from an unknown supplier that produces the YLFC700. The fan speed controller is designed to control the speed of a single-pole 120V AC motor at a maximum AC current of 5A.

I own two units of the YLFC700, all of which have failed in the same manner. The problem with the controller is that the slide potentiometer partially fails over time, within 2 to 3 years, causing a specific range of usage on the potentiometer to no longer control the motor's speed. To fix this problem I created my own personal hobbyist fan speed controller. I will call this version Fan Speed Controller (FSC) for the remainder of this document.

Signs of Failure

Unfortunately, there are not any obvious signs that the unit begins to fail internally. The first external sign that the operator will notice is arcing across the contacts inside the slide potentiometer used in the YLFC700. The next sign of internal failure is when the contacts on the potentiometer become burnt out enough that contact can no longer be made and the motor stops operating in that position on the slide potentiometer. The slide range on the two YLFC700 units fail:

1. just below max speed (max speed still works) and
2. just above the halfway point on the slider.

Theory for Failure

The potentiometer is likely rated to withstand 100mW of power. When a 120V AC current is applied and the controller is initially turned on, the potentiometer is its lowest resistance range which correlates to operating the motor at max speed. At this point, the transient state of the controller is affected by the inrush of current and a back EMF voltage spike from the motor initially receiving power from the controller. Inside the YLFC700, this transient voltage spike harms the 47nF 400V Film Capacitor C1, which in turn causes the 100mW potentiometer to fail as it is the next weakest link.

The reason capacitor C1 fails slowly is because a film capacitor is used and most film capacitors are self-healing. Since the transient condition that causes the failure only occurs at startup, the capacitor self-heals under normal operation; however, the self-healing characteristics degrade after each transient shock occurs. The reason the slide potentiometer only fails in the faster fan speed range of the controller is that this is the range of highest wattage consumed by the potentiometer.

Theoretical Design Flaws

1. The YLFC700 does not use a snubberless TRIAC, yet the product was designed without a true snubber configuration being a resistor in series with C1. Due to the nature of the load (AC motor), the device should use a snubber to absorb the harsh opening and closing nature of the TRIAC.
2. Since the YLFC700 is designed to control motors, overvoltage transient protection using a TVS diode should probably be employed.
3. Depending on the load, a higher voltage-rated C1 capacitor may be a solution.
4. To reduce transient current inrush when the YLFC700 is turned on and connected to the AC motor, the slide potentiometer should be flipped 180 degrees to start the motor at its lowest speed instead of its highest speed.

Specifications

The following specifications cover the motor that the YLFC700 is connected to, the components inside the YLFC700, and the components used in my hobbyist fan speed controller.

AC Motor

Manufacturer: Fasco
Model Number (Type): U73B1
Voltage: 120V AC @ 60Hz
Current: 1.8A
Speed: 1550 RPM

In testing, the motor operated just below 1.8A when set at its max speed by the YLFC700 controller. This is normal and the motor ran as expected.

YLFC700

Product Image

Figure 1 - YLFC700 OEM Product Image

The image in figure 1 displays the YLFC700 fan speed controller that is used in Travis Industries Apex 42 fireplace controller.

Component List

Table 1 contains the list of components found inside the YLFC700 fan speed controller and the replacement components used in my hobbyist version.

Table 1 - YLFC700 Components

Original Components	**Replacement Components (Hobbyist Version)**
Slide Potentiometer, 20mm, 20-300k Ohms Logarithmic, 100mW	Rotary Potentiometer: RV1, 0.2-250k Ohms Linear, 2W
Resistor, 2.4k, Wattage NA	Resistor: R1, 2.4k*
Resistor, 270k, Wattage NA	Resistor: R2, 270k, 0.5 W
Resistor, 18k, Wattage NA	Resistor: R3, 18k, 0.5W
Resistor, 240k, Wattage NA	Resistor: R4, 240k, 0.5W
Film Capacitor: C1, 47nF, 400V	Ceramic Capacitor: C1, 47nF, 1kVdc (X7R)
Film Capacitor: C2, 100nF, 250V	Film Capacitor: C2, 100nF, 250V*
Film Capacitor: C3, 100nF, 250V	Film Capacitor: C3, 100nF, 250V*
TRIAC, BTA16-600B, non-insulated tab	TRIAC: U1, BTA16-600B, non-insulated tab*
DIAC, DB3, Breakdown Current NA	DIAC: D1, DB3, Breakdown Current NA*
Inductor: L1, Syle: Radial Vertical, Inductance Rating: Unknown, Measured at 7uH @ 1kHz	Reused Original Part*

* Components reused from the original PCB and resoldered to the new PCB board I created.

Fan Speed Controller (FSC)

Component List

Table 2 contains a list of components I used in my hobbyist version.

Table 2 - Fan Speed Controller v1.0 Components

Rotary Potentiometer: RV1, 0.2-250k Ohms Linear, 2W **
Resistor: R1, 2.4k *
Resistor: R2, 270k, 0.5 W **
Resistor: R3, 18k, 0.5W **
Resistor: R4, 240k, 0.5W **
Resistor: R5, 24, 1W ***
Ceramic Capacitor: C1, 47nF, 1kVdc (X7R) **
Film Capacitor: C2, 100nF, 250V *
Film Capacitor: C3, 100nF, 250V *
TRIAC: U1, BTA16-600B non-insulated, Style: Through-Hole *
DIAC: D1, DB3, Style: Through-Hole, Breakdown Current NA *
Inductor: L1, Style: Radial Verticle, Inductance Rating: Unknown, Measured at 7uH @ 1kHz *
¼" Dia. Metal Knob for Potentiometer ***
Fuse: F1, 4A Fast Blow. ***

* Components reused from the original PCB and resoldered to the new PCB board I created.
** Components different from the YLFC700 but serve the same purpose.
*** Components added to the circuit that was not in the YLFC700 circuit.

Equipment Used

Hardware

- Fluke 87V Digital Multimeter
- Siglent SDS 1104X-E 100MHz 4Ch Oscilloscope
- Krohn-Hite Model 1600 3MHz Frequency Generator
- Generic 5[V] 1[A] Fixed Power Supply
- Hakko Soldering Station
- Quick Hot Air Soldering Station

Software

- Windows 10
- KiCAD 5.1
- Matlab 2017

Procedure

The following steps are the procedure followed when re-engineering the YLFC700 while searching for the probable cause of failure.

1. Use the original PCB inside the YLFC700 to draw the schematic out in LTspice
2. Check resistor and capacitor values with Fluke 87V
3. Measure the inductor value with a frequency generator and Siglent oscilloscope
4. Record inductor values in Matlab and plot inductor characteristic curves
5. Calculate the power factor of the LTspice circuit to check if the potentiometer is within power spec
6. Draw schematic in KiCAD
7. Design PCB in KiCAD
8. Send PCB design to OSHpark for fabrication
9. Transfers reusable components from YLFC700 to FSC
10. Test motor with FSC and AC power source

Design

YLFC700

The construction of the YLFC700 PCB is a one-sided board that uses all through-hole mounted components.

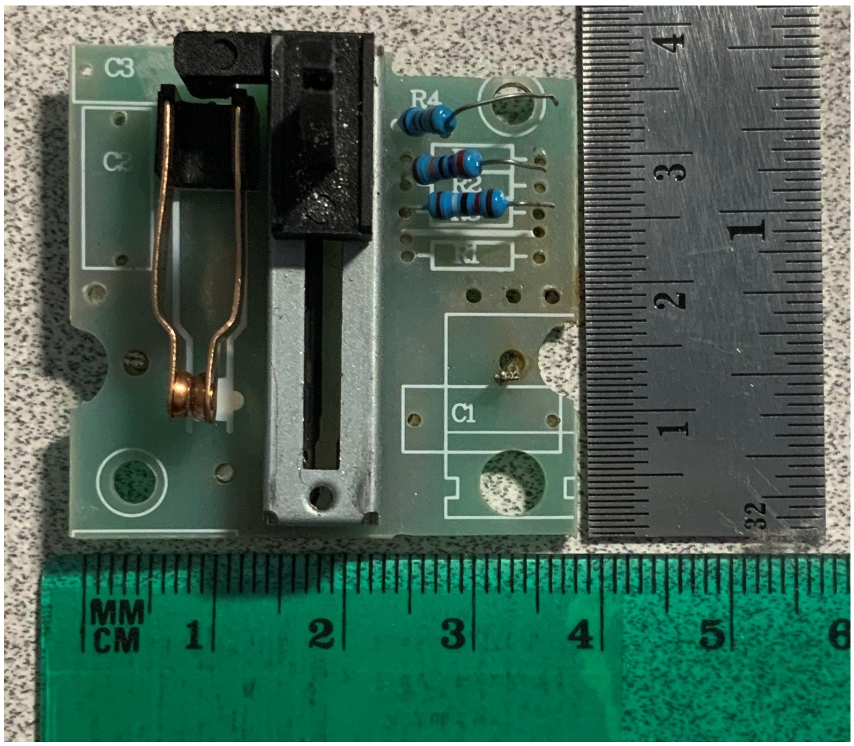

Figure 2 - YLFC700 PCB Front Side View

Figure 2 depicts an image of the PCB's front side. This is the side of the board that faces the user when operating the fan controller. Some components have been removed from the board for the purpose of measuring their values. The removed components are as followed: C1, C2, C3, L1, TRIAC, DIAC, and R1. The dimensions of the PCB are 38mm along the translucent green ruler and 37mm along the metal silver ruler.

The long component located in the center of the board is the logarithmic slide potentiometer. The potentiometer has a slide distance of 20mm, a knob height of 20 mm, and dimensions of 35mm x 8.3mm x 6mm (L x W x H). The potentiometer is mounted to the board by 4 through-hole pins, two of which are necessary for operation. The pitch between the potentiometer's pins is 3.5mm. Through research, I think this potentiometer is made by Panasonic and is rated for 100mW. Unfortunately, Panasonic no longer produces this exact potentiometer.

Next, the copper clip to the left of the slider is the power disconnect switch. The user feels this switch as a detent when turning off the controller.

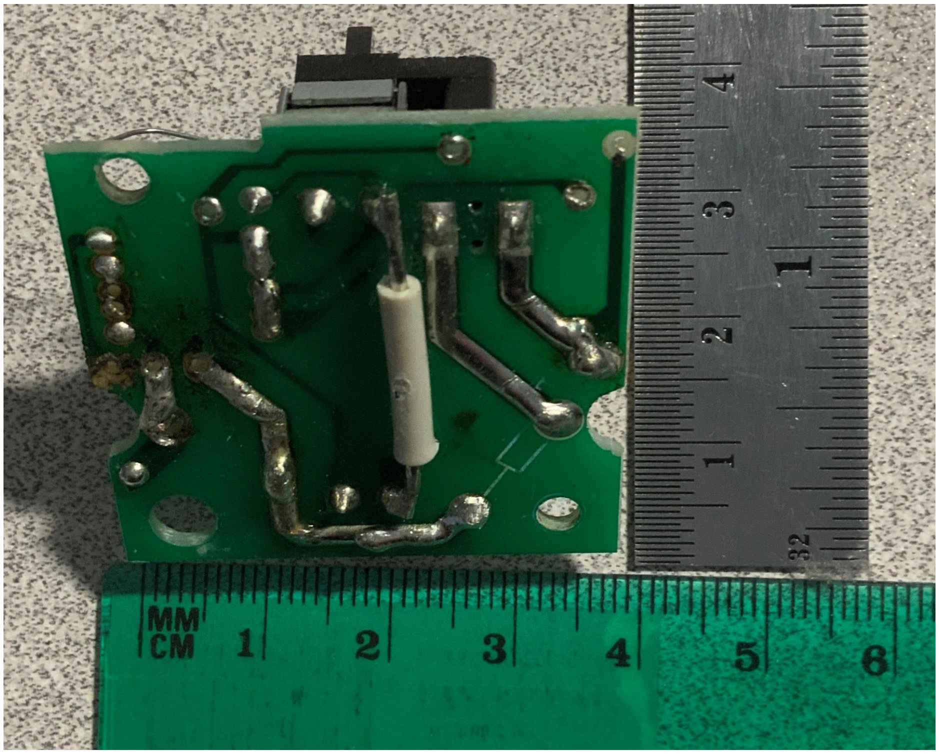

Figure 3 - YLFC700 PCB Back Side View

Figure 3 shows a view of the backside of the board, which is the side of the board that faces the wall when the user is operating the fan controller. Open traces were used along the main power route from the mains power side through the inductor, TRIAC, and out to the motor. Using exposed traces is a cheap way to carry a lot of current while dissipating heat. The black ABS plastic shielding that covers the PCB on the backside of the YLFC700 is required to shield the open traces.

Measured Inductor Characteristics

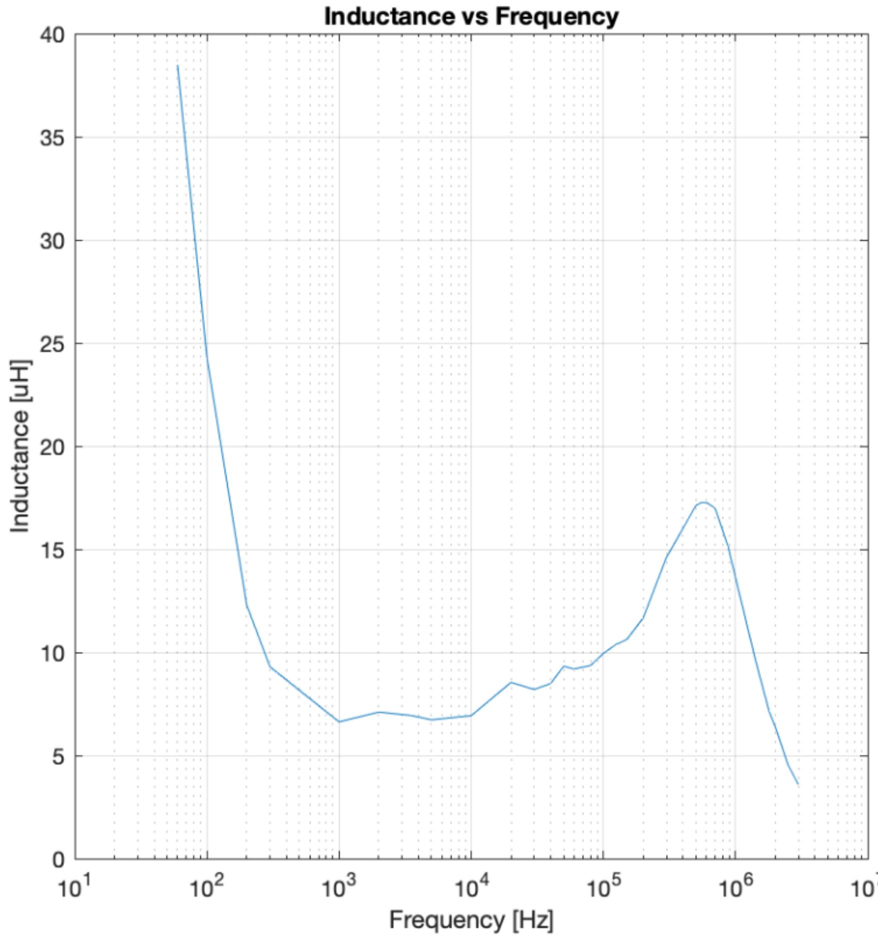

Figure 4 - Inductor (L1) Inductance vs Frequency

The inductor characteristics, shown in figure 4, used data collected and saved in a Matlab script to plot the above inductance versus frequency curve. The first point in the plot was collected at 60 Hz, which is the frequency the inductor will be operating at inside the YLFC700. Hence, an inductance value of 37uH will be used in the following LTspice simulations. See Appendix I, for the full Matlab characterization script with data.

LTspice Schematic

After measuring the discrete components and sketching the PCB traces, the following schematic was created in LTspice. To simplify simulating an AC motor, an inductor in series with a resistor was implemented. It is my assumption that the motor would be relatively close to the value of the inductor L1 so 47uH was chosen. Secondly, the resistor value for R6 was chosen such that the motor would draw 1.8A when the potentiometer is set to operate the motor at max RPM. Note, all simulations use a 120V 60Hz sine wave input.

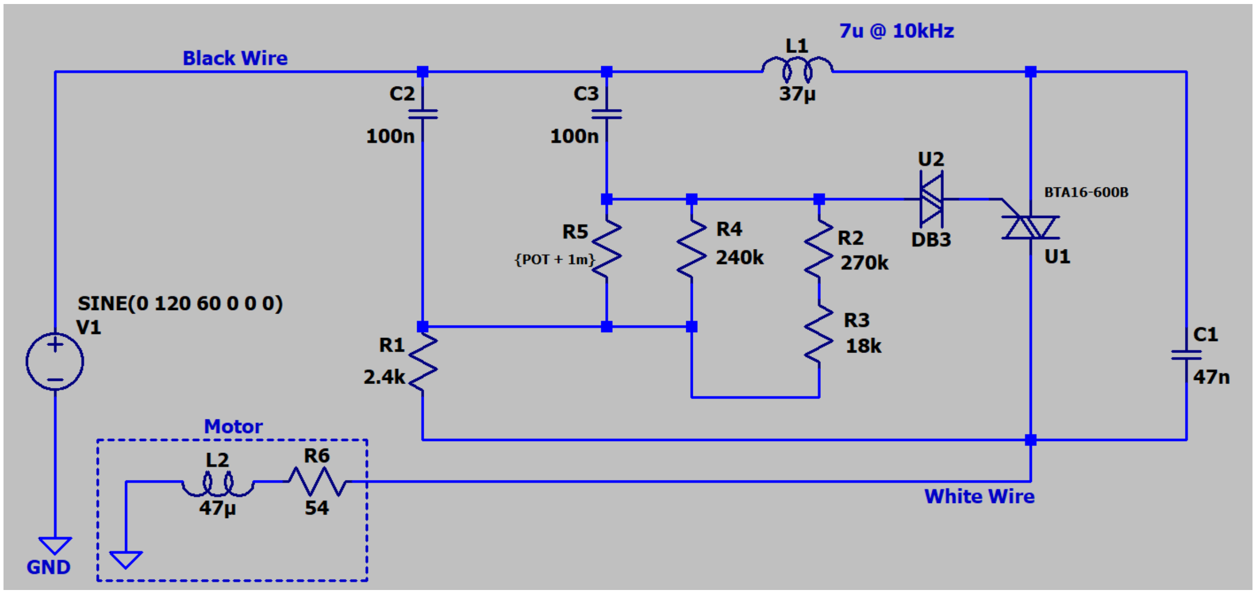

Figure 5 - YLFC700 Schematic Standard Values

Figure 5 contains the schematic of the PCB in figures 2 and 3 found inside the YLFC700 with the standard values (i.e., ideal values) for each component.

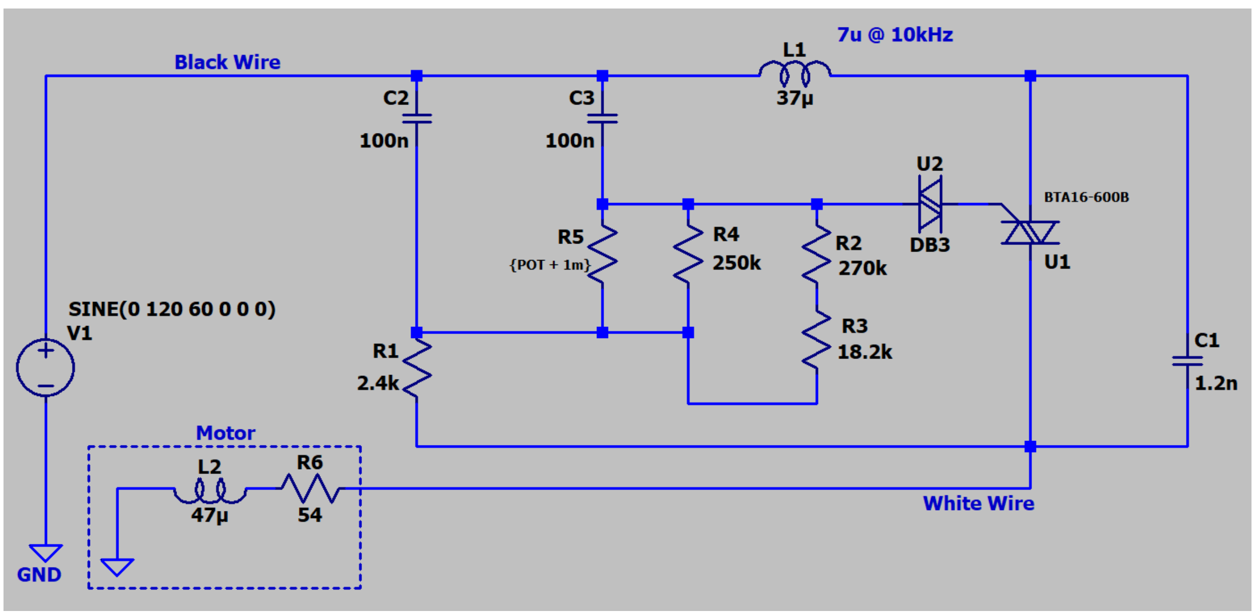

Figure 6 - YLFC700 Schematic Measured Values

Figure 6 has the same circuit configuration as figure 5 except with the actual component values as measured by an Oscilloscope & Function Generator for L1 or a DMM for everything else. Notice, the value of the capacitor labeled C1 has changed drastically.

Schematic Operation

To break down the operation of the circuit from the schematic in figures 5 and 6, let's first discuss the DIAC and TRIAC (labeled U2 and U1). Under normal operation, the TRIAC opens and closes allowing current to flow through when a specific voltage is met at its gate. The DIAC controls the TRAIC's gate. The DIAC turns on allowing current to flow through once a specific breakdown current occurs inside the DIAC. This breakdown current event can only occur once the capacitors C2 and C3 are charged. Hence by adjusting the rate at which C2 and C3 charge using the resistor network R1-5, the user can control DIAC.

The RPM of the AC motor is controlled by chopping the sine wave input; whereby, the motor does not see the full length of the sine wave over each period which manipulates the speed. The inductor L1 operates as an inductive line choke to keep the noise from the motor out of the mains. L1 and C1 are used to absorb the voltage spike caused by the motor when the TRIAC closes. Also, the capacitor C1 is used to fill the load when the TRIAC first opens; thereby, reducing the inrush current pulled from the mains.

Note, that if a resistor had been placed in series with C1, this part of the circuit would be a true snubber configuration.

LTSpice Simulation

Component Specs
DIAC: DB3
Vbo=13.6V
Ibo=10uA

TRIAC: BTA16-600B
Igt=100mA
Ih=50mA

Include Files
.inc STTRIAC.lib
.inc STDIAC.lib

Component Models
.model TVS D(Ron=.4 Roff=50Meg Vfwd=120 epsilon=46 Vrev=140 Vpk=120 revepsilon=46 mfg=Littlefuse type=TVS)

Simulation Directives
.tran 0 0.04 0.016 10u
.step dec param POT 100 300k 5
.step dec param POT 40 1000 10

Calc Operations
.four 50 I(V1)
.meas R1_PWR PARAM 0.84*I(R1)*V(N007,N006)
.meas R5_PWR PARAM 0.84*I(R5)*V(N006,N003)

Comments
L1 - Measured on Oscilloscope, 7uH @ 10kHz

Figure 7 - LTspice Operations

The Spice operations used to simulate figures 5 through 6 are shown above in figure 7. Since the exact spice libraries for the DIAC and TRIAC used in the YLFC700 do not come with LTspice, one must download the files from STMicroelectronics and tell LTspice to include them. The circuits are simulated from 16ms to 40ms with a maximum timestep of 10us. The circuit has reached steady-state by 16ms. For each time simulation, a different potentiometer value is used in a logarithmic step from 100 Ohms to 300 kOhms with 5 points per decade.

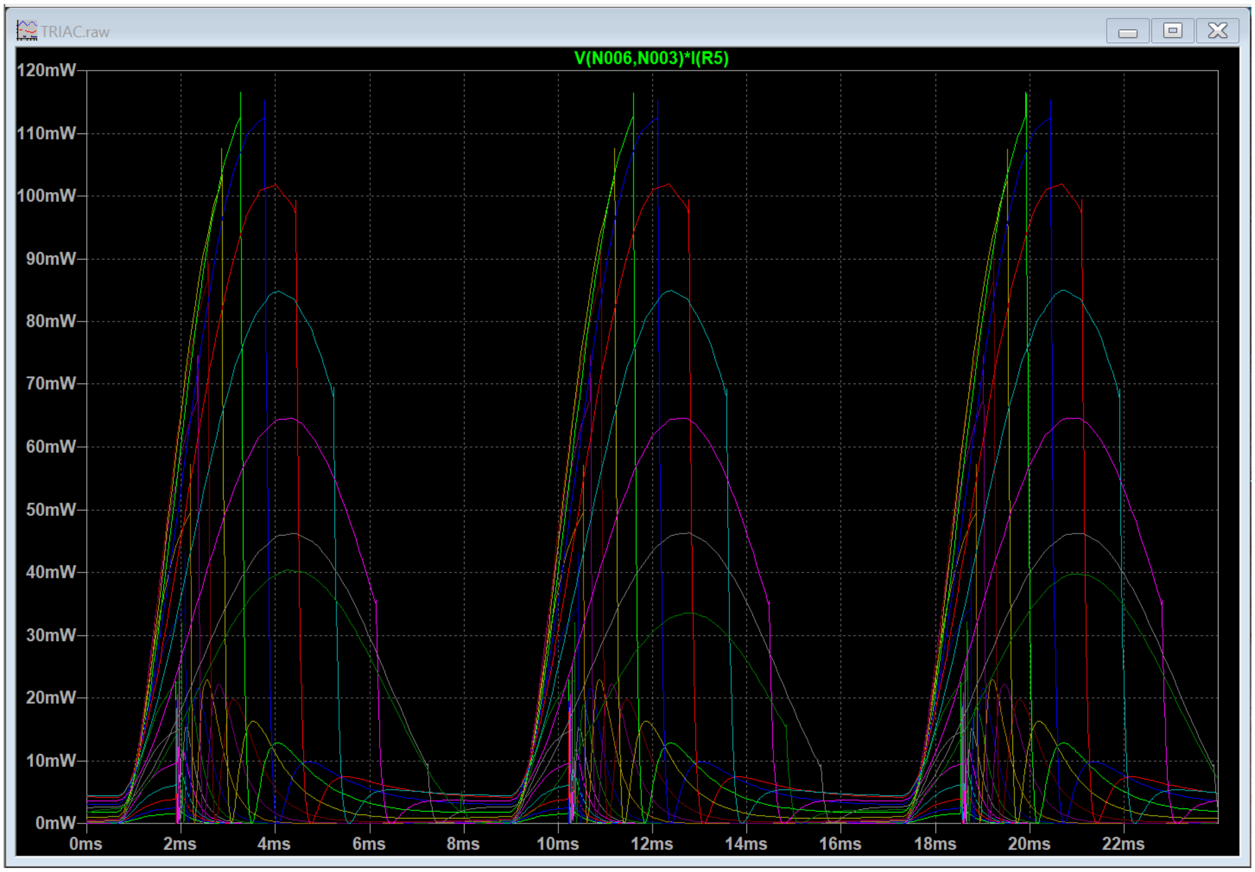

Figure 8 - Potentiometer Power Using Standard Values

To produce the simulation shown in figure 8, the circuit in figure 5 (actual values) and the operations in figure 7 are applied. When considering a power factor of approximately 86% for the potentiometer's resistance values between 100 and 30,000 Ohms, the above results would be within specification. See Appendix I, for the Matlab script containing the power factor data collected from running the **.four 50 I(V1)** command in LTspice.

So, what happens when C1 starts to fail?

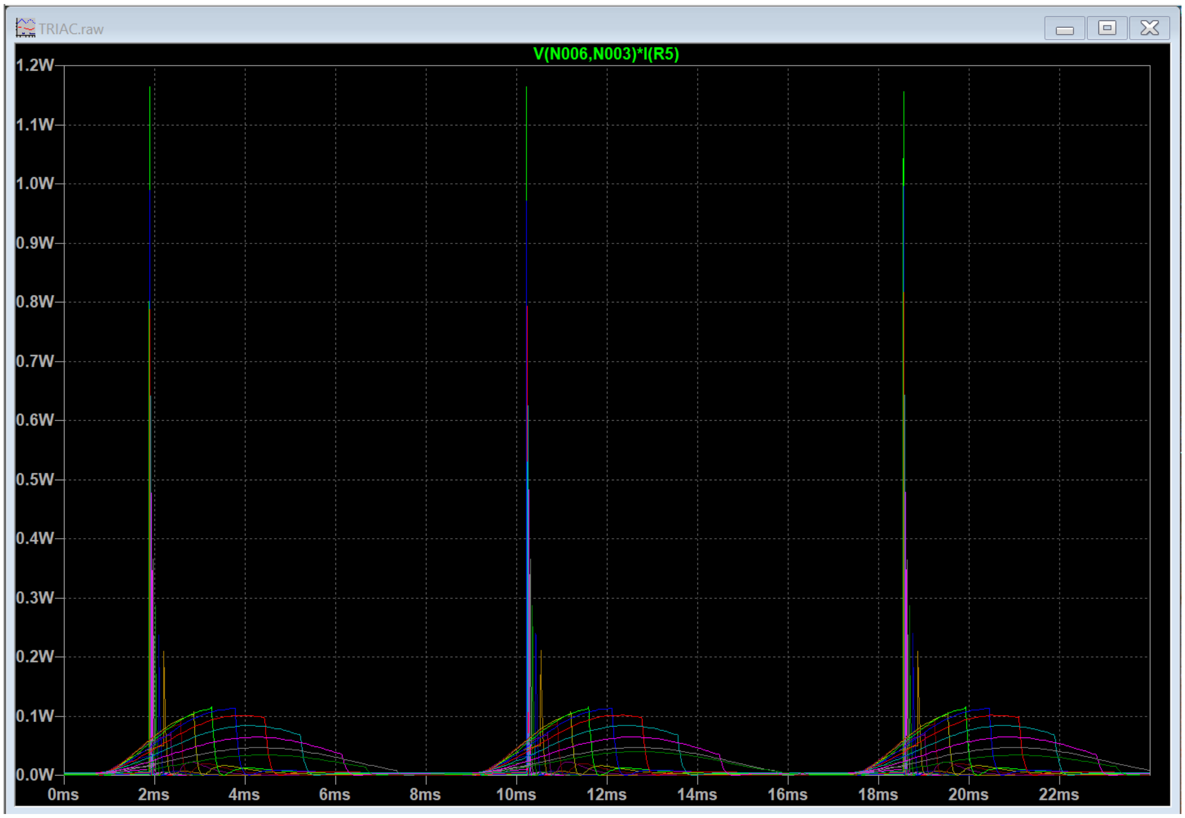

Figure 9 - Potentiometer Power Using Measured Values

To produce the simulation shown in figure 9, the circuit in figure 6 (measured values) and the operations in figure 7 are applied. Now one can see that when C1 fails and its capacitance decreases, the potentiometer falls dramatically out of specification over a range of resistance values from 100 to 30,000 Ohms. Hence, this is why the potentiometer inside the YLFC700 fails only in the upper-speed range, while the lower-speed control range remains functional.

Testing

Transient Over Voltage

During testing of the YLFC700 design, a transient voltage spike was seen when turning the unit on. I made an error in using my Oscilloscope without a high voltage differential probe. I was rather scared that I had ruined something inside my scope and I forgot to take a screenshot of the transient voltage spike. My probes were set at x10, my scope has a max peak to peak voltage of 400V, and my vertical V/div was set at the scope's maximum. Under these conditions, I was unable to see the peak of the spike and I had my trigger set at 200V; therefore, I am assuming that the spike is around 400 volts or greater. Hence, the conditions would be met for the 400V rated capacitor to fail slowly.

Capacitor Measurements

Capacitor C1 was measured before and after removal from the PCB. For both measurements, C1 was measured to be 1.2nF. Capacitors C2 & C3 were measured at 100nF.

Solutions

There are two approaches to fixing the design flaws of the YLFC700:

1. Fix a brand new YLFC700 unit, or
2. Build a new fan speed controller.

Fixing A New YLFC700

To fix a brand new YLFC700, place a Transient Voltage Suppression (TVS) diode on the right side of the circuit in parallel with C1, as seen in the figure below. This addition will protect C1 from the transient voltage spike cause when starting the motor.

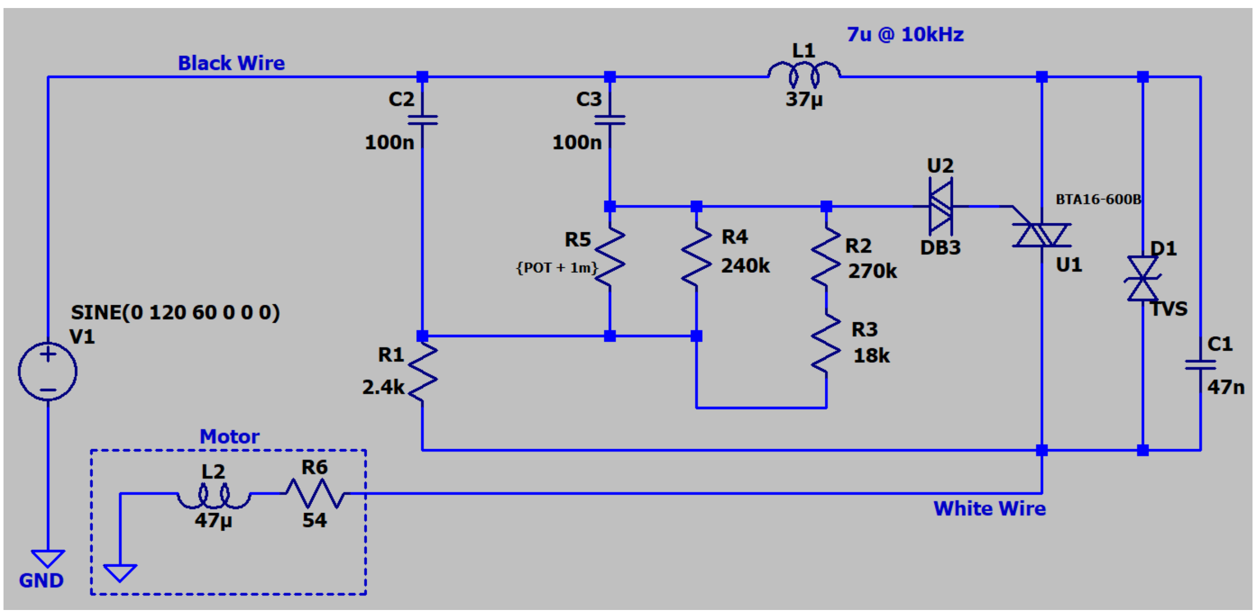

Figure 10 - Adding Transient Voltage Protection

A TVS diode such as the 5KP220CA by Littlefuse would be a good component for this problem since it will keep C1 from seeing a voltage greater than +/- 371V. Luckily, there is room to add a TVS diode to the YLFC700.

Engineering A Fan Speed Controller

There are a few design considerations I made when re-engineering the circuit.

1. We want to reuse the original TRIAC mounted to the metal installation wall bracket along with the black ABS plastic cover used on the YLFC700; therefore, our new circuit board must fit inside the existing housing. See figure 17 as an example.
2. We may want to add a heftier wattage potentiometer than necessary. Slide potentiometers do not exist in a 2W package under our design constraints, so a rotary potentiometer will be used. A resistor (R5) must be added in series with the potentiometer to match the minimum resistance of the original slide potentiometer. This is necessary for the potentiometer chosen for our design because its minimum resistance is 0.2 Ohms.
3. A toggle switch (SW1) will be added to emulate the detent in the YLFC700 to disconnect the controller from the mains.
4. It never hurts to add a fuse, so a 4 Amp fuse will be added.
5. A 1kV ceramic capacitor will be used to replace the 400V film capacitor (C1). The ceramic cap will be much smaller than the film capacitor and it will fit better in the design.

Note: A film capacitor would still fit. Ceramic capacitors do not have self-healing properties like film capacitors; however, since our 600V rated TRIAC is not failing, I am assuming that a 1000V capacitor will survive.

KiCAD Schematic

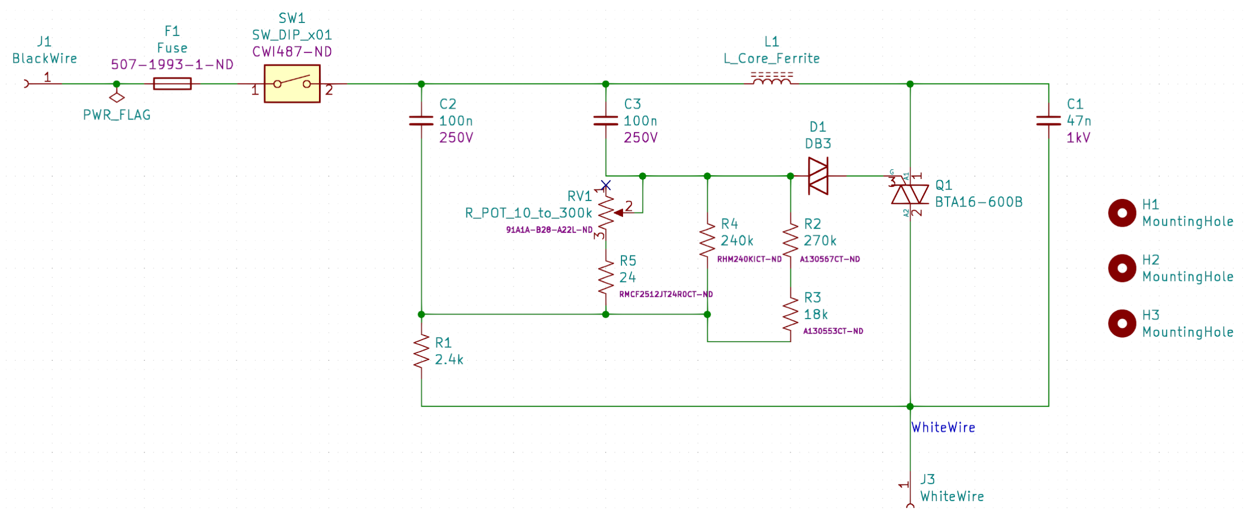

Figure 11 - KiCAD Schematic

Figure 11 shows the modified circuit that is used in my Fan Speed Controller design. The wire colors used on the YLFC700 correspond to the labels used in the above schematic. Notice, the original PCB had 3 mounting holes that were of different sizes and not connected to any traces on the board.

KiCAD PCB Design

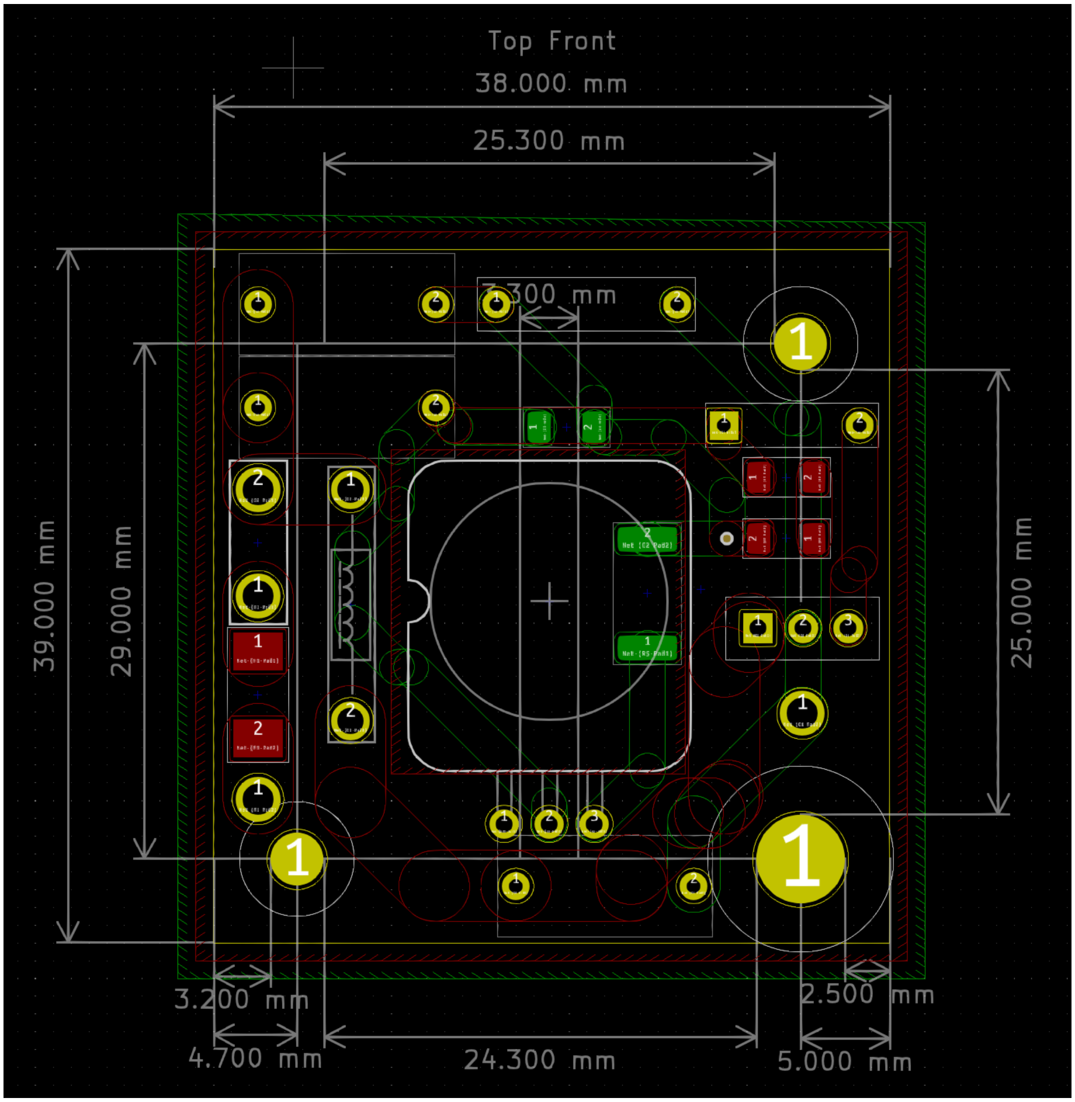

Figure 12 - KiCAD Design

Figure 12 shows the dimensions and spacing of components on the board. The diameter of the mounting holes and spacing between the mounting holes is critical if we want to reuse the existing YLFC700 mounting bracket and ABS plastic back cover. To add additional room for components, the height of the board increased by 2mm along its y-axis.

The yellow outline around the board marks the cut line that the fabricator will follow when they CNC our board. The red and green outline around the yellow cut line marks where the soldering mask will be poured. These two red and green boxes can be arbitrarily set anywhere outside the yellow cut line. Note, that the solder mask will be excluded from the top red layer, behind the potentiometer. This extra measure was implemented in the event that the potentiometer wiggles and wears on the PCB face to keep the potentiometer from ever touching the top layer traces. This should never occur under normal circumstances, but at the time of the KiCAD design, I didn't know how snuggly the unit would go together.

Different trace widths were used in various areas of the design. By my estimation, the exposed traces on the original YLFC700 PCB were meant to handle a sustained 16A along the main route from the power input to the motor. However, we know our load uses a max 1.8A AC.

Using the Track Width PCB calculator in KiCAD, and knowing our fabricator will be OSHpark which uses a trace thickness of 0.0356mm, we can calculate the necessary trace thickness to handle the currents we expect using the IPC 2221 standard.

Thus, a 4mm wide internal trace with a temperature rise of 80C will allow the circuit to handle a max current of 8.25A along the main power trace from the 120V AC power input to the load. Similarly, a 2mm wide internal trace will handle 5A. This design uses either 4mm or 2mm traces because it is better to have extra thermal dissipation overhead than less. Considering the high voltage within this circuit and the transient voltage spike issue, a 0.2 mm space between traces was implemented for safe operation at high altitudes.

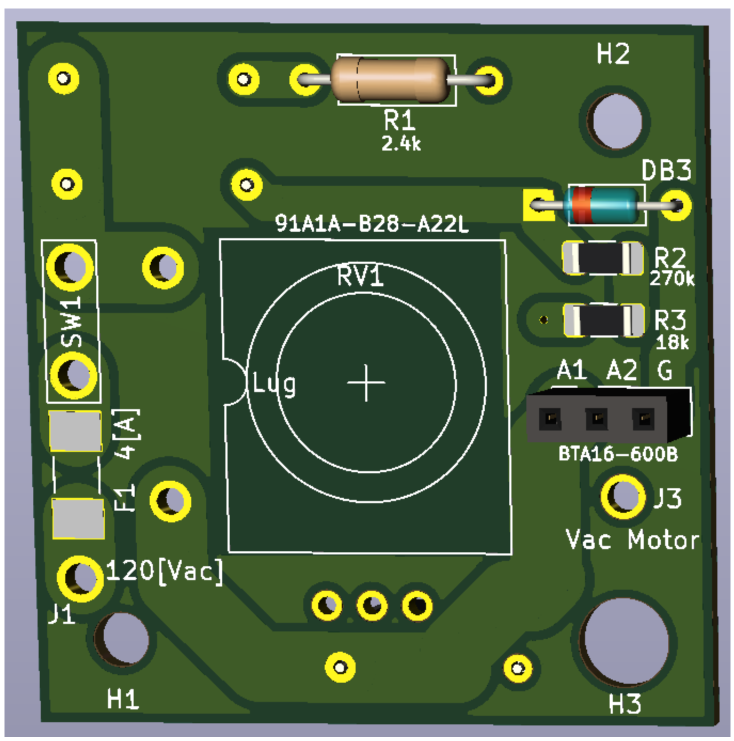

Figure 13 - KiCAD PCB 3D Rendering Front Side

Figure 13 shows the other side of the PCB depicted in the previous figure. This view clearly shows the difference in drill hole sizes and through-hole sizes. Note, the drill holes labeled H1 and H2 are the same in size at 3mm in diameter and H3 is 5mm in diameter. The through-holes for the 120[Vac] power input, switch (SW1), and Vac Motor are all 1.5mm in diameter to handle the larger gauge wires necessary for operation. The potentiometer's rotary shaft is placed at the center of the PCB.

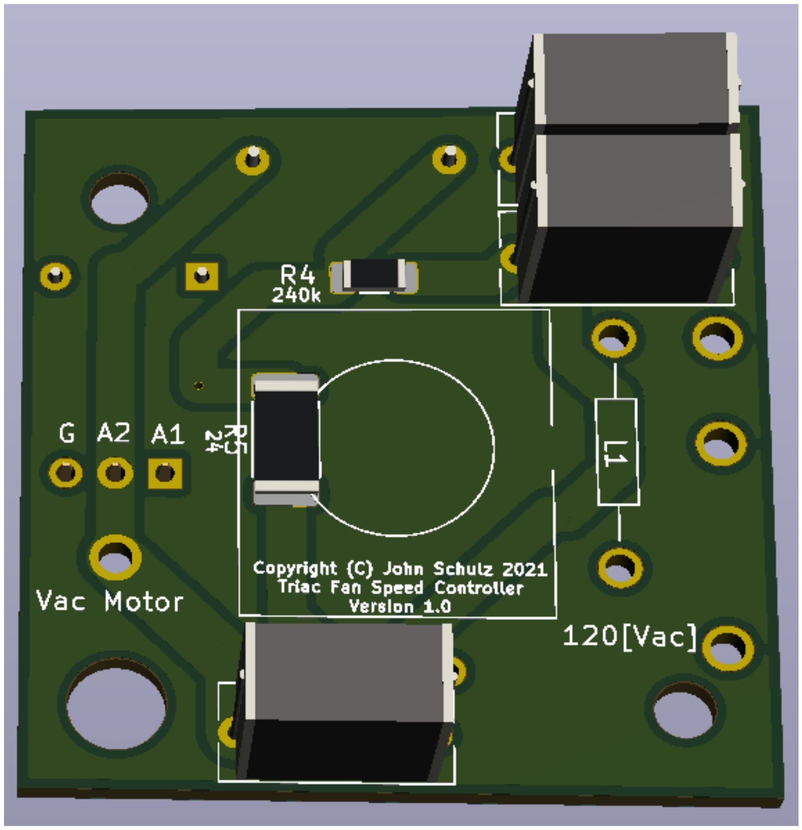

Figure 14 - KiCAD PCB 3D Rendering Back Side

Figure 14 depicts a 3D rendering of the backside of the design shown in figure 13. The capacitors are represented by the large brick objects on the board. The three legs of the TRIAC are clearly marked by the labels: Gate, A2, and A1.

Results

All reusable components were removed with a soldering iron, except for the TRIAC. The TRIAC required a hot air station and some *pliers of persuasion* to desolder the 3 leads without damaging them.

Figure 15 - FSC Disassembled Front Side

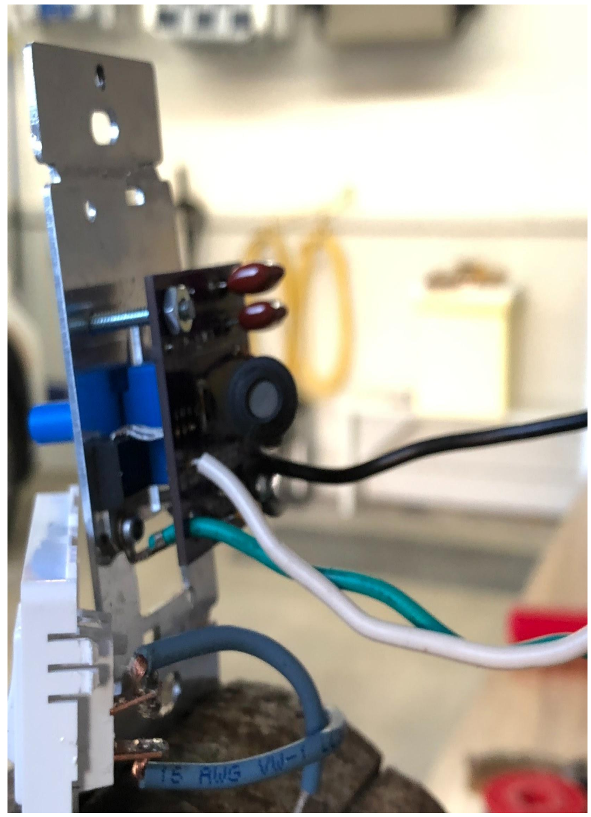

Figure 16 - FSC Disassembled Back Side

Figure 15 shows the front side of the Fan Speed Controller (FSC) without the white front plastic covering and the modifications made to the metal mounting bracket. A Dremel, file, and battery drill were used to make the modifications seen in figures 15 and 16.

The PCB was mounted using screws from a hardware store that are shown in figure 16. Although not visible in figure 16, a rubber shield made from electrical wire heat shrink is used to shield the head of the screw in hole H1 from ever contacting the wire inserted at hole J1. This is extra protection in the event of rubbing. Under the intended operating environment, contact should never be made.

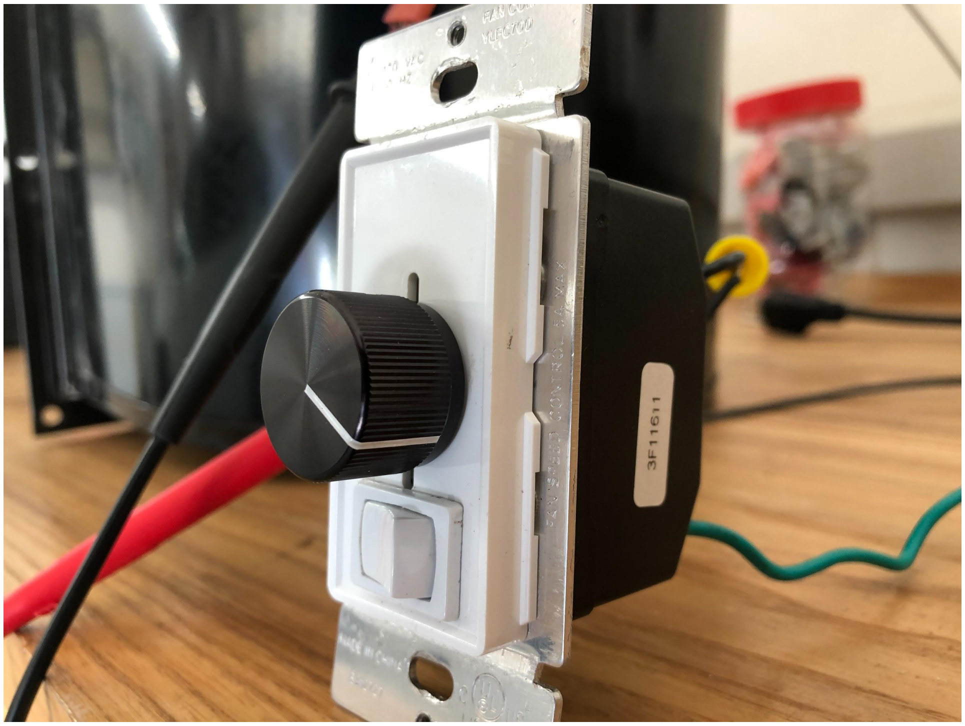

Figure 17 - Finished Hobbyist Fan Speed Controller

Figure 17 shows a front side view of the finished design. Pretty clean if I do say so myself!

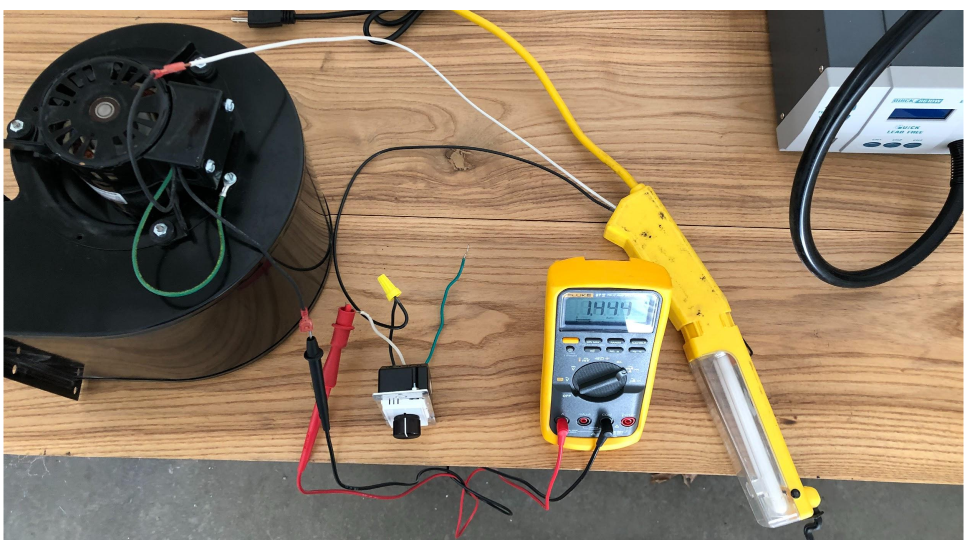

Figure 18 - Testing Setup

Figure 18 shows the testing setup used to make sure the FSC was controlling the fireplace blower. The wall-socket at the base of the yellow work light was used as the 120V AC source. The FSC was tested by running the fan at max speed for 1-hour with the ambient room temperature being 60 degrees Fahrenheit. The test was successful and the motor pulled 1.78 Amps AC at max speed.

Conclusion

- Capacitor C1 inside the YLFC700 is failing, likely due to a transient voltage spike at startup.
- Potentiometer fails in a specific resistance range as a result of C1 failing.
- The overvoltage issue can be addressed in several ways: TVS diode, higher voltage rated C1, or making the potentiometer start at its maximum resistance upon startup.

Appendix I - Code

Inductor Characterization.m

The following Matlab code uses logged values to plot the inductor (L1) characterization curves.

```
%{
Creator: AlledgedEngineering
Date: 2/7/2021
Tile: Inductor Characterization
Description: Plot recorded value to characterize an inductor used
in a TRIAC circuit for AC Motor Speed Control.

Equipment:
 Oscilloscope: Siglent SDS1104X-E 100MHz 4Ch
 Frequency Generator: Krohn-hite Model 1600 3MHz
 DMM: Fluke 87V

Signal:
 Sinewave with 10[Vpp]

Circuit:

Function Generator
.------------------|
|       50 Ohm     |    Rref     Va2
|   .---^^^^-------*---^^^^^---*
|   |              | Va1       |
|   |              |           >
|  (~) Vin         |           > Resr
|   |              |           >
|   |              |           |
|   |              |           &
|   |              |           & L
|   |              |           &
|   |              |           |
|   '---------------- GND -----'
'------------------'
%}
clc
clear all

% DC Resistance
Vdc = 4.983; % Volts
Idc = 0.567; % Amps
Rdc = Vdc/Idc;
fprintf('DC Resistance: %0.2f [V]\n', Rdc);

% Reference Resistor
Rref = 99.9; % ohms
fprintf('Reference Resistor: %0.1f [Ohms]\n', Rref);
```

```
% Data Points Collected
Va1 = [9.8, 10, 10.2, 10.0, 10,  10, 10, 10, 10, 10, 10, 10.2, 10.2, 10.2, 10.2, 10.2,
10.2, 10.2, 10.4 10.4, 10.4, 10.8, 11, 11.2, 11.4, 11.6, 12.2, 12.6, 13.6, 13.8, 14.4,
14.6, 15.4, 15.8]; % Volts
Va2 = [0.004, 0.0044, 0.0044, 0.0052, 0.0132,  0.0276, 0.0464, 0.0648, 0.1072, 0.1314,
0.246, 0.372, 0.472, 0.596, 0.704, 0.904, 1.12, 1.38, 1.62, 2.12, 3.18, 4.16, 5.04,
5.52, 6, 6.8, 8.08, 8.88, 10.88, 11.2, 12.16, 12.72, 13.4, 13.6]; % Volts
theta=[92.5, 92, 92.7, 91.4, 90.1,  -89.5, -89.2, -89.4, -89.5,-89.23, -83.11, -84.2,
-82.2, -80.1, -80.4, -79.3, -77.75, -76.7, -75.2, -72.8, -67.4, -63.1, -57.2, -56.6,
-54.7, -50.2, -45, -40.6, -30.3, -28.6, -21.5, -19.4, -10, -6]+90; % Deg
freq =[60, 100, 200, 300, 1000, 2000, 3500, 5000, 8100, 10000, 20000, 30000, 40000,
50000, 60000,80000, 100000, 125000, 150000, 200000, 300000, 400000, 500000, 550000
604000, 700000, 876639, 1*10^6, 1.41*10^6, 1.5*10^6, 1.8*10^6, 2.01*10^6, 2.5*10^6,
3*10^6]; % Hz



% Impedance [Ohms]
z = Va2*Rref ./ sqrt( (Va1.^2) - 2 * Va1 .* Va2 .* cosd(theta) + Va2.^2);
[val,indx] = max(z);
fprintf('Resonance Frequency: %.1f [kHz]\n', freq(indx)*10^-3);

% Angle of Impedance [Degrees]
angle = theta - atand(-1*Va2.*sind(theta)/ (Va1-Va2.*cosd(theta)));

% Now we can convert to rectangular form ZZ of the impedance to find the
% resistance and capacitance.
%       Z  = Resr + j*X
%          => Resr + j*2*pi*freq*L
%          => Z*cos(angle) + j*Z*sin(angle) %}

Resr = z .* cosd(angle);
L = z.*sind(angle) ./ (2 * pi * freq);

% Inductive Reactance
X = 2*pi.*freq.*L;


figure(1)
    subplot 231
    semilogx(freq, z), grid on;
    xlabel('Frequency [Hz]'), ylabel('Impedance [Ohms]');
    title('Inductor Impedance');

    subplot 232
    semilogx(freq, angle), grid on;
    xlabel('Frequency [Hz]'), ylabel('Phase [deg]');
    title('Angle of Impedance');

    subplot 233
    semilogx(freq, abs(L*10^6)), grid on;
    xlabel('Frequency [Hz]'), ylabel('Inductance [uH]');
    title('Inductance vs Frequency');

    subplot 234
```

```
semilogx(freq, Resr), grid on;
xlabel('Frequency [Hz]'), ylabel('Resr [Ohms]');
title('Resr vs Frequency');

subplot 235
semilogx(freq, X), grid on;
xlabel('Frequency [Hz]'), ylabel('Inductive Reactance [Ohms]');
title('Reactance X_L vs Frequency');

subplot 236
semilogx(freq, (Va1-Va2)./Rref), grid on
xlabel('Frequency [Hz]'), ylabel('Current [A]');
title('Current over Rref');
```

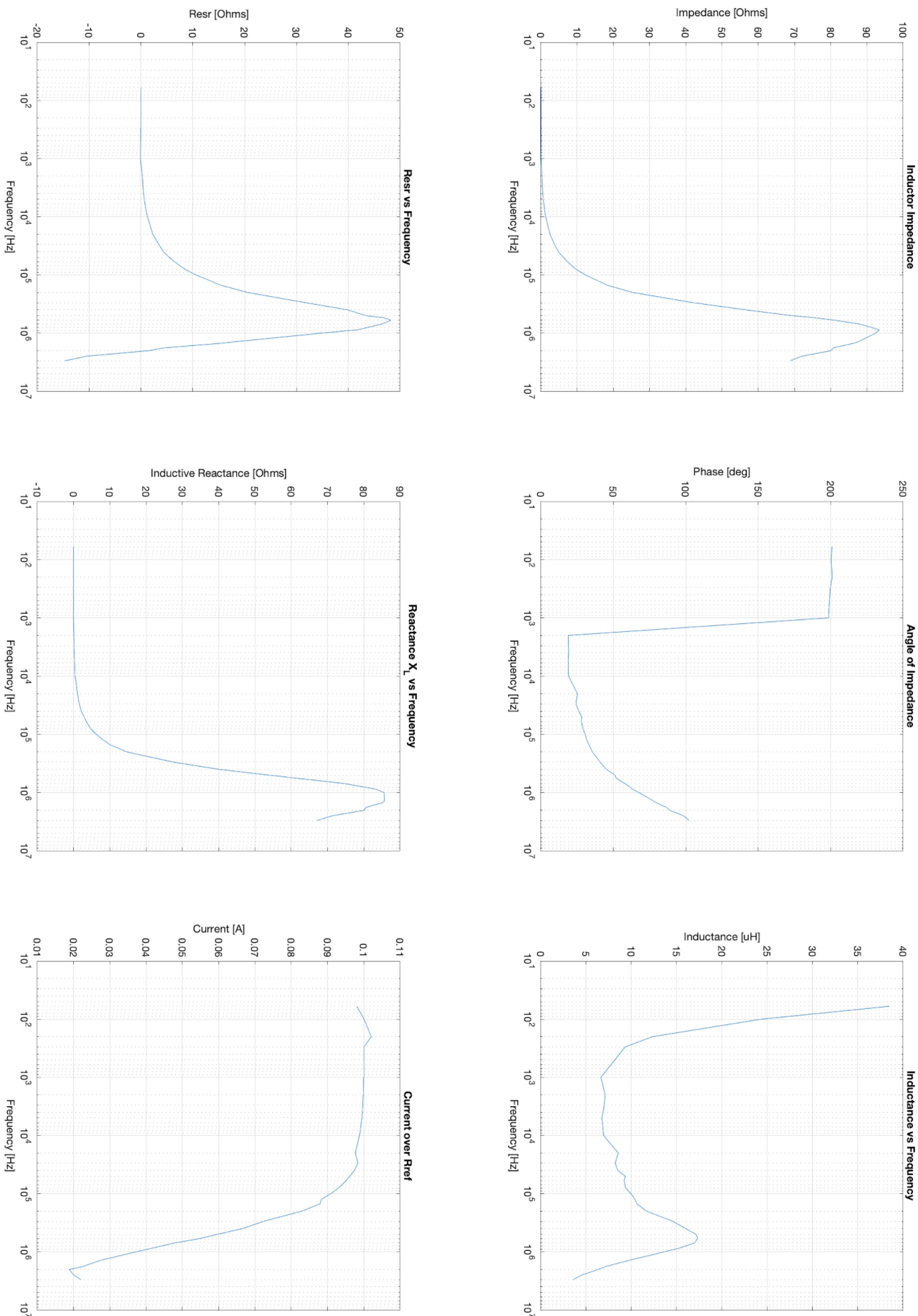

Figure 19 - Full Inductor Characterization Plots

Power Factor.m

```
%{
Creator: AlledgedEngineering
Date: 3/20/2021
Tile: Inductor Characterization
Description: Plot recorded value of the power factor at different potentiometer
resistance amounts.
Collect values from LTspice.


%}
clc
clear all

% Data Points Collected
Rpot = [100, 158.5, 251.19, 398.1, 631, 1000, 1584.89, 2511.89, 3981.07, 6309.6,
10000, 15849, 25119, 39810, 63095, 100000, 158489, 251189, 300000]; % Potentiometer
Resistance
PF = [0.8421, 0.8423, 0.8426, 0.8431, 0.8438, 0.8422, 0.8466, 0.8493, 0.8500, 0.8555,
0.8674, 0.8728, 0.8922, 0.9065, 0.8940, 0.8174, 0.6967, 0.4625, 0.4921]; % Power
Factor


figure(1)
    plot(Rpot, PF), grid on;
    xlabel('Potentiometer Resistance [Ohms]'), ylabel('Power Factor');
    title('Power Factor vs Potentiometer Resistance');
```

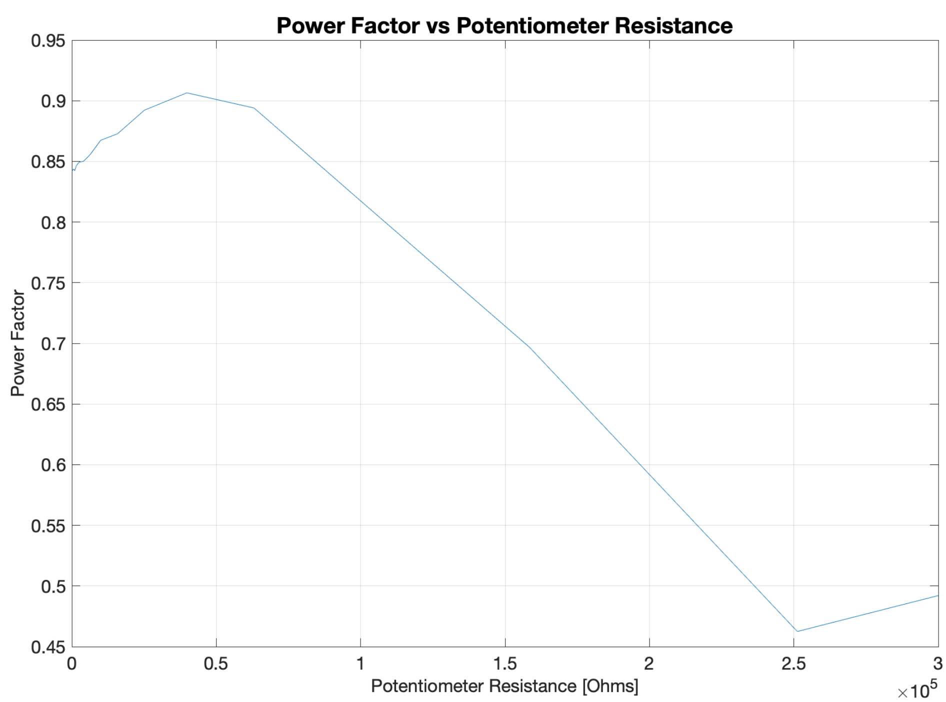

Figure 20 - Power Factor LTspice Data Plot

LTspice Netlist

```
Version 4
SHEET 1 1120 680
WIRE -560 -240 -976 -240
WIRE -352 -240 -560 -240
WIRE -176 -240 -352 -240
WIRE 128 -240 -96 -240
WIRE 304 -240 128 -240
WIRE -560 -224 -560 -240
WIRE -352 -224 -352 -240
WIRE -352 -96 -352 -160
WIRE -256 -96 -352 -96
WIRE -112 -96 -256 -96
WIRE -16 -96 -112 -96
WIRE 80 -96 48 -96
WIRE 128 -96 128 -240
WIRE -352 -80 -352 -96
WIRE -256 -80 -256 -96
WIRE -112 -80 -112 -96
WIRE -112 16 -112 0
WIRE -976 48 -976 -240
WIRE -560 48 -560 -160
WIRE -352 48 -352 0
WIRE -352 48 -560 48
WIRE -256 48 -256 0
WIRE -256 48 -352 48
WIRE 304 48 304 -240
WIRE -256 128 -256 48
WIRE -112 128 -112 96
WIRE -112 128 -256 128
WIRE -560 176 -560 128
WIRE 128 176 128 -32
WIRE 128 176 -560 176
WIRE 304 176 304 112
WIRE 304 176 128 176
WIRE -832 224 -896 224
WIRE -720 224 -752 224
WIRE 128 224 128 176
WIRE 128 224 -640 224
WIRE -976 288 -976 128
WIRE -896 304 -896 224
FLAG -976 288 0
FLAG -896 304 0
SYMBOL voltage -976 32 R0
WINDOW 123 24 124 Left 2
WINDOW 39 0 0 Left 0
WINDOW 3 -299 -41 Left 2
SYMATTR Value SINE(0 123 60 0 0 0)
SYMATTR InstName V1
SYMBOL ind -736 208 R90
WINDOW 0 5 56 VBottom 2
WINDOW 3 32 56 VTop 2
SYMATTR InstName L2
SYMATTR Value 10µ
```

```
SYMATTR SpiceLine Ipk=1.8
SYMBOL res -736 240 R270
WINDOW 0 32 56 VTop 2
WINDOW 3 0 56 VBottom 2
SYMATTR InstName R6
SYMATTR Value 30
SYMBOL res -544 144 R180
WINDOW 0 36 76 Left 2
WINDOW 3 36 40 Left 2
SYMATTR InstName R1
SYMATTR Value 2.4k
SYMBOL res -96 112 R180
WINDOW 0 -43 72 Left 2
WINDOW 3 -74 43 Left 2
SYMATTR InstName R2
SYMATTR Value 18.2k
SYMBOL res -96 16 R180
WINDOW 0 -36 69 Left 2
WINDOW 3 -84 42 Left 2
SYMATTR InstName R3
SYMATTR Value 270k
SYMBOL res -240 16 R180
WINDOW 0 -42 79 Left 2
WINDOW 3 -66 47 Left 2
SYMATTR InstName R4
SYMATTR Value 250k
SYMBOL cap -544 -160 R180
WINDOW 0 24 56 Left 2
WINDOW 3 24 8 Left 2
SYMATTR InstName C2
SYMATTR Value 100n
SYMBOL cap -336 -160 R180
WINDOW 0 24 56 Left 2
WINDOW 3 24 8 Left 2
SYMATTR InstName C3
SYMATTR Value 100n
SYMBOL cap 288 48 R0
SYMATTR InstName C1
SYMATTR Value 47n
SYMBOL ind -192 -224 R270
WINDOW 0 32 56 VTop 2
WINDOW 3 5 56 VBottom 2
SYMATTR InstName L1
SYMATTR Value 10µ
SYMBOL res -336 16 R180
WINDOW 0 36 76 Left 2
WINDOW 3 28 44 Left 1
SYMATTR InstName R5
SYMATTR Value {POT + 1m}
SYMATTR SpiceLine pwr=0.01
SYMBOL Misc\\TRIAC 96 -32 M180
WINDOW 3 48 72 Left 1
SYMATTR Value BTA16-600B
SYMATTR InstName U1
SYMBOL Misc\\DIAC 48 -128 R90
```

```
WINDOW 0 0 32 VBottom 2
WINDOW 3 64 32 VTop 2
SYMATTR InstName U2
SYMATTR Value DB3
TEXT 408 72 Left 2 !.tran 0 0.04 0.016 10u
TEXT 408 16 Left 2 !.inc STTRIAC.lib\n.inc STDIAC.lib
TEXT 408 -232 Left 2 ;DIAC: DB3\nVbo=13.6V\nIbo=10uA
TEXT 408 -96 Left 2 ;TRIAC: BTA16-600B\nIgt=100mA\nIh=50mA
TEXT 408 96 Left 2 ;.step dec param POT 100 250k 30
TEXT -808 160 Left 2 ;Motor
TEXT 8 240 Left 2 ;White Wire
TEXT -832 -256 Left 2 ;Black Wire
TEXT -1008 320 Left 2 ;GND
TEXT 416 168 Left 2 ;.four 50 I(V1)
TEXT 416 192 Left 2 !.meas R1_PWR PARAM 0.84*I(R1)*V(N007,N006)\n.meas R5_PWR PARAM
0.84*I(R5)*V(N006,N003)
TEXT 416 128 Left 2 !.step dec param POT 1 1000 10
RECTANGLE Normal -624 336 -928 176 1
```

Appendix II - Bill of Materials

Bill of Materials

Reference	Quantity	Value	Footprint	Datasheet	Other	Part	digikey
C1	1	47n	Capacitor_THT:C_Rect_L11.5mm_W5.2mm_P10.00mm_MKT	https://content.kemet.com/datasheets/KEM_C1055_HIVOLT_GOLDMAX_300_X7R.pdf	Ceramic Cap, 1kV	C330C473KDR5TA	399-14748-ND
C2 C3	2	100n	Capacitor_THT:C_Rect_L11.5mm_W5.2mm_P10.00mm_MKT	https://www.illinoiscapacitor.com/pdf/seriesDocuments/MSR%20series.pdf	250V	104MSR400K	1572-1012-ND
D1	1	DB3	Diode_THT:D_DO-35_SOD27_P7.62mm_Horizontal	https://www.st.com/content/ccc/resource/technical/document/datasheet/23/5c/f1/97/51/d1/4a/8f/CD00002289.pdf/files/CD00002289.pdf/jcr:content/translations/en.CD00002289.pdf	Ipk=2A, Ibr=15uA, Vbr=30~34V	DB3TG	497-3134-2-ND
F1	1	Fuse	my_lib:FUSC6125X279N	https://belfuse.com/resources/datasheets/circuitprotection/ds-cp-0679l-series.pdf	4 Amp	0679L4000-05	507-1993-1-ND
H1 H2	2	MountingHole	MountingHole:MountingHole_3mm	~			
H3	1	MountingHole	MountingHole:MountingHole_5mm	~			
J1	1	BlackWire	my_lib:Pin_D1.7mm	~			
J3	1	WhiteWire	my_lib:Pin_D1.7mm	~			
L1	1	L_Core_Ferrite	my_lib:TRIAC_Choke	~			
Q1	1	BTA16-600B	Connector_PinSocket_2.54mm:PinSocket_1x03_P2.54mm_Vertical	https://www.st.com/resource/en/datasheet/bta16.pdf	16A, 600V, Vgt=1.3V, Igt=50mA	BTA16-600BRG	497-2397-5-ND
R1	1	2.4k	Resistor_THT:R_Axial_DIN0207_L6.3mm_D2.5mm_P10.16mm_Horizontal	~	2W		
R2	1	270k	Resistor_SMD:R_1206_3216Metric_Pad1.30x1.75mm_HandSolder	https://www.te.com/commerce/DocumentDelivery/DDEController?Action=srchrtrv&DocNm=9-1773463-9&DocType=DS&DocLang=English	1% 1W	CRGP1206F270K	A130567CT-ND
R3	1	18k	Resistor_SMD:R_1206_3216Metric_Pad1.30x1.75mm_HandSolder	https://www.te.com/commerce/DocumentDelivery/DDEController?Action=srchrtrv&DocNm=9-1773463-9&DocType=DS&DocLang=English	1% 1/2W	CRGP1206F18K	A130553CT-ND
R4	1	240k	Resistor_SMD:R_1206_3216Metric_Pad1.30x1.75mm_HandSolder	https://d1d2qsbl8m0m72.cloudfront.net/en/products/databook/datasheet/passive/resistor/chip_resistor/esr-e.pdf	5% 1/2W	ESR18EZPJ244	RHM240KICT-ND
R5	1	24	Resistor_SMD:R_2512_6332Metric_Pad1.40x3.35mm_HandSolder	https://www.seielect.com/catalog/sei-rmcf_rmcp.pdf	5% 1W	RMCF2512JT24R0	RMCF2512JT24R0CT-ND
RV1	1	R_POT_10_to_300k	my_lib:91A1A-B28-A22L-Bottom	https://www.bourns.com/docs/Product-Datasheets/91_95.pdf	2W 0.2 to 250k	91A1A-B28-A22L	91A1A-B28-A22L-ND
SW1	1	SW_DIP_x01	my_lib:GRS-2011-2055	https://media.digikey.com/pdf/Data%20Sheets/CW%20Industries%20PDFs/GRSV-4011-0123_THRU_-0127_Dwg.pdf	13A 125VAC	GRSV-4011-0126	CWI487-ND

Figure 21 - DigiKey Bill of Materials

Appendix III - Packaging

Figure 22 - YLFC700 Packaging

Appendix IV - Legal Notice

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