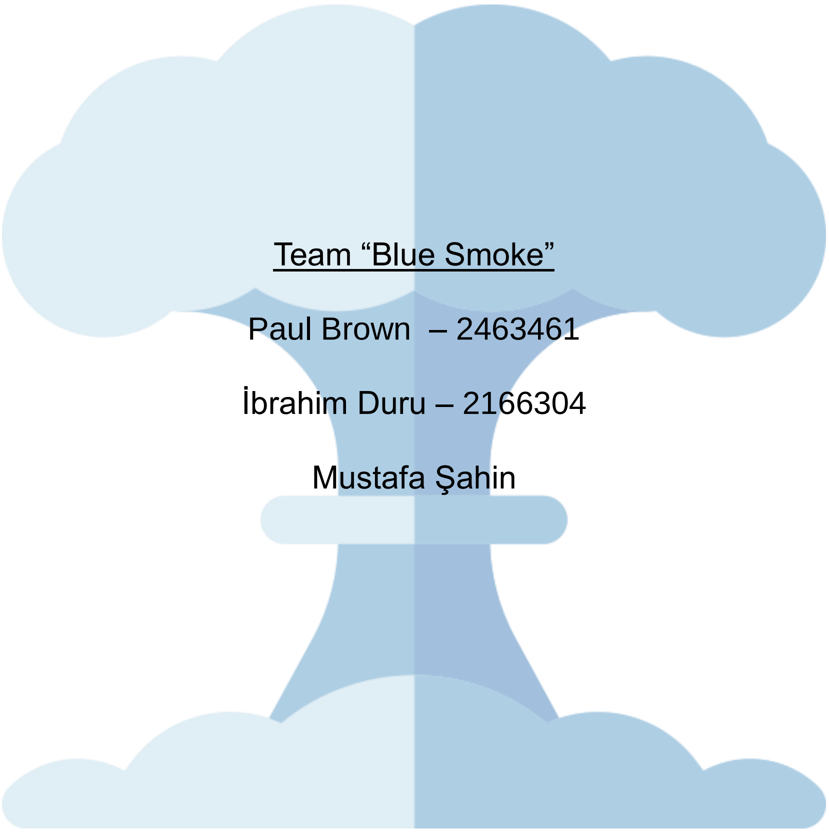
EE463 Hardware Project
Final Report

15 January 2020



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Formula Sheet

$V_t = E_a + I_a \times R_a$ (1)

$E_a = L_{af} \times I_f \times w_m$ (2)

$T = L_{af} \times I_f \times I_a$ (3)

$E_a = V_t - I_a \times R_a$ (4)

$E_a \times \frac{I_a}{\omega_m} = T$ (5)

$T = P/\omega_m$ (6)

Introduction

This report presents designing a rectifier circuit that will be used to drive a DC motor. The circuit implemented for the project was a diac-controlled triac circuit. This circuit essentially utilizes an RC circuit with a diac to control the firing angle of the triac. The triac operates on both the positive and negative half-cycles of the input AC voltage supply to chop the voltage down. The chopped AC voltage is then rectified through a full-wave diode bridge rectifier to become a controlled DC output to drive the DC motor.

The design process began with simulations of various candidate topologies. The simulation of candidate topologies that were not selected as well preliminary component selection can be found in the team’s Simulation Report (submitted 4 December 2019).

This report describes the simulations of the selected diac-controlled triac circuit topology with modifications relative to the previous submission since component models were updated based on the selected components. We then briefly present the alternative circuit topologies that were considered and the reasons for choosing the diac-controlled triac circuit. The report goes on to present the thermal design calculations for the project, the procurement and assembly process, and project testing and demonstration. Throughout this report, lessons learned through the experiences of the project team are summarized.

Simulations

Simulations were performed for various topologies under consideration to better understand the advantages and disadvantages among them and to show some of the component ratings that would be needed for those topologies to be applied. The topologies simulated were a three-phase thyristor rectifier, a three-phase diode rectifier with buck converter, and a TRIAC-based AC chopper to diode bridge rectifier. After presenting some common calculations, the simulations results for the selected TRIAC-based AC chopper circuit will be shown. Results for the other topologies that were not selected can be found in the projects’ simulation report. Since some modeled component values were changed based on parameters from the datasheets of the selected components, the results presented here are different from those in the previously submitted simulation report.

Voltage Source Model

The converter designed in this project will be fed from a variable transformer (variac) adjusted to give the desired output voltage. It is assumed that the variac output voltage will be adjusted to a desired setpoint prior to connecting load to the output of our converter. For the three-phase rectifier and buck converter models, a variac output voltage of 120 $V_{rms,l-n}$ was selected. This voltage level allows the converters to be in the middle of their regulating range while providing 175 V_{DC} output.

For the triac-based model, since it is fed from single-phase voltage source and because the diac circuit needs a substantial voltage headroom over the motor back EMF in order to charge, the variac is simulated as set to 220 $V_{rms,l-n}$. Based on simulations, this voltage allows the circuit to achieve 175 V_{DC} (average) output to the motor.

The source impedance of the lab AC power supply and variac is not known, but for modeling purposes, it was represented with a resistance of 50 mΩ and an inductance of 180 μH. This works out to an available short-circuit current at 120 V of 1590 A.

Motor Calculations and Modeling

In this project, the DC motor load to be driven by the electronic power converter should be represented in the simulations. In Simulink, it is possible to represent the DC motor load as a motor with a torque load or using the Ea, Ra, La equivalent circuit elements. Both representations were developed for our Simulink model, but for the simulation results, the Ea, Ra, La equivalent circuit elements were used.

The parameters for the DC motor model were calculated based on the nameplate data of the motor and parameters provided with the project assignment.

The nameplate is shown in Figure 1 below.

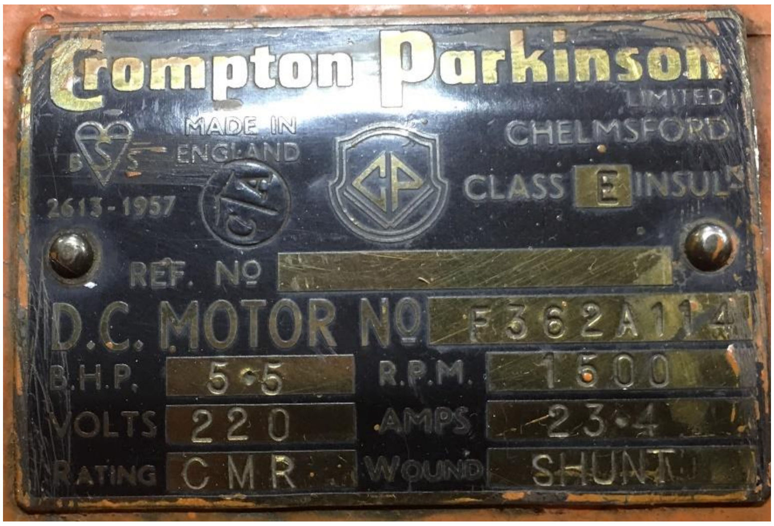

Figure 1: DC Motor Nameplate

Additional motor parameters were provided with the project assignment. The motor data taken from this information is summarized in Table 1.

Table 1: DC Motor Provided Parameters

Parameter	Value
Pmec	5.5 HP
RPM	1500
VS	220 V
IS	23.4 A
Armature Winding	0.8 Ω, 12.5 mH
Shunt Winding	210 Ω, 23 H
Interpoles Winding	0.27 Ω, 12 mH

The DC motor model in Simulink takes some additional parameters that were not provided, but which can be calculated from the available information.

Rated speed (rad/s) = $\frac{1500x2x\pi}{60}$ = 157 rad/s

Rated field current (A) =$\frac{220V}{208\Omega}$ = 1.06 A

Simulink also takes parameters for armature-field mutual inductance Laf as well as a friction coefficient. These can be calculated from the provided values for motor operation at rated speed, power, voltage, and current, as is shown in the following subsection.

<u>Motor Operation at Rated Load</u>

The equivalent circuit parameters for a DC motor are the following:

$$V_t = E_a + I_a \times R_a \quad (1)$$
$$E_a = L_{af} \times I_f \times w_m \quad (2)$$
$$T = L_{af} \times I_f \times I_a \quad (3)$$

(In many formulations, Ka*Φ is used instead of L_{af}*I_f, but since Simulink will use L_{af}, it is convenient that we use this formulation.)

P_{rated} = (5.5 HP) x (746 $\frac{W}{HP}$) = 4103 W. This power is mechanical output.

At rated speed of 157 rad/s, rated mechanical torque is
(4103 W)/(157 rad/s) = 26.12 N-m.

Since the motor is rated for a shunt configuration,
I_f = $\frac{220V}{210\Omega}$ = 1.05 A

Rated electrical input is (220 V) x (23.4 A) = 5148 W (neglecting any reactive power). So rated efficiency is approximately 0.80.

Resistive losses in armature = $(22.4\ A)^2 \times (0.8\ \Omega)$ = 401 W. Remaining losses are in the field resistance and friction.

At full load V_t = 220 V and $E_a = V_t - I_a \times R_a$ = 220 V - (0.8 Ω)*(22.4 A) = 202 V.   (4)

$L_{af} = \frac{E_a}{I_f \cdot \omega_m} = \frac{202}{1.05x157} = 1.23$ H

L_{af}*I_f = 1.05 A * 1.23 H = 1.29

The electrical torque can be calculated as
$E_a \times \frac{I_a}{\omega_m} = \frac{(202V)x(22.4A)}{157}$ = 28.76 N-m.   (5)

Since the rated output mechanical torque is 26.1 N-m, apparently there are additional mechanical torque losses. The simplest is to model them as Coulomb friction losses (i.e. constant torque):
T_e - T = 28.76 N-m - 26.12 N-m = 2.64 N-m

At rated speed, this works out to friction loss of
2.64 N-m * 157 rad/s = 415 W.

<u>Simulink Parameters</u>

When modeled as a DC motor in Simulink, the parameters entered are as shown in Figure 2.

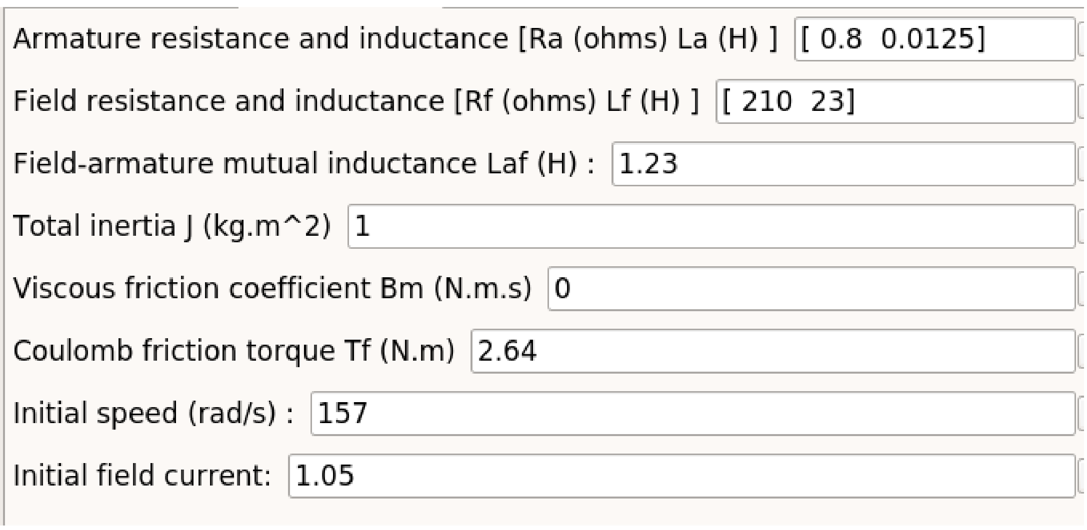

Figure 2: DC Motor Simulink Parameters

When modeled using E_a, R_a, and L_a, R_a and La are entered directly as shown in the datasheet, but back EMF E_a should be calculated based on the operating speed. Ea was calculated for rated load above, and is calculated for other load conditions in the following subsections, the results of which are summarized in Table 1. A terminal voltage of 175 V is chosen since the problem specifies that V_{max} < 180 V, but lower voltages require higher current to get the same power output.

Table 2: Equivalent E_a for Various Load Conditions

Load Condition	**V_t (V)**	**E_a (V)**	**ω_m (rad/s)**	**External T (N-m)**
Starting	175	0	0	283
No Load	175	171	133	2.6
Kettle Load (1600 W)	175	164	127	15.4
Rated Load	220	202	157	26.1

<u>Startup</u>

At startup, ω_m = 0, so E_a = 0.

Torque and current at startup will depend on how much voltage is applied. If full rated voltage were applied, startup current would be

$I_a = \frac{175V}{0.8\Omega} = 219$ A

T = 219 * 1.29 = 283 N-m

This is too much current and torque, so the applied voltage must be reduced for starting the motor.

<u>No Load</u>

The motor running at no load has only to output mechanical power equal to the friction of the running motor and coupled AC synchronous machine.

Neglecting voltage drop on the armature winding such that Ea = Vt, speed can be estimated as

$\frac{E_a}{L_{af} \cdot \omega_m} = \frac{175}{1.29} = 136$ rad/s

Based on the coefficient of friction calculated in the full load section above, the mechanical power at this speed can be estimated as

2.65 N-m x 136 rad/s = 360 W

Estimating additionally that the connected synchronous maching has a similar amount of friction, the total "no load" load is estimated as 700 W.

At no-load, this friction loss will have the following circuit values:

V_t = 175 V

I_a x E_a = 700 W ⇒ $E_a = \frac{700W}{I_a}$

$\frac{700W}{I_a}$ = 175 V - I_a x (0.8 Ω)

700 W = (175 V) x I_a - I_a^2 x (0.8 Ω)

0 = 0.8 x I_a^2 – 175 x I_a + 700

$I_a = \frac{175-\sqrt{175^2-4x0.8x700}}{2x0.8}$ = 4.1 A.

$E_a = \frac{700W}{4.1A}$= 171 V

No-load speed can be calculated as

$\omega_m = \frac{E_a}{L_{af} \cdot I_f} = \frac{171V}{1.29}$ = 133 rad/s.

This is 133/157 = 85% of rated speed.

The external torque to account for the synchronous generator friction is estimated as 350 W / 133 rad/s = 2.6 N-m

Kettle Load

For the "Robust Design" bonus, the motor must be run such that it supplies power to a 1600-W water kettle connected to the output of the synchronous machine coupled to the DC motor. Based on the additional friction load calculated for "no-load" operation, the total mechanical power for the kettle load is 2300 W.

The kettle load is calculated to have the following circuit values:

V_t = 175 V

I_a x E_a = 2300 W ⇒ $E_a = \frac{2300W}{I_a}$

$\frac{2300W}{I_a}$ = 175 V - I_a x (0.8 Ω)

2300 W = (175 V) x I_a – I_a^2 x (0.8 Ω)

0 = 0.8 x I_a^2 - 175 x I_a + 2300

$I_a = \frac{175-\sqrt{175^2-4x0.8x2300}}{2x0.8}$ = 14.0 A.

$E_a = \frac{2300W}{14.0A}$= 164 V

Speed can be calculated as

$\omega_m = \frac{E_a}{L_{af} \cdot I_f} = \frac{164V}{1.29} = 127$ rad/s.

This is $\frac{127}{157}$ = 81% of rated speed.

At ω_m = 127 rad/s, the estimated 1950 W external mechanical load will have a torque of

$T = P/\omega_m = \frac{1950}{157} = 15.4$ N-m. (6)

TRIAC AC Chopper + Diode Bridge Rectifier

The last topology that was considered is a simple triac AC chopper circuit connected to the DC motor through a diode bridge. This topology was not presented in class, but when asked about how to generate the gate signals for a thyristor rectifier, he suggested that we could use triac and diac components and recommended basic driver circuits. After some research on possible thyristor driver circuits, we found a circuit in the Littlefuse “Phase Control Using Thyristors” Application Note AN1003 that we thought could possibly work for this project. A schematic of the circuit we designed is shown in Figure 3.

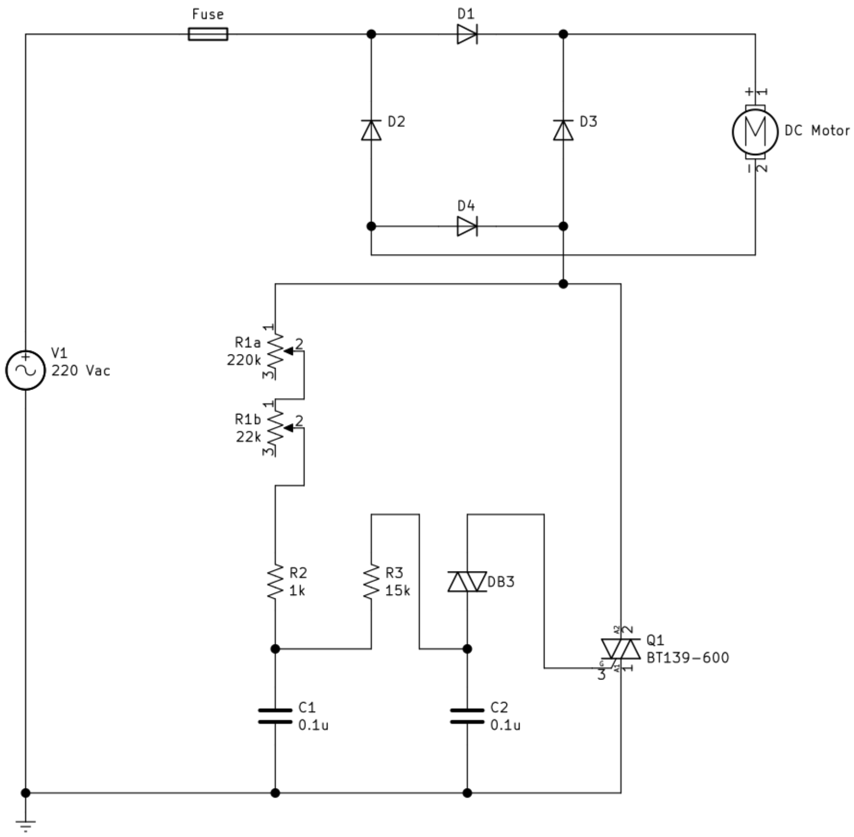

Figure 3: TRIAC DC Motor Control Circuit

Simulating this circuit is complicated in Simulink by the fact that Simulink does not have any triac or diac models in the toolbox. In order to implement the circuit in Simulink, a triac model was developed by placing two thyristors in parallel but with opposite polarity and connecting the firing signals together. Based on the selected BTA26 triac, the forward voltage was modeled as 1.3 V based on the datasheet maximum forward voltage drop for the triac. The triac was modeled with a resistance of 16 mΩ based on the dynamic resistance stated on the datasheet. The input resistance of the triac gate was modeled with a resistance of 1 kΩ since that gives a gate current pulse of 10-20 mA when the diac fires and seems to be in the right order of magnitude.

A Simulink diac model was created by making the same counter-parallel connection as was done for the triac and then creating logic in the firing circuit such that the diac fires when the voltage across the device exceeds its characteristic turn-on voltage. A diac breakover voltage V_{bo} of 32 V was used based on the selected DB3 diac. The DB3 has a minimum dynamic breakover voltage ΔV of 5 V, so the diac was modeled with a forward voltage of 27 V.

Figure 4 shows the full triac-based Simulink model.

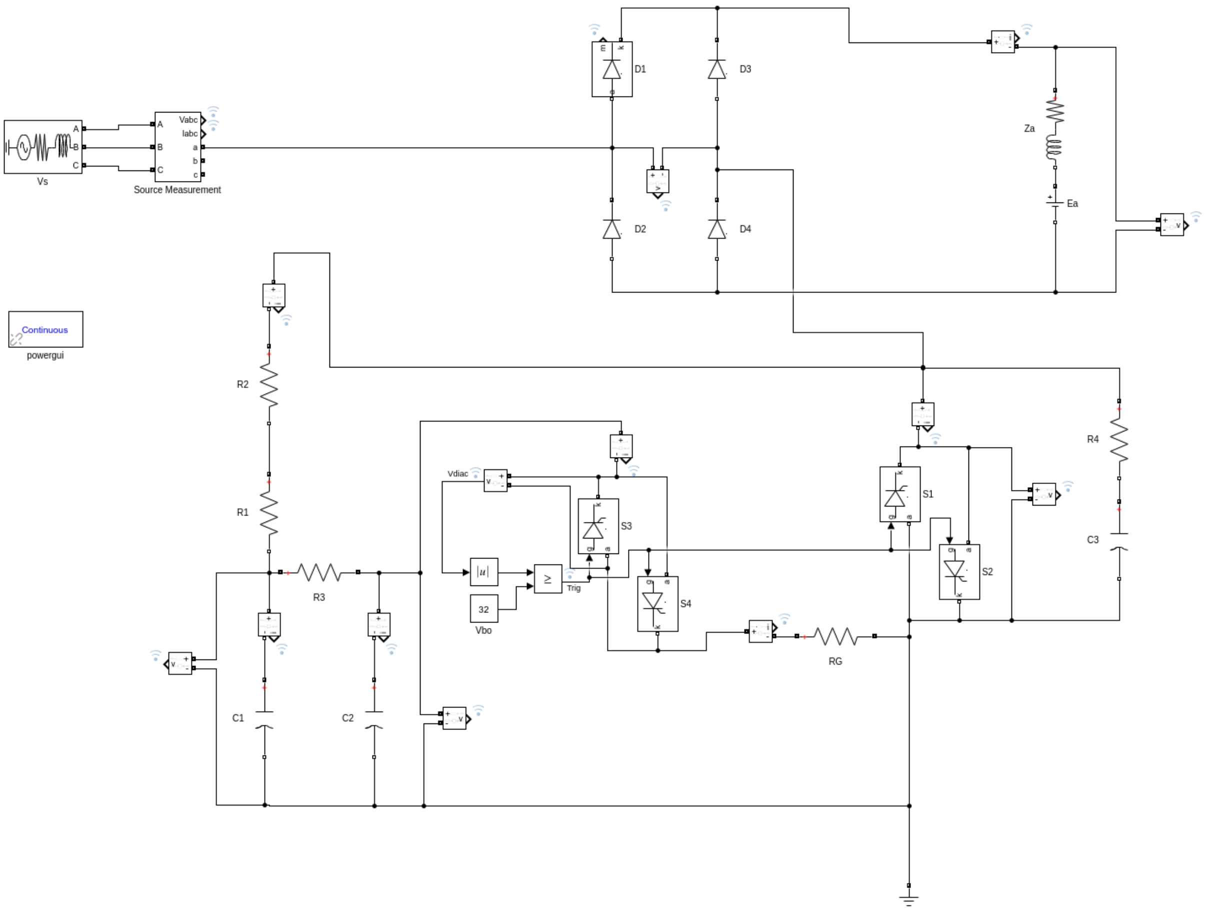

Figure 4: Triac-Diac Simulink Model

Small Resistive Load

In order to test that the circuit works as expected and see the range of control of the triac, the model was first tested using relatively small resistive load of 100 Ω on the rectifier output. The resistance of R1, representing the control potentiometer, was varied and the output voltage and current waveforms recorded. Results of these simulations are shown in Figure 5.

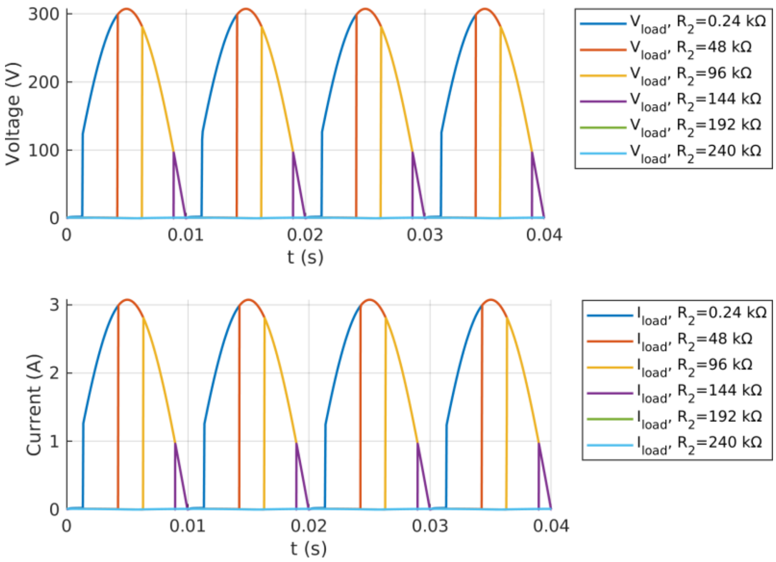

Figure 5: Triac-Diac Simulink Results with Small Resistive Load

As can be seen from Figure 5, the diac firing circuit is limited in its ability to fire at angles near 0° and near 90°. From what we have read about diac-triac circuits, this “snapping on” behavior is typical of this type of circuit, and we observed it during testing as well.

DC Motor Load

Once the circuit was simulated using the small resistive load and was giving reasonable results, we passed to simulations using the equivalent circuit for the DC motor as we did for the other topologies. For each load condition, the R1 resistance was adjusted to give an average output voltage appropriate to the load condition. For the motor start, this was set to obtain current near or less than the rated current of the motor. For no load and kettle load conditions, the output voltage was adjusted to 175 V. In this case, the rated motor load was not simulated since a phase-to-neutral supply voltage of 220 V was not sufficient to obtain an output voltage of 220 V_{DC}. Since the problem statement restricts the output voltage to less than 180 V_{DC} anyway, the rated load simulation is not essential to the project.

Figure 6 shows the output voltage and current waveforms for the simulations of the triac-based control model.

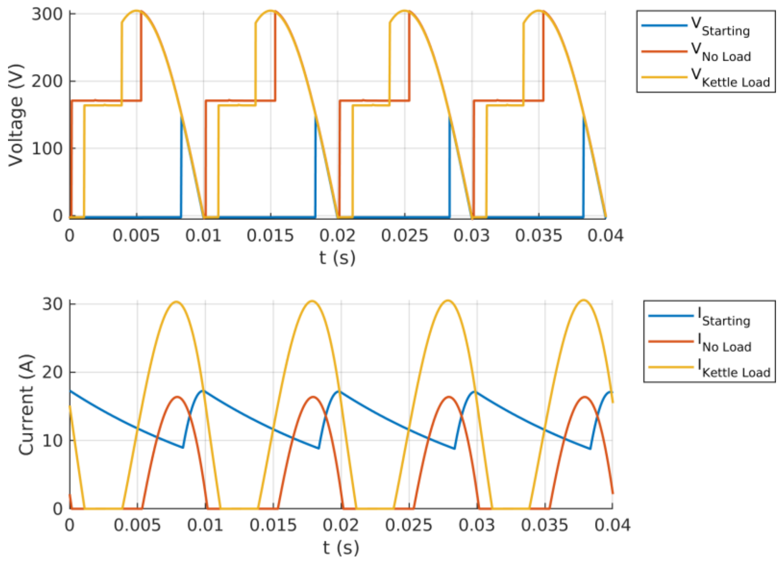

Figure 6: Triac-Diac Simulation Output Waveforms

In Figure 6, we can see that the output current is continuous only for the starting case. In the other two load cases, current was discontinuous. This is largely due to the use of a single-phase AC voltage source rather than three-phase.

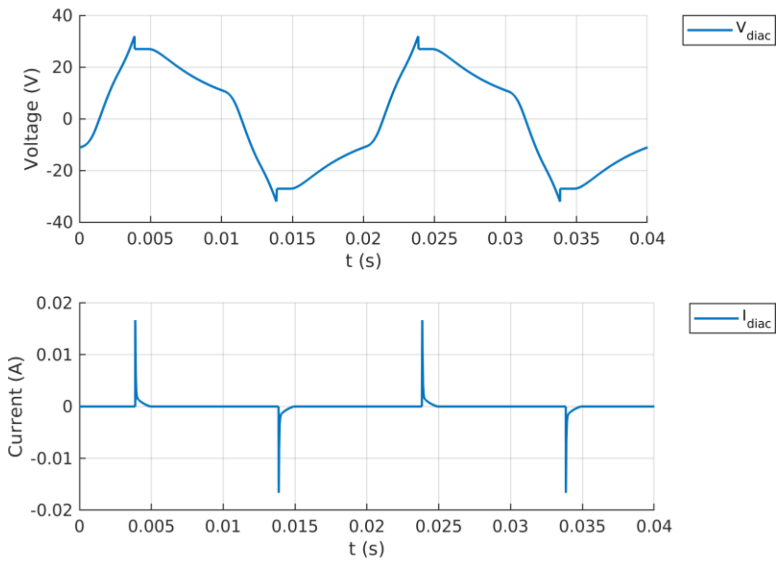

Figure 7: Triac-Diac Control Voltage & Current

In Figure 3, the diac control voltage and current are shown for the kettle load simulation. This is provided for comparison against oscillography recorded during testing.

Tables 3 and 4 show summary values of the input and output side voltages and currents from the simulations.

Table 3: Triac-Diac Simulation Summary (Input Side)

Load	R2 (kΩ)	V_{IN} (V_{RMS})	I_{IN} (A_{RMS})	P_{IN} (W)	Q_{IN} (var)	S_{IN} (VA)	PF	I_{IN} THD (%)
Starting	137	219.8	6.48	179.1	1414	1425	0.13	135.2
No Load	21	219.5	8.22	961.8	1526	1804	0.53	64.06
Kettle Load	17	218.8	17.95	2582	2958	3926	0.66	39.31

Table 4: Triac-Diac Simulation Summary (Output Side)

Load	V_{OUT} (V_{AVG})	V_{OUT} Ripple	I_{OUT} (A_{AVG})	I_{OUT} Ripple	P_{OUT} (W)	Efficiency (%)
Starting	10.46	152.3	13.21	8.67	143	79.87
No Load	175.1	309	5.19	16.41	941	97.84
Kettle Load	175.1	307.4	13.77	30.61	2523	97.71

Additional key information about components was extracted from the simulations and is shown in Tables 5, 6, 7, and 8. The values from preliminary simulations presented in the previously submitted simulation report were used for component selection. The values shown here are from subsequent simulations utilizing updated model parameters based on the selected components and are verified against the selected component ratings to verify adequecy.

Table 5: Triac-Diac Simulation Key Diode Values

Load	I_{avg} (A)	I_{RMS} (A)	V_{MAX} (V)	P_{Loss} (W)
Starting	6.6	7.5	151	7.8
No Load	2.6	5.8	305	3.2
Kettle Load	6.9	12.7	306	9.2

Table 6: Triac-Diac Simulation Key Triac Values

Load	I_{avg} (A)	I_{RMS} (A)	V_{MAX} (V)	P_{Loss} (W)
Starting	2.8	6.5	311	4.3
No Load	5.2	8.2	138	7.8
Kettle Load	13.1	18.0	126	22.2

Table 7: Triac-Diac Simulation Key Capacitor Values

Load	C_1 I_{RMS} (mA)	C_1 V_{MAX} (V)	C_2 I_{RMS} (mA)	C_2 V_{MAX} (V)
Starting	0.9	41.3	0.9	32.0
No Load	1.6	60.2	1.0	32.0
Kettle Load	1.5	55.4	1.0	32.0

Table 8: Triac-Diac Simulation Key Resistor Value

Load	R_1 I_{RMS} (mA)	R_1 P (mW)	R_2 I_{RMS} (mA)	R_2 P (mW)	R_3 I_{RMS} (mA)	R_3 P (mW)
Starting	1.5	2.3	1.5	309	0.7	8
No Load	2.2	4.7	2.2	98	0.9	13
Kettle Load	2.0	4.1	2.0	69	0.8	10

Topology Comparison and Selection

Each of the topologies considered will be discussed briefly.

Three-Phase Thyristor Rectifier

This circuit offers us higher output average voltage and less ripple compared to the other alternatives without using parallel output capacitor. However, it requires six thyristors and required gate signal driver circuits. In order to arrange the feedback and behavior of circuit, we need to change the firing angle of thyristor. In addition, number of thyristor is more than our chosen topology. This effects the size and cost of the project. As a result, in order to work toward compactness and simplicity bonuses, this topology was judged as not appropriate.

Rectifier + Buck Converter

This circuit offers us a simpler way to finish the project compared to the three-phase thyristor rectifier. However, it requires six diodes and a buck convertor part. In addition, arranging the filter and the calibration of buck convertor without using a microcontroller can be problem. Similar to our opinion for the three-phase thyristor rectifier, in order to work toward compactness and simplicity bonuses, this topology was judged as not appropriate.

Single-Phase Thyristor Rectifier

This circuit offers us more simple way compared to the three-phase thyristor rectifier. However, it has less output voltage and more ripple comparing to a three-phase rectifier. Again, in this topology, we need to drive four thyristors in synchronism with each other. In addition to that, according feedback data from the output firing angle of the four thyristors should be changed. The gains in eliminating two thyristors to drive still did not achieve the level of simplicity that we desired.

Chosen Topology: Single-Phase Diac-Controlled Triac rectifer

The single-phase diac-controlled triac rectifier has several advantages for which we selected it. The primary advantage is its simplicity. There is a single controlled element, the triac, for which a gate signal is required. The diac can be used to control the triac by adjusting the value of the variable resistor in the circuit. Because the control circuit is powered from the mains voltage, no additional power supply or regulation is needed for the control circuit as it would be in other configurations.

One disadvantage of this topology is that it is not easily adapted to any type of feedback control. It is also limited to single-quadrant operation by the diode bridge that supplies the DC motor load.

Table 9: Comparison According to Components

Topology	Required Semiconductor	Required Manageable Components
3-phase Thyristor	6 Thyristor	6 Thyristor
Rectifier+ Buck	6 Diode + Mosfet	Mosfet
1- phase Thyristor	4 Thyristor	4 Thyristor
Diac- Triac	4 Diode+ 1 Diac+ 1 Triac	1 Diac

Table 10: Comparison According to Bonuses

Topology	Industrial Design Bonus	Robust Design Bonus	Closed-loop Voltage/Current Control Bonus
3-phase Thyristor	Applicable	Applicable	Need to change in firing angle
Rectifier+ Buck	Applicable	Applicable	Need to change in mosfet signal
1- phase Thyristor	Applicable	Applicable	Need to change in firing angle
Diac- Triac	Applicable	Applicable	Need to change in resistance value

Table 11: Comparison According to Bonuses (continued)

Topology	Compactness Bonus	Simplicity Bonus	Four-Quadrant Bonus
3-phase Thyristor	Too much component	Can be hard due to firing	Applicable
Rectifier+ Buck	Too much component	Can be hard due to mosfet signal	Not Applicable
1- phase Thyristor	Applicable	Can be hard due to firing	Not Applicable
Diac- Triac	Applicable with ease	Easy thanks to diac-triac	Not Applicable

Final words about the choosing the topology;

We need to decide what bonuses we want to aim. In order to be in the safe side, simplicity bonus is chosen. Complexity of the topologies are due to controlling thyristor or MOSFET. Thanks to diac-triac, we are dealing this complexity easily. Also, compactness bonus is achievable with this topology thanks to simplicity of the circuit. As a result, topology is chosen according to which bonuses we can achieve and what cost.

Component Selection

Triac Selection

In all possible cases, we observe 311 V_{max}. Current value depends on how we start to system. Therefore, we choose a tentative value for the current. In order to be safe side we choose BTA26-600 Triac.

Symbol	Parameter	BTA24[1]	BTB24	BTA25[1]	BTA26[1]	BTB26	T25	Unit
$I_{T(RMS)}$	RMS on-state current	25	25	25	25	25	25	A
V_{DRM}/V_{RRM}	Repetitive peak off-state voltage	600 / 800	600 / 800	600 / 800	600[2] / 800	600	600 / 800	V
I_{GT} (Snubberless)	Triggering gate current	35 / 50	35 / 50	50	35 / 50	-	35	mA
I_{GT} (Standard)	Triggering gate current	-	50	50	50	50	-	mA

Figure 8: Triac Ratings

Diac Selection

First we checked the Digikey for the possible components. However, most of the components were obsolete. Then, we look the Direnc.net, we find DB3 DO-35 36 V diac. It is appropriate for the circuit since its blocking voltage is similar to our expected voltage. In addition, in the circuit diac does not carry too much current so 2A current rating is useful for the circuit.

Symbol	Parameter			Value		Units
				DB3	DB3TG	
V_{BO}	Break-over Voltage	@ C=22nF	**Min.**	28	30	V
			Typ.	32	32	V
			Max.	36	34	V
$\pm V_{BO}$	Break-over Voltage Symmetry	@ C=22nF	**Max.**	±3	±2	V
I_{BO}	Break-over Current	@ C=22nF	**Max.**	100	15	µA
ΔV	Dynamic Break-over Voltage	@ I_{BO} to I_F=10mA	**Min.**	5	9	V
I_B	Leakage Current	@ V_B=0.5V_{BO}(Max.)	**Max.**	10		µA
V_O	Output Voltage	*see diagram 1	**Min.**	5		V
P_D	Power Dissipation			150		mW
I_{FRM}	Repetitive Peak Forward Current,	Pulse Width=20µsec		2		A

Figure 9: Diac Ratings

Capacitor Selection

In our reference circuit, capacitor value is given as 0.1uf 400 V. We did some changes in reference circuit and we are still in range of capacitor so we can use that values for capacitor. According to this values we choose ceramic disc capacitor.

Figure 10: Capacitor Ratings

QUICK REFERENCE DATA	
DESCRIPTION	**VALUE**
Ceramic Class	2
Ceramic Dielectric	Y5V
Voltage (V_{AC})	400
Min. Capacitance (pF)	9000
Max. Capacitance (pF)	100 000
Mounting	Radial

Resistor Selection

Based on simulations, fixed resistance values of 1 kΩ and 15 kΩ were selected. Simulations showed resistor power dissipation of less than 100 mW, so even 1/8 W resistors would be sufficient.

For the potentiometer, at Dr. Keysan's suggestion, we chose to use one 220 kΩ potentiometer for gross adjustment and an additional 22 kΩ potentiometer for fine adjustment. The greatest power dissipation for the potentiometers is in the starting condition, when the triac spends most of its time non-conducting (and therefore voltage is applied across the control circuit, mostly dropped across the potentiometer). We did not choose to find potentiometers with power ratings more than the ones available off the shelf, the power rating of which we are not exactly sure.

Thermal Design

In order to select heatsinks for the diode bridge and the triac, thermal design was done. Since the project is being completed in winter time, we estimate the ambient temperature to be maximum 25°C.

Diode Bridge

Based on simulations, the diode bridge is estimated to have power losses of 9.2 W per leg or 37 W total in the kettle load condition. Based on the datasheet for the diode bridge, the thermal resistance from junction to case is 2.1°C/W per leg. For four legs in parallel, the equivalent thermal resistance would be 2.1/4 = 0.53°C/W. According to the datasheet, the maximum junction temperature for the diode bridge is 150°C.

ΔT_{max} = 150°C – 25°C = 125°C (maximum junction temperature rise)

$R_{\theta total} = \Delta T_{max} / P_{max}$ = (125°C) / (37 W) = 3.4°C/W

$R_{\theta\text{-}hs}$ = 3.4 – 0.53 = 2.9°C/W (heat sink thermal resistance to ambient)

To determine approximate dimensions of a heat sink of this thermal resistance, we used filtering on the DigiKey website, and found that most heat sinks with approximately this thermal resistance under natural airflow were dimensioned approximately 30 mm x 50 mm.

Triac

Based on simulations, the triac is estimated to have power loses of 22.2 W in the kettle load condition. Based on the datasheet for the triac, the thermal resistance from junction to case is 0.6°C/W and the maximum operating junction temperature is 125°C.

ΔT_{max} = 125°C – 25°C = 100°C (maximum junction temperature rise)

$R_{\theta total} = \Delta T_{max} / P_{max}$ = (100°C) / (22 W) = 4.5°C/W

$R_{\theta\text{-}hs}$ = 4.5 – 0.6 = 3.9°C/W (heat sink thermal resistance to ambient)

To determine approximate dimensions of a heat sink of this thermal resistance, we used filtering on the DigiKey website, and found that most heat sinks with approximately this thermal resistance under natural airflow were dimensioned approximately 25mm x 40 mm.

Implementation

This section discusses our project implementation, including procurement of parts and assembly.

Component Procurement

We identified three alternatives for where to get components from.

Ordering from the global websites like Digikey. Advantages of this choice is availability of almost all type of components in various ratings. However, it has disadvantageous like being very expensive due to Dollar- TL currency and additional taxes and long delivery time.

Buying from local shops like in Konya Sokak. Advantages of that is we can get directly to components without a delivery time. Disadvantages of this choice are lack of datasheets and limited variety of components. We have used this choice as an emergency way.

Ordering from websites like Direnc.net or Robotistan. Advantages of that is availability of large amount of type at affordable prices and 2 or 3 days delivery time.

As a result, we get initial componenents from Direnc.net, additional compenents were supplied by local shops, specifically replacement of the bridge diode after the original one failed. We tried to find an enclosure and larger heat sinks for the diode bridge and triac locally, but we were not successful.

Table 1 lists the complete bill of materials for the project along with the procurement source and pricing. The total cost of materials for the project was approximately 95 TL.

Table 12: Bill of Material

Qty	Description	Unit Price	Ext. Price	Source
1	4mm Protected Born Jack, Red (DC+)	2.86	2.86	Direnc.net
1	4mm Protected Born Jack, Black (DC-)	2.86	2.86	Direnc.net
1	4mm Protected Born Jack, Brown (AC L1)	2.86	2.86	Direnc.net
1	4mm Protected Born Jack, Blue (AC N)	2.86	2.86	Direnc.net
1	20mm Fuse Holder	1.09	1.09	Direnc.net
5	5x20mm Glass Fuse	0.15	0.75	Direnc.net

Qty	Description	Unit Price	Ext. Price	Source
5	5x20mm Glass Fuse	0.15	0.75	Direnc.net
2	Capacitor, polyester 100nF 400V	0.66	1.32	Direnc.net
2	Resistor 1kΩ 0.125W	0.03	0.06	Team stock
2	Resistor 15kΩ 0.125W	0.03	0.06	Team stock
1	Potentiometer, 220 kΩ	1.02	1.02	Konya Sk.
1	Potentiometer, 220 kΩ	1.02	1.02	Konya Sk.
2	Potentiometer knob	0.68	1.36	Konya Sk.
1	Diode bridge, 35A 1000V	5.80	5.80	Direnc.net & Konya Sk.
1	Heat sink (diode bridge)	9.50	9.50	Local Electronic Repair Shop
1	Screw (diode bridge heat sink)	0.50	0.50	Local Electronic Repair Shop
1	Triac, 25A 600V (BTA26)	11.59	11.59	Direnc.net
1	Heat sink (triac)	9.50	9.50	Local Electronic Repair Shop
1	Screw (triac heat sink)	0.50	0.50	Local Electronic Repair Shop
1	Thermal paste			Team stock
1	Diac, 36V trigger	0.14	0.14	Direnc.net
1	Terminal Block, 3-pin	3.57	3.57	Direnc.net
1	Perfboard 12x12	6.82	6.82	Class materials
1	Wire	10.00	10.00	Local Electrical Shop
1	Enclosure, 85x155x60mm	18.68	18.68	Direnc.net
	TOTAL		**95.47**	

Procurement Lessons Learned

- Even knowing the simulated voltage and current value within the limit of component, buy more than one. A wrong switching or closing can burn the most reliable component. (We had purchased duplicates of the triac and the diac, but neither of them failed. We had one diode bridge, and it failed. Murphy's Law….)

- Online listing may not match the received material so do not choose other components without seeing visually by yourself. (In fact, we tried to find heat sinks and enclosure locally, but did not find a local source.)

- Inner dimensions of the box can be different due to parts that used in connection of box, try to buy locally where it can be “tried on” in the shop, or order a bigger box.

- Find a local shop that you can go easily in case of emergency situation like forgetting to order components or burning case.

- Order to suitable input-output terminals and implement your circuit. When you are on the implementation phase of circuit, you need to plug the input and output cable so many times and this can cause a trouble for circuit.

- Order different rating fuses, you can use low rating fuses at the start of your project.

Project Assembly

As soon we we had procured the essential components for our project circuit, we began temporary assembly with wires twisted together and minimal soldering. After making the initial circuit connections, we start to test our circuit. According to our test result we made changes in the circuit such as changing potentiometer rating for good control at output and changing the size of heatsinks. Once we were confident that our design would work, we moved to make the connections on the perfboard neat and soldered connections.

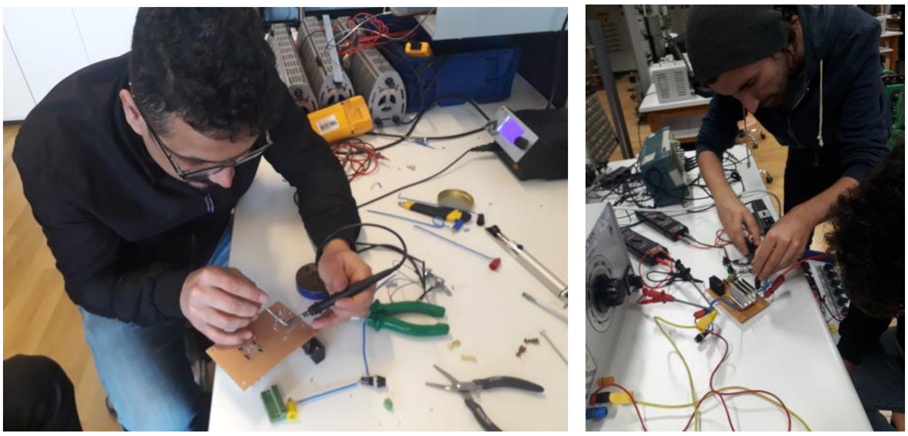

Figure 11: Photos of Project Assembly and Testing

Figures 12, 13, and 14 show photos of the final assembled project.

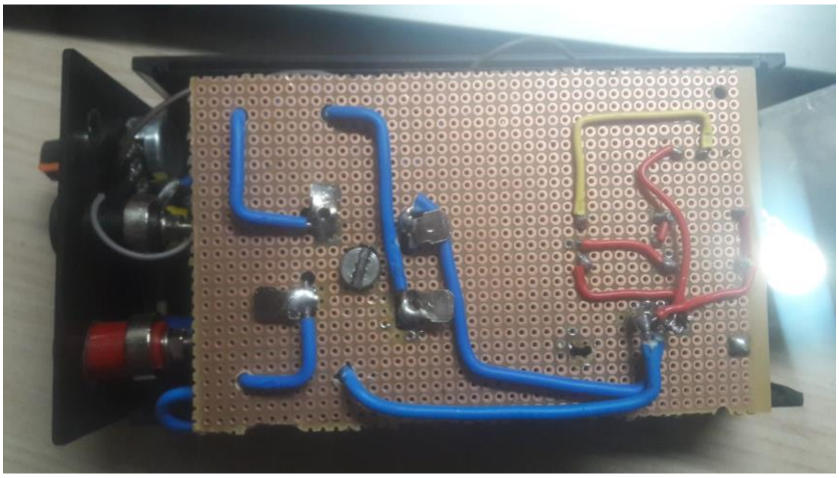

Figure 12: Wiring on Perfboard

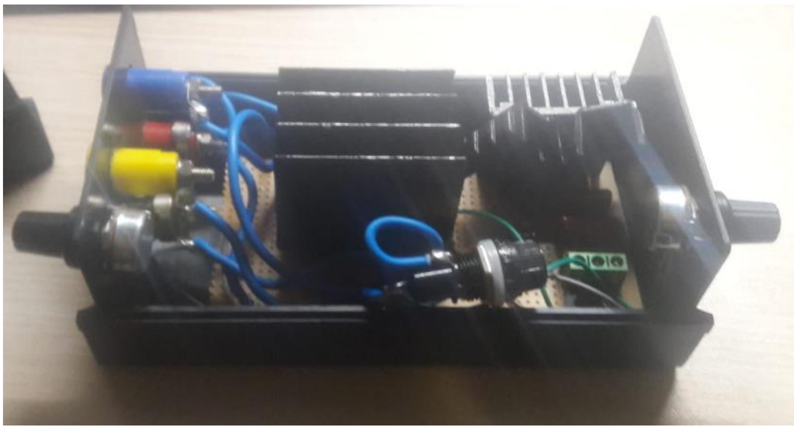

Figure 13: *Components Mounted in Enclosure*

Figure 14: *Views of Enclosure Exterior*

During testing, we had observed that the triac heat sink was running hotter than we wanted at load levels that were slightly less than what we expected from the kettle load. As such, we preferred to use a larger heat sink for the triac. We were not successful in locating heat sinks and an enclosure locally, so we ordered these parts from Direnc.net.

Although the dimensions for the heat sink and enclosure as listed on the website should have been adequate, the enclosure turned out to be constructed with the connection between the upper and lower halves of the enclosure such that it majorly interfered with utilizing all the interior volume of the enclosure. We were able to modify the interior of the box, cutting out the supports that were interfering with mounting our components in the enclosure, but then the enclosure did not close securely as it was designed to do.

Additionally, the heat sink that we received was several centimeters larger than the published dimensions of the heat sink on the Direnc.net website, so it was unable to fit in the enclosure. As such, we had to stay with our first heatsinks and were not able to change them out as we had wanted to do based on our testing. Instead, we mounted some smaller additional heatsinks to the triac heatsink to somewhat lower the thermal resistance of the heatsink.

Project Assembly Lessons Learned

- Drawing the circuit schematic *including pinouts & connections* can be logical for project. Our circuit was so simple that it seemed we could assemble it from memory, but in fact we lost time troubleshooting wrong connections that could have been prevented by more careful design documentation, particularly layout with attention to device pinouts.

- Terminals of the triac and bridge rectifier did not fit the holes in our perfboard. So, we drilled holes for those components. After that point, connection changes in these two components cause us lots of trouble. We could have bought terminal blocks (of appropriate current and voltage rating) for these components and connected them to the circuit board with the help of the terminal blocks.

- Doing minimal assembly so as to begin testing as early as possible worked well in most regards, but there were instances where we had to resolder connections due to the stresses of connecting and disconnecting from connectors that were not mounted in an enclosure as they are intended to be.

Testing

This section describes the testing process we went through during our project development.

Resistive Load Testing in Power Electronics Lab

Throughout our testing, we standardized on the following oscilloscope connections:

- Channel 1: Input Voltage
- Channel 2: Output Current
- Channel 3: Control Voltage (C2/diac input to ground)
- Channel 4: Output Voltage

In the power electronics lab, we utilized a rheostat adjusted to approximately 220 Ω to test the circuit with a relatively small (<1 A) load.

<u>Day 1 of Assembly and Testing (16 December)</u>

The first day that we assembled our circuit and began testing was 16 December. We made the connections loosely, only soldering what needed to be soldered in order to make good electrical connection and leaving some connections twisted together. As this circuit topology has not been used by teams in the past, we wanted to verify that the circuit would work before moving toward more permanent connections.

Initially we were unsuccessful in firing the triac using our control circuit. The problem was that we had not carefully noted the pin assignments of the triac and had not wired the control signal to the gate pin. Additionally, although the triac is a bipolar device, the gate is tied to one side of the triac, so it does matter which of the main triac legs is connected to ground and which is connected to the incoming line. We had reversed that connection, which also led to a failure to fire the triac. Once the triac connections were made correctly, the control circuit fired the triac as designed.

Figure 15 shows oscillography recorded from an intial test with a large resistive load intended to be gentle on the circuit but prove whether the design would work for voltage control or not.

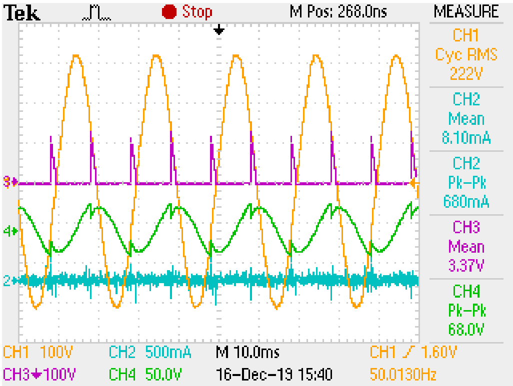

Figure 15: Small Resistive Load Testing: Minimum Output Voltage

In Figure 15, we can see that the triac is firing appropriately each half cycle and that a minimal output voltage was able to be obtained.

Next we increased the output voltage by adjusting the potentiometer resistance.

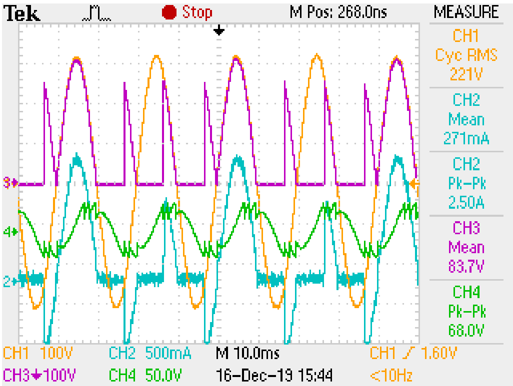

Figure 16: Small Resistive Load Testing: Medium Output Voltage

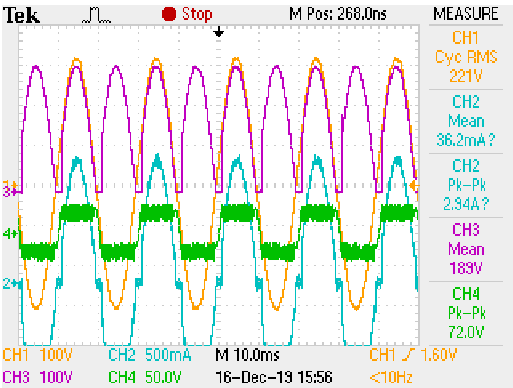

Figure 17: Small Resistive Load Testing: Maximum Output Voltage

Although it was somewhat visible in the minimum voltage control voltage waveform, it becomes more evident in the medium output voltage and maximum output voltage waveforms that there is some oscillation or ringing in the control circuit around the point of maximum voltage where the diac breaks over to fire the diac.

After re-examining the circuit, what we found was the the circuit had been miswired such that the RC-diac control portion of the circuit was wired from the AC line side of the diode bridge rather than from the triac side of the bridge. As a result, the voltage across the control circuit was not being shorted by firing of the triac, so it was continually charging the capacitors and then partially discharging through the diac and triac gate. The circuit worked to some extent, but not as designed, and with unnecessary stress on the control circuit. A close-up view of the repeated charging and firing during a negative half cycle is shown in Figure 18.

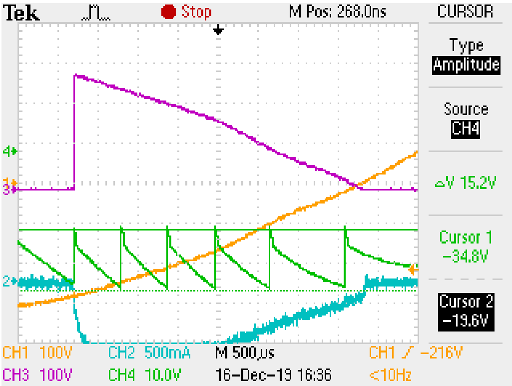

Figure 18: Miswired Circuit Repeated Firing

<u>Day 2 of Assembly and Testing (17 December)</u>

On the second day of assembly and testing, we discovered and corrected the miswiring of the control circuit. Once that was fixed, resistive testing in the power electronics lab went very smoothly. Oscillography of the corrected circuit is shown in Figures 19, 20, 21, and 22.

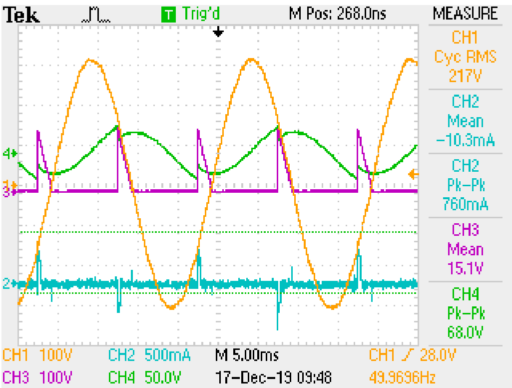

Figure 19: Corrected Control Circuit: Initial "Snap On"

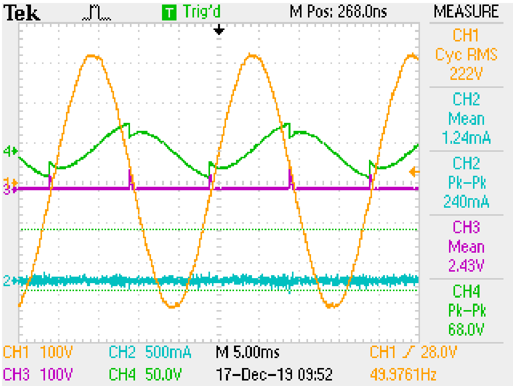

Figure 20: Corrected Control Circuit: Minimum Output Voltage

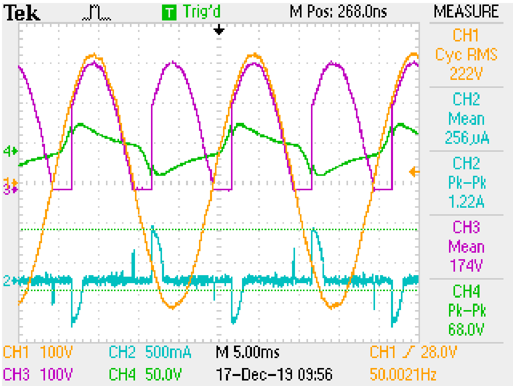

Figure 21: Corrected Control Circuit: 175 V Output

Figure 21 shows good agreement with the control voltage waveform shown in simulations (see Figure 3). The repeated firing of the incorrectly wired control circuit was completely eliminated.

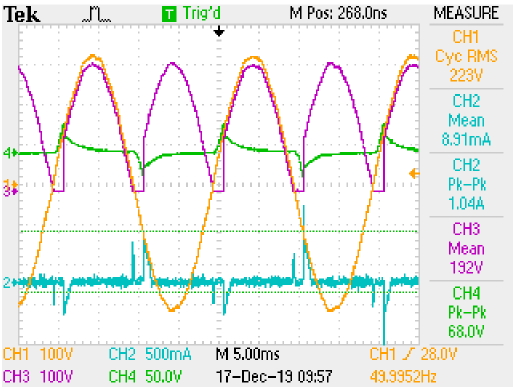

Figure 22: Corrected Control Circuit: Maximum Output

The waveforms in Figures 19, 20, 21, and 22 show that there may have been an issue with the current probe connection or battery, since the measured current does not follow the output voltage waveform as expected for a resistive load.

Resistive Load Testing in the Machines Lab

<u>Day 2 of Assembly and Testing (17 December), Continued</u>

Once the circuit was working properly with a small resistive load in the power electronics lab, we moved to the machines lab to set up to test the circuit on the DC motor that was the design load for the project. When we went to the machines lab, the assistant had not yet set up the DC motor for the project and had not learned the excitation method that was to be used. While we waited for the motor test setup to be prepared, we utilized the resistive load banks available in the machines lab to test our circuit with a substantial resistive load.

The oscilloscope used in the machines lab was different from the oscilloscope used in the power electronics lab. At the assistant, Furkan's, suggestion, differential probes were used for monitoring the higher voltage input and output voltage signals. The differential probes used a 200:1 attentuation, but the oscilloscope does not have a 200:1 attentuation setting, so an attentuation setting of 20:1 was used. As such, the readings on Channels 1 & 4 are smaller than the actual measurements by a factor of 10.

- Channel 1: Input Voltage times 0.1.
- Channel 2: Output Current
- Channel 3: Control Voltage (C2/diac input to ground)
- Channel 4: Output Voltage times 0.1.

The resistive load bank in the electric machines lab has multiple steps of resistive load that can be switched on. We started with a small load of approximately 400 W. Then, while monitoring the waveforms and thermal imagery, the load was increased incrementally every couple minutes as shown in the following sequence of figures numbered 23 through 13.

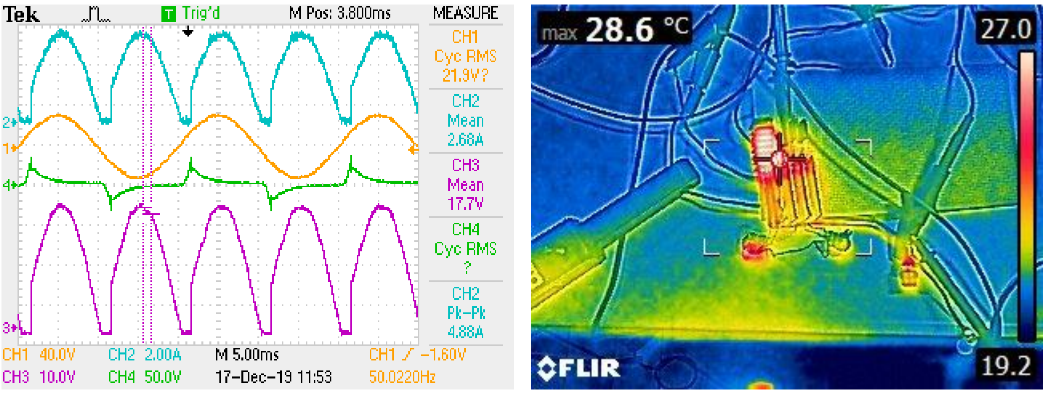

Figure 23: Resistive Load Testing: 175 V, ~400 W Load

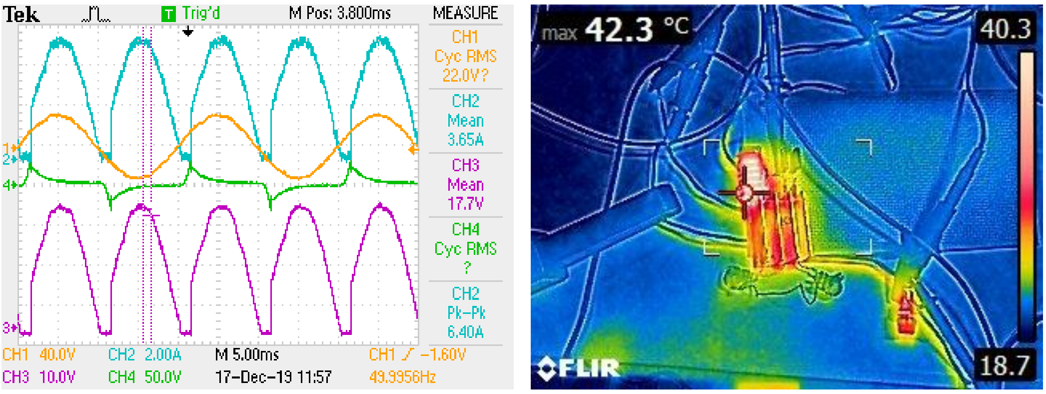

Figure 24: Resistive Load Testing: 175 V, ~600 W Load

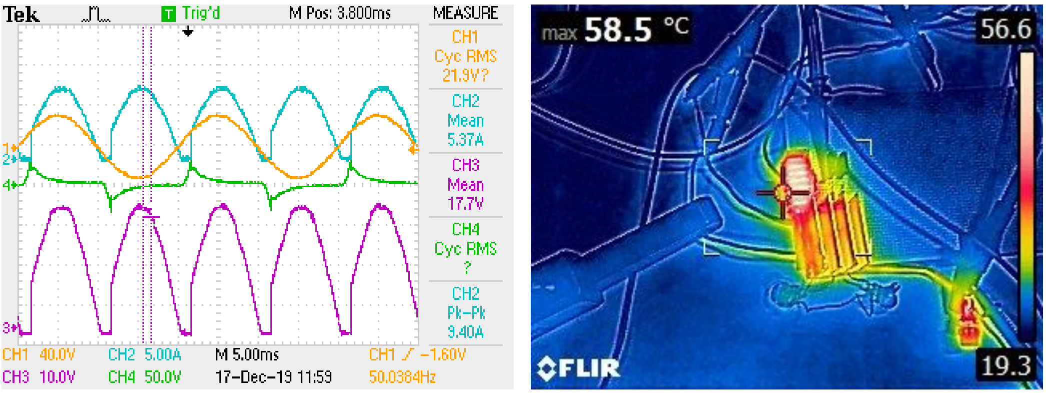

Figure 25: Resistive Load Testing: 175 V, ~800 W Load

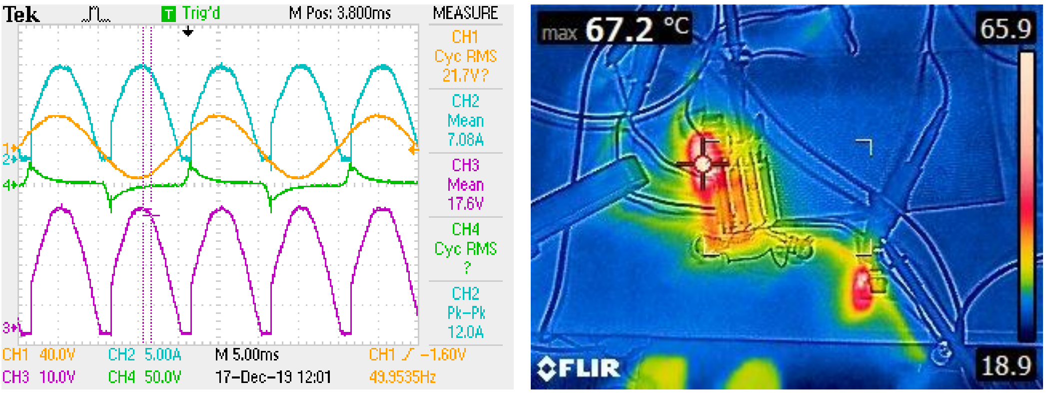

Figure 26: Resistive Load Testing: 175 V, ~1200 W Load

To protect the circuit during testing, a 5 A fuse was used in order to more quickly disconnect the circuit in case of a short-circuit. Thermal imagery showed the fuse holder getting hot, and then the fuse blew as shown in Figure 27.

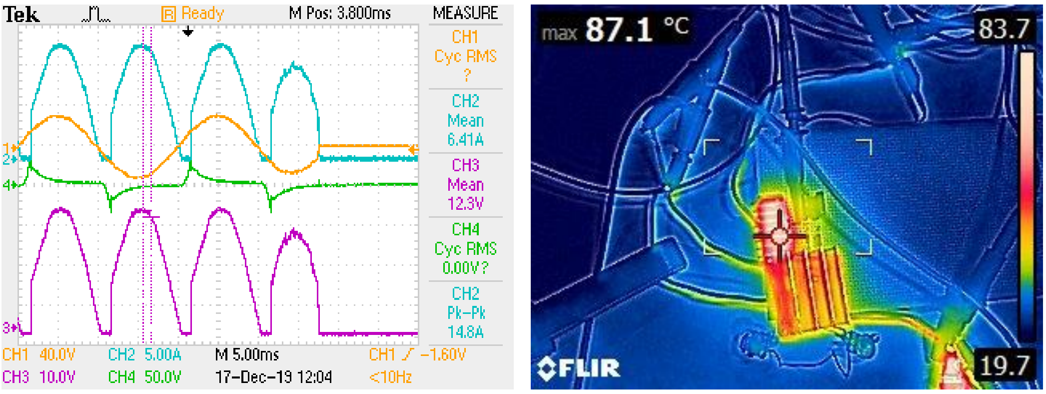

Figure 27: Resistive Load Testing: 1800 W; 5 A Fuse Blew

The peak temperature measured at the end of testing was 87.1°C on the triac heatsink. Because the aluminum heatsink on the diode bridge was shiny instead of anodized, the thermal imagery of that heatsink may not have reflected its true temperature.

Based on the triac heat sink temperature of nearly 90°C after testing with approximately 1800 W of load, we would have liked to use a larger heat sink for the triac so as to be more confident of its survival under the kettle load.

Motor Load Testing without Mechanical Load

<u>Day 3 of Assembly and Testing (18 December)</u>

Following successful testing of the circuit under substantial resistive load, the DC motor field circuit had been prepared by the course assistant, so we connected our circuit to the DC motor to run the motor unloaded (except for friction losses). Based on our analytical calculations with the motor nameplate, we estimated that the motor and coupled generator friction losses would be approximately 700 W.

On the first attempt, the circuit successfully started the motor. (We captured that happy moment on video.) Oscillography of the circuit driving the unloaded DC motor is shown in Figure 28.

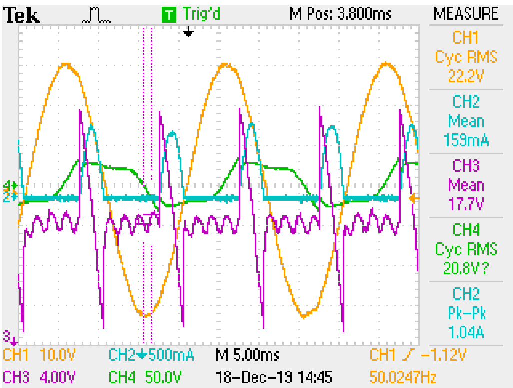

Figure 28: Driving Unloaded Motor

Figure 28 shows the discontinuous output current expected based on our simulations. The triac conductors for a relatively brief period during each half cycle. The effect of motor inductance to pull current even while the output voltage is less than the back EMF can be seen.

Another phenomenon that we can observe in Figure 28 is the ripple in the back EMF while the triac is not conducting. The frequency of the ripple appears to be at approximately 600 Hz, or 12 times the fundamental frequency. Because the triac is blocking output voltage from our circuit at that time, the ripple is owing to the field current or the motor itself. Since the field current is fed from a three-phase diode rectifier, a 6^{th} harmonic component to the back EMF can be expected. We aren't sure why the back EMF seems to have a ripple frequency of approximately twice that frequency.

While preparing to proceed to the kettle load test, while beginning to provide field current to the synchronous generator coupled to the DC machine, suddenly there was a loud noise from the variac supplying the field current to both machines and the circuit breaker supplying the workstation blew. The course assistants gathered to look at the machine and observe the problem. As the field voltage was increased gradually, the noise and excessive current to the field was observed again. This time, with more eyes and attention on the synchronous machine, arcing and smoke was observed in the synchronous machine field winding. Thus it was determined that the kettle load test could not be completed.

Further, while restarting the circuit after making some wiring changes, the variac supplying the project circuit made a distressing growling sound, the AC circuit breaker feeding the circuit blew, and the circuit stopped working. After checking components with a digital multimeter, we found that the diode bridge had failed open on three legs and shorted on one phase.

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After procuring a replacement diode bridge and rebuilding the circuit with more permanent wiring, additional load testing using the resistive load bank in the machines lab was performed to verify that the circuit had been rewired correctly prior to the Demo Day. The testing did turn out a few wiring problems that we were able to correct and get the circuit working again.

Demo Day

On demo day (27 December), our project was demonstrated first. We had to make some modifications to the test circuit wiring since we used the safer "protected" ("korumalı") banana plug terminals, which unfortunately could not receive the space terminals used on the wires in the lab.

For the demonstration of our project to start and drive the unloaded DC motor, our project enclosure was kept open so that we could connect the oscilloscope. Recorded oscillography is shown in Figure 28.

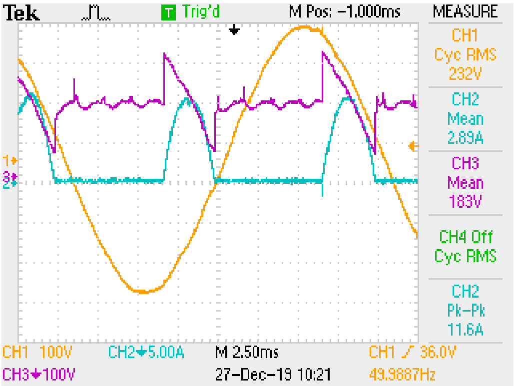

Figure 29: Demo Day Driving Unloaded DC Motor

A thermal image was recorded when the motor start test was completed. This image is shown in Figure 30. Similar to testing we did prior to the demo day, the triac heat sink showed to be the hot spot. The ambient temperature at the time was approximately 21°C, so the temperature rise above ambient was 22°C at the heat sink.

Figure 30: Thermal Image – End of Motor Start Test

After completion of the unloaded motor start test, the “robust design” kettle load test was prepared. For that test, the lid of the project enclosure was placed on the project. The motor was started unloaded, then the kettle load was connected by closing the switch on the power strip supplying the kettle.

When the kettle load was connected, the loading of the motor and circuit was audible. The voltage drop on the output of the circuit was significant. We did not note at the time how much of the output voltage drop was due to the input voltage dropping and how much was dropped across our circuit. The voltage drop resulted in lower power draw by the kettle load, which reduced the load on our circuit and possibly allowed it to survive the kettle load.

For the kettle test, the course assistants noted input power of 1.8 kW and an output power of 1.5 kW. This gives losses of 300 W and an efficiency of 83%. This level of losses is far above what our simulations show (by a factor of 5!), and given the size of our heat sinks, would likely give a much higher temperature rise (not survivable by our components) than what we observed. We were surprised to see such a low recorded efficiency, but did not have the opportunity at the time to explore what the issue might be.

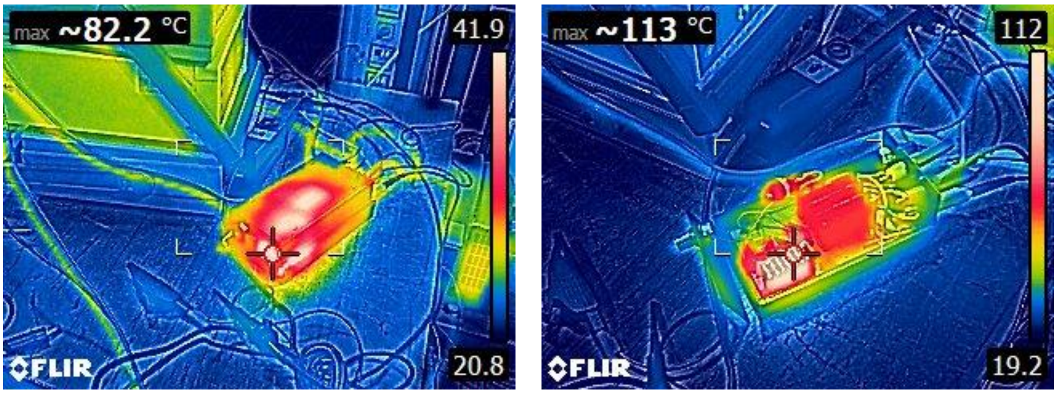

Figure 31: Thermal Images – End of Kettle Load Test (Left: Case closed, Right: Case open)

<u>Lessons Learned</u>

- We learned a few lessons from our experience with the demo day.
- Becoming familiar with the full testing setup (including connectors & measurement devices) before the demo would have helped smooth the bumps or given opportunity to address the apparently large losses (possibly due to measurement setup?) prior to the demo and would have made us better prepared to gather measurements during the demo.
- Finishing touches like making sure the connections and knobs are securely mounted to the enclosure would have really improved making the product feel solid to use.
- Connectors that may be technically superior or safer are not so useful if they don’t match the customer’s wiring terminations.
- The extensive load testing that we did prior to demo day did increase our confidence that our circuit would work as designed to start the motor (at least) and have a good chance of driving the kettle load (which was never available in the lab ahead of time to test). It would have been even better if we had done the testing with the components mounted in the enclosure so we could be more confident in the control locations and thermal performance with the enclosure lid on.

- Designing a simple circuit eases our work on possible error that occurring in demo day.
- We should prepare measurement terminals like input and output in order to obtain nice measurement results without opening circuit box.

Conclusions

As we have described in the previous sections of this report, we successfully implemented a simple circuit to drive a DC Motor with a manually controllable output voltage. We learned many lessons as a team about the design and implementation of this project. It required significant effort throughout the semester, with several critical design aspects being covered in class very late in the semester (e.g. thermal design & gate drive circuits—although we found a circuit where this last topic was not an issue). Not everything was done as well as we would have liked, and if we were doing it over again, there are certainly things we would do differently.

In spite of the shortcomings in our project work, we are proud of what we have accomplished. The circuit that we implemented was very simple, and as far as we know unique among all the designs in the class, both past and present. We implemented our circuit and had it ready to test driving the motor load before it seems that many teams had begun much work on assembling their circuits. Sometimes it is the first product to market—rather than the best product—that wins market share. In the future, perhaps a “first to market” bonus could be considered for the team(s) that successfully test earliest in the semester.

Project Video

As required by the project assignment, we created a project video and uploaded it to Youtube. It can be accessed from the following URL:

https://www.youtube.com/watch?v=D-QbwB4EDQM