Senior Design Experience:
Formula SAE Electric Charge Circuit Board

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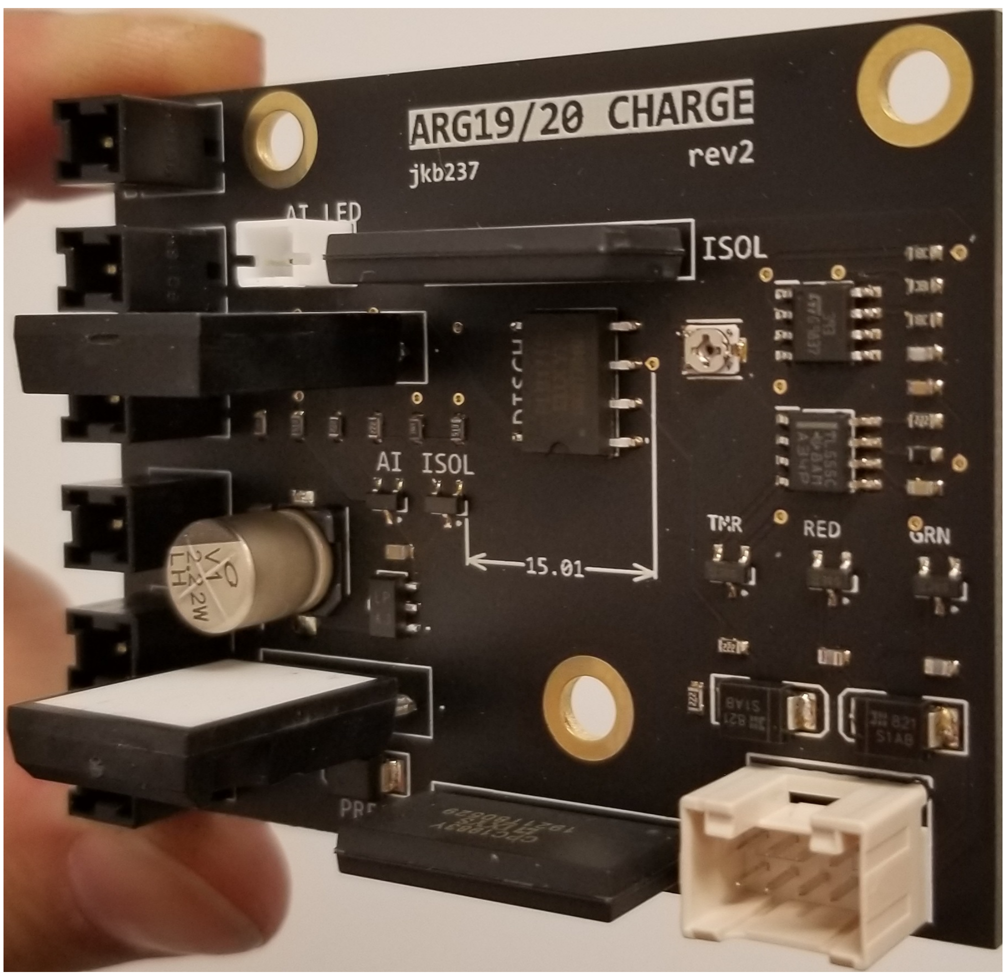
Submitted 18 December 2019
Revised 18 May 2020
Fall 2019



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1 Introduction

Formula SAE is a design competition series where students from universities all over the world build, test, and compete with a car of their own design. Cornell University has a long and storied history of success in the combustion class of this competition series, winning nine separate international competitions between the year 1987 and present day (2019) under the name Cornell Racing. However, for the first time in over 30 years, in 2019 Cornell Racing was absent from any competitions, instead spending the year working on an electric powertrain vehicle. In the same way that Cornell Racing was quick to join the scene and enjoy success in the primitive years of the combustion competition, it is the hope that by switching to an electric powertrain in the early years of FSAE Electric in America, Cornell Racing will enjoy similar success in the coming years. Aside from the obvious challenges associated with any new engineering challenge, this switch to an electric powertrain has necessitated the addition of several components to the yearly design work, two of which are a pre-charge and discharge circuit for the tractive system.

Figure 1: ARG07 at Competition at Michigan International Speedway in 2007

2 Design Background

The electric powertrain has a relatively simple design: a 420 volt battery pack (hereafter referred to as the "accumulator") is isolated in a case of steel and polycarbonate from a tractive system featuring a Cascadia Motion PM100DX 3-phase inverter which powers an Emrax 228 Permanent Magnet 3-phase AC motor. The accumulator is only connected to the tractive system after several safety checks have been performed by a combination of technicians, passive circuitry, and active circuitry. Once the checks have been performed the connection is made via two isolating contactors known as Accumulator Isolation Relays (AIRs). However, due to the internal capacitance of the tractive system and the inverter in particular, simply closing these isolation relays would result in dangerous levels of inrush current - potentially damaging the AIRs or the inverter itself. This danger necessitates a pre-charge circuit designed to inhibit the inrush of current to the tractive system.

The need for the discharge circuit arrives if the car is shut off (whether by choice or or one of the several safety systems forcing the car to turn off) and the AIRs are opened. Without an active discharge method, due to the high magnitude of the internal capacitance of the inverter (440 μFarads), a dangerous amount of energy remains stored within the tractive system for a substantial amount of time (over 150 seconds). High voltages may linger on tractive system surfaces in this scenario, risking harm to those who may work on the vehicle without proper protection equipment.A discharge circuit alleviates this issue.

By virtue of these goals, the circuit board which houses these circuits is a mixture of high-voltage (HV) and low-voltage (LV) components - requiring careful planning and separation distances to avoid damaging other high-voltage and low voltage components, as well as a reliable board which does not damage itself while accomplishing its function.

A final requirement comes from the rules of the competition, which require that each electric vehicle is fitted with a Tractive System Active Light (TSAL). This light serves as an indicator to technicians and bystanders the charge state of the tractive system, illuminating green when the system is below HV levels (<60V) and flashing red when the system is above HV levels (>60V). Similar to this is the Accumulator Indicator Light, which illuminates when the voltage on the vehicle side of the AIRs is above HV levels. This light must be powered using the accumulator itself such that it may operate even when the accumulator is removed from the car. Because the board with the pre-charge and discharge circuits has direct access to both the HV and LV circuits of the car, it is logical to add to this board an auxiliary circuit which controls the logic of the TSAL and Accumulator Indicator Light.

3 Design-Driving Rules

A significant portion of the design drivers for this circuit board stem from the Formula SAE 2020 Rules[1], and the relevant rules are listed below (some portions of rules irrelevant to the electrical design of the circuits are omitted):

3.1 EV.1 GENERAL REQUIREMENTS

- EV.1.2.4 Separation of Tractive System and GLV system:
  - The entire Tractive System and GLV system must be completely galvanically separated.
  - The border between Tractive and GLV system is the galvanic isolation between both systems. Therefore, some components, such as the motor controller, may be part of both systems

3.2 EV.4.2 Electrical Configuration

- EV.4.2.8 Each Accumulator Container must have a prominent indicator, such as an LED that will illuminate, when a voltage greater than 60 V DC is present at the vehicle side of the AIRs.
  - The voltage being present at the connectors must directly control the indicator using hard wired electronics (no software control is permitted). Activating the indicator with the control signal which closes the AIRs is not sufficient.
  - The Accumulator voltage indicator must always work, even if the container is disconnected from the GLVS or removed from the vehicle.
  - The indicator should be located where it is clearly visible when connecting/disconnecting the Accumulator Tractive System connections
  - The indicator must be labeled "Voltage Indicator"

3.3 EV.7.1 Separation of Traction System and Grounded Low Voltage System

- EV.7.1.2 There must be no connection between the frame of the vehicle (or any other conductive surface that might be inadvertently touched by a crew member or spectator), and any part of any Tractive System circuits.
- EV.7.1.7 If Tractive System and GLV are on the same circuit board:
  - They must be on separate, clearly defined areas of the board
  - The Tractive System and GLV areas must be clearly marked on the PCB
  - Required spacing related to the spacing between traces / board areas are as follows:

Voltage	Over Surface
0-50 V DC	1.6mm
50-150 V DC	6.4mm
150-300 V DC	9.5mm
300-600 V DC	12.7mm

3.4 EV.7.9 Pre-Charge and Discharge Circuits

- EV.7.9.1 A circuit that is able to pre charge the intermediate circuit to at least 90% of the current accumulator voltage before closing the second AIR must be implemented. This circuit must be disabled by a deactivated Shutdown Circuit, see EV.8.2. Therefore, if the Shutdown Circuit is open, the pre charge circuit must not be able to pre charge the system.
- EV.7.9.2 Any pre charge circuitry must be supplied directly from the TSMS
- EV.7.9.3 It is allowed to pre charge the intermediate circuit for a conservatively calculated time, before closing the second AIR. A feedback via measuring the current intermediate circuit voltage is not required.
- EV.7.9.4 If a discharge circuit is needed to meet EV.8.2.3, it must be designed to handle the maximum discharge current for at least 15 seconds. The calculation proving this must be part of the ESF.
- EV.7.9.5 The discharge circuit must be wired in a way that it is always active when the Shutdown Circuit is open. Furthermore, the discharge circuit must be fail safe such that it still discharges the intermediate circuit capacitors if the HVD has been opened.
- EV.7.9.6 The pre charge and discharge circuits must not be fused.

3.5 EV.7.10 Tractive System Active Light - TSAL

- EV.7.10.1 The vehicle must include a Tractive Systems Active Light (TSAL) that must:
  - Illuminate when the GLVS is energized to indicate the status of the Tractive System
  - Be directly controlled by the voltage present within the Tractive System using hard wired electronics. Software control is not permitted.
  - Not perform any other functions.
- EV.7.10.2 The TSAL may be composed of multiple lights within a single housing
- EV.7.10.3 When the voltage outside the Accumulator Container(s) exceeds 60 V DC or 25 V AC RMS, the TSAL must:
  - Be Color: Red
  - Flash with a frequency between 2 Hz and 5 Hz
- EV.7.10.4 When the voltage outside the Accumulator Container(s) is below the voltages listed in EV.7.10.3 above, the TSAL must:
  - Be Color: Green
  - Remain continuously illuminated

3.6 EV.8.2 Shutdown Circuit

- EV.8.2.4 If the Shutdown Circuit is opened/interrupted:
  - The Tractive System must be shut down by opening all Accumulator Isolation Relay(s)
  - All Accumulator current flow must stop immediately.

  - The voltage in the Tractive System must drop to under 60 V DC or 25 V AC RMS in less than five seconds after opening the Shutdown Circuit.

4 Design and Functional Description

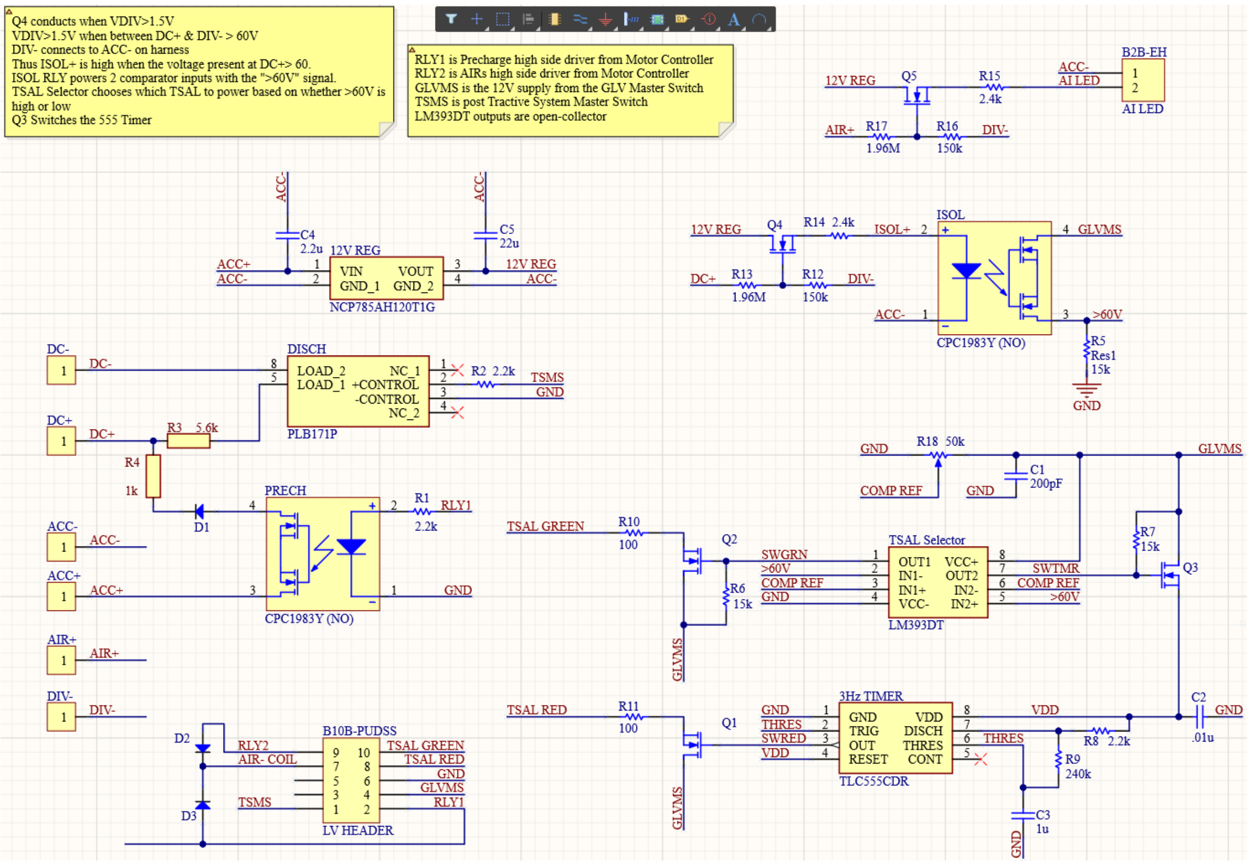

Figure 2: Charge Board Schematic

4.1 Pre-Charge and Discharge

The schematic of the charge circuit can be seen above. The following explanation will detail both how components and functions were selected, and the design process with important calculations. The motor controller itself signals for pre-charge to begin by supplying an input to the charge board through input RLY1, powering the pre-charge relay and the AIR on the negative terminal of the accumulator closed. This allows limited current to flow through the pre-charge relay and the limiting resistor (R4 in the schematic above) into the motor controller's DC+ terminal, charging the internal capacitors.

The first step to design these circuits is to select an appropriate resistor to limit inrush current and act as a dissipator during the discharge process. Per the inverter's hardware manual, a maximum resistance value of 1200Ω is suitable to act as the pre-charge resistor.[2] A resistance value of 1000Ω was selected to act as the inrush limiter for the precharge circuit. For the discharge circuit, rule EV.7.9.4 states that the discharge circuit (more specifically, the discharge relay and resistor) must be designed to handle the maximum discharge current (and power) for at least 15 seconds. This requirement is checked during the review of the Electrical System Form, as the team is required to attach a data sheet evidencing the fact that the discharge resistor can handle the power output. If the data sheet for the chosen resistor does not support this claim, then a test may be required. Because of this continuous power requirement, it is reasonable to select the largest possible resistor while still meeting the 5 second discharge stipulated by EV.8.2.4, minimizing the continuous power the resistor must withstand.

Initially the same value was chosen for both circuits so that a single resistor could be used in both circuits, however it was realized some time into the design phase that using a single resistor could result in shorting the accumulator if the discharge relay were to fail closed and the system attempted to pre-charge. After this realization, the design features two resistors of equal value (1000Ω). However, due to the power requirements described above and the fact that a 1000Ω resistor resulted in too high of a power dissipation requirement the resistance of the discharge resistor was increased to 5600Ω. These resistance values allow pre-charge to 90% of nominal voltage to occur within roughly 1 second, and discharge below 60V to occur in around 4.8 seconds.

Figure 3 below was used to discern a suitable value for the precharge resistance, and Figure 4 below shows the resulting performance of the pre-charge and discharge circuits using 1000Ω and 5600Ω resistors, respectively. Figure 4 also demonstrates the design's compliance with rule EV8.2.4, with the system theoretically discharging below the required voltage in under 5 seconds.

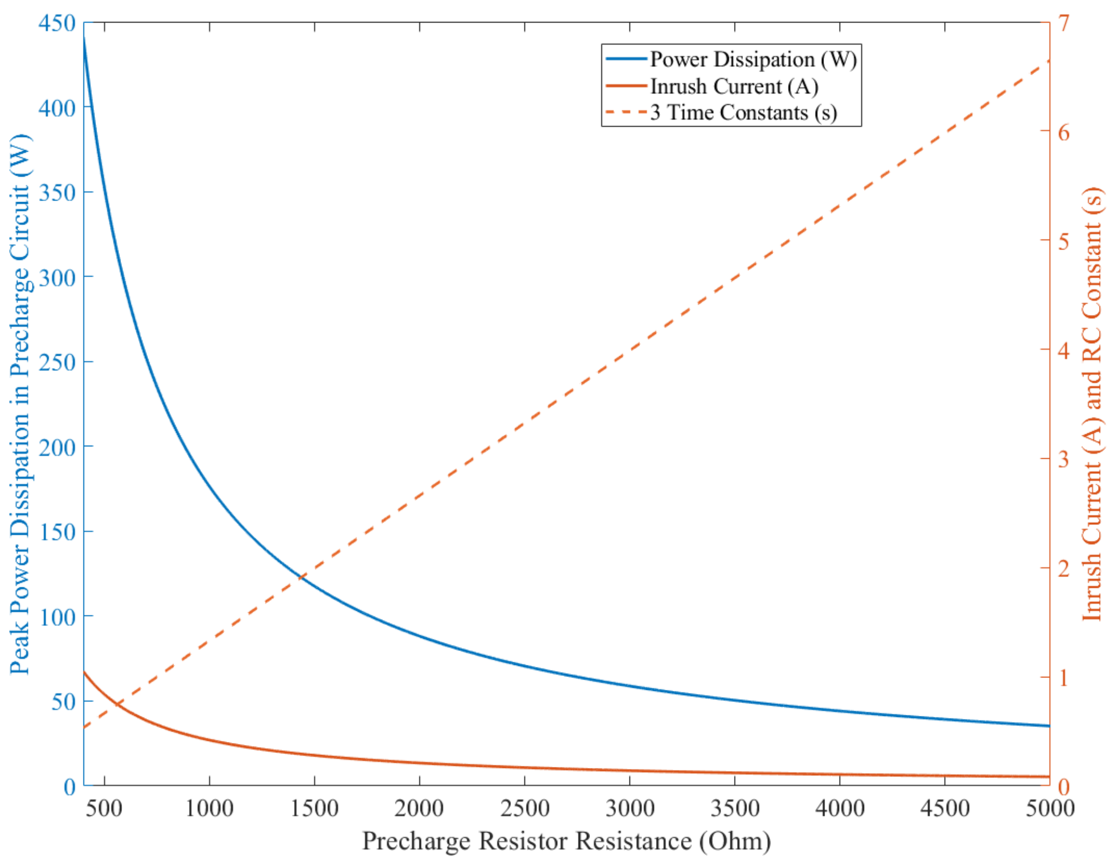

Figure 3: Precharge Circuit Time Constant, Inrush Current, and Peak Power Dissipation vs. Precharge Resistance

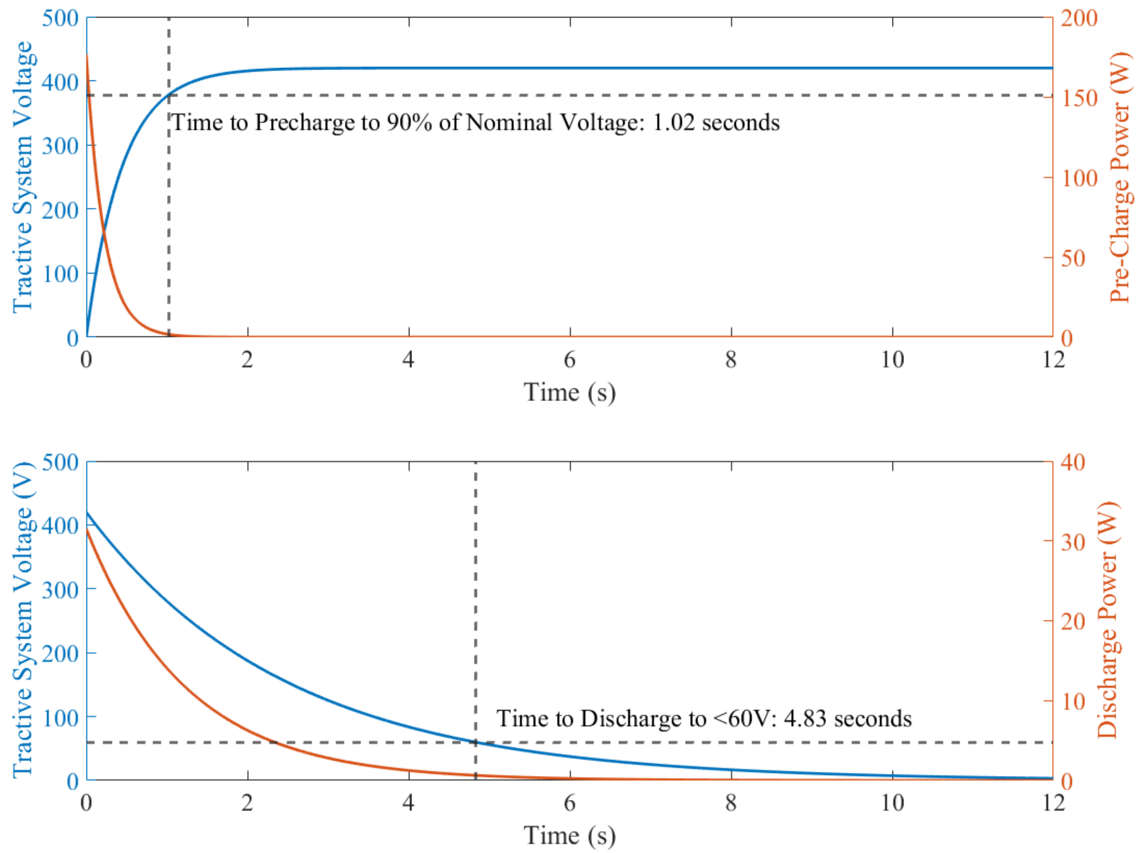

Figure 4: Instantaneous Voltage and Power in Precharge (Upper)/Discharge (Lower) Scenarios

Based on Figure 3, a larger resistance value may have been usable (up to 1200Ω, as limited by the motor controller's specification), however for this purpose we selected the smallest resistor that would result in the highest peak power dissipation permissible by commonly available resistors in order to minimize pre-charge cycle time. 5600Ω was chosen for the discharge resistor as this is the highest commonly-available high-power resistor value that meets the discharge time requirement set out by EV.8.2.4.

For both pre-charge and discharge circuits, optically coupled photo-relays are utilized to maintain galvanic isolation between the HV and LV components. In order to activate the pre-charge circuit, a normal open relay was selected such that a failure in operation meant that the circuit will fail open, preventing a short circuit. To comply with rule EV.7.9.5, a normal closed relay is used to switch the discharge circuit so that when all power is removed from the LV circuit of the car, the discharge relay will close and allow for discharge to occur.

The chosen pre-charge relay is an IXYS CPC1983Y with a rated blocking voltage of 600V, making it suitable for our high voltage application, as well as a 500mA continuous ampacity without a heatsink[3]. Because the maximum inrush current through either of these circuits assuming zero resistance in the rest of the loop is 420mA,

$$I_{inrush} = \frac{V_{accumulator}}{R_{precharge}} = \frac{420V}{1000\Omega} \tag{1}$$

the CPC1983Y's rated ampacity is sufficient. The chosen discharge relay is the IXYS PLB171P, which has also a maximum load current of 80mA[4]. This relay is powered directly after the Tractive System Master Switch, such that whenever the shutdown circuit is fully closed the relay will be powered open. This is done to avoid losses associated with having a 1000Ω branch in parallel with the actual load of the circuit (the inverter). These two pairs of relays and resistors comprise the entirety of the pre-charge and discharge components of the design, satisfying rule EV8.2.4 by quickly dissipating stored energy in the tractive system and reducing the chance of damaging the inverter's internal capacitors or the AIRs by limiting inrush current.

The PLB171P was chosen in the spring to act as the discharge resistor instead of the AQZ404. While filling out the ESF we found that the previously chosen AQZ404 was only rated to 400V (20V short of our peak). In contrast, the PLB171P can withstand 800V.

4.2 Voltage Sensing

In order to comply with the remaining rules concerning the two voltage indication lights (TSAL and AI Light), voltage sensing circuits must be implemented to determine when and where high voltage levels are present outside of the accumulator container. This is accomplished using two voltage dividers which step down the voltage present at two points in the HV system: the DC+ input to the motor controller, and directly after the AIR on the positive pole (*AIR+*) of the accumulator. These dividers use the negative pole of the accumulator (*ACC-*) as the low level of the divider (despite the fact that the negative of the accumulator is not grounded - to comply with rule EV.7.1.2), and step the voltage down to between 0-10.5V, with the divided signals each driving the gate of an N-channel enhancement MOSFET (Q4 and Q5 in Figure 2).

In order to reduce the power dissipated by the voltage divider (which is a closed circuit at all times), a sufficiently high value for the series resistance of the voltage divider must be selected.

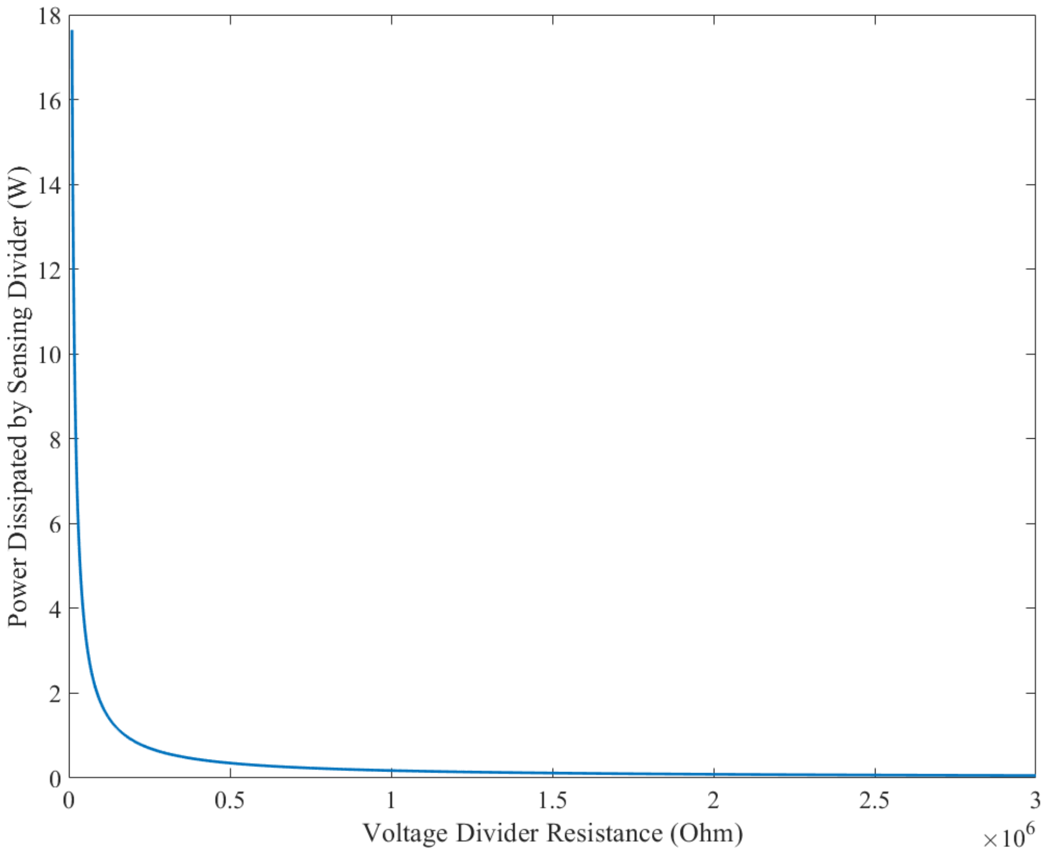

Figure 5: Power Dissipated by 60V-Sensing Voltage Divider vs. Series Resistance of Divider

Based on Figure 5, 2MΩ is sufficiently far into the asymptotic region of the curve, and serves as an estimate of the series resistance of the voltage divider being used. The threshold voltage of the MOSFETs being driven by this voltage divider is 1.5V maximum, therefore to ensure proper operation: when the voltage being sensed is 60V, the divided voltage should be 1.5V. A 51kΩ and 1.96MΩ resistor were initially chosen to meet the specifications, and the resulting voltage divider should have output >1.5 Volts when the voltage within the tractive system reached 60V:

$$60V\left(\frac{56\Omega}{56\Omega + 1960\Omega}\right) = 1.52V \tag{2}$$

After assembling a test spin system using the first board revision and the old module design, it was found through iteration that the 51kΩ resistor did not result in a high enough voltage to switch the MOSFETs. Measuring the voltage at the gate indicated that the MOSFET should have been switching, however it failed to do so. Calculating the charging rate of the MOSFET yielded no further indication as to the reason for malfunction, so we turned to increasing the size of the secondary resistor. Increasing from 51kΩ to 150kΩ fixed the problem, nearly tripling the voltage at the gate of the MOSFET.

4.3 Powering TSAL and AI Light

4.3.1 Accumulator Indicator Light

This concludes the voltage sensing methods, and brings us to powering the TSAL and AI Light. In the case of the AI Light the associated wiring remains in the accumulator (unlike the TSAL which sits just below the top of the rear roll hoop). As a result, when the sensing circuit detects HV levels the switching MOSFET (Q5) directly connects the LED to the output of a 12V regulator powered by the accumulator. This is done to comply with rule EV.4.2.8, allowing the light to operate without the presence of power from the Ground Low Voltage System, and complies with rule EV.1.2.4 because the aforementioned wiring remains internal to the accumulator.

4.3.2 Tractive System Active Light

For the Tractive System Active Light the same method is used to determine when Tractive System voltage constitutes high levels. Instead of directly activating the red TSAL by connecting it to power, the MOSFET (Q4) driven by the sensing circuit instead closes a normally open CPC1983Y relay (the same model used in the precharge circuit). Closing this relay connects a signal named *>60V* to the GLV supply. Thus, *>60V* is either high or low based on the voltage present in the tractive system, with high signalling that $V_{DC+} > 60 = TRUE$ and low signalling that $V_{DC+} > 60 = FALSE$. Optocoupling a signal via the CPC1983Y is required to maintain total galvanic separation in compliance with EV.1.2.4, rather than simply connecting the Q4 drain to the GLV supply and having the >60V net connected to the Q4 source.

The 12V regulator which powers the AI Light and the ISOL relay has a maximum output current of 10mA, and this is accounted for by using 2.4kΩ resistors to limit the output current to the AI LED and ISOL relay. Some instability in the power supplying these may lead to future increase of this value.

A comparator then determines which TSAL should be illuminated by comparing the level of the *>60V* signal to an intermediate reference input (between 0-12V, adjustable) from the LV system controlled by a potentiometer (R5), and selects which TSAL to power based on this. A low signal from *>60V* will cause the comparator to raise the gate of a MOSFET (Q2) that switches TSAL Green directly, in compliance with rule EV7.10.4. A high signal from *>60V* raises the gate of a MOSFET (Q3) which switches power to a 555 Timer (V_{DD}). The comparator selected for this purpose is the ST Microelectronics LM393DT. The outputs of this comparator require 15kΩ pull-up resistors, as the outputs are actually open-collectors to ground. When either output pin "outputs," the connection to ground within the integrated circuit is opened, and the output will be pulled high by the GLV supply.

The 555 Timer is operated in an astable mode, meaning it is constantly charging and discharging a capacitor selected by the user. The timer switches between charging and discharging each time the voltage across the plates reaches some fraction of V_{DD} (1/3 and 2/3) and outputs a high or low signal based on whether the capacitor is charging or discharging, thus outputting a square wave. The frequency of the square wave is determined by the values of the capacitors and resistors which are put in series between the Discharge, Threshold, and Ground pins of the chip. Details of this operation mode are available in the datasheet including a schematic and the equations used below.[5] With the target of a 50% duty cycle and a 3Hz frequency, supporting calculations are summarized below in Equations 3-5.

$$t_L = t_H = .693(R_B)C \tag{3}$$

Where t_L is the time in seconds that a high signal is output in one period, t_H is the time in seconds spent outputting a low signal in one period, R_B is the value of the resistor between the DISCH pin on the timer and the capacitor being charged/discharged, and C is the capacitance of that resistor. To achieve a 50% duty cycle, the time spent at high and low should be equal.

$$P = 3\text{Hz}^{-1} = t_L + t_H = (2(.693)R_B C) \Rightarrow R_B \cdot C = .241 \tag{4}$$

Where P is the period of the square wave output in seconds. A suitable value for C is chosen to be 1μFarad (this value is widely available in a compact package), and a matching resistor value is then calculated:

$$.241 = R_B \cdot C \Rightarrow C = 1\text{E}^{-6} \Rightarrow R_B = 241k\Omega \approx 240k\Omega \tag{5}$$

To avoid shorting between V_{DD} and ground when the timer is operating, a 2.2kΩ resistor is used as R_A, the resistor between the DISCH pin and V_{DD}. This value is sufficiently low that is does not affect the frequency of flashing (F) significantly, and is conveniently used elsewhere on the board:

$$F = P^{-1} = [.693(1000 + 2(240000))(1\text{E}^{-6})]^{-1} = 3.000\text{Hz} \tag{6}$$

The 3Hz output from the 555 timer will only operate when the supply voltage V_{DD} is great enough (>2V). V_{DD} is controlled by the comparator as detailed above. Thus, when the tractive system voltage exceeds 60V, circuit 2 in the comparator outputs high and the timer begins outputting a square wave switching signal to Q1 which flashes the TSAL Red at the same 3Hz frequency.

One final function of the Charge Board is to output a high signal when Pre-charge is complete. This signal is actually just spliced from the motor controller's *RLY2* signal, which is the relay driver for both AIRs, and thus will only be a high (approx. 12V) signal once pre-charge is complete, and will remain high until the motor controller discharges or shuts off.

5 Layout and Bill of Materials

Below is the 2D layout of the circuit board, as well as a table including all of the components which populate the board. A 2-layer board is necessary and use of vias was minimized to avoid complexity.

The voltage dividers reference *ACC-* in the schematic shown in Figure 2, however the layout in Figure 6 shows that voltage dividers reference *DIV-*. This is because presently the rules are unclear as to whether the sensing circuits which determine the system voltage should reference chassis ground, earth ground, or pack negative. The cause for significance is that without grounding the pack negative to comply with EV.7.1.2, potentials greater than 60V may be exhibited between the tractive system and, say, a student working on the car (grounded to the Earth). However without referencing an object at similar ground potential to the student, the sensing circuit may be working correctly but still result in unsafe potential differences, leading to unsafe scenarios not being indicated by the Accumulator Indicator and TSAL. A rules question was submitted to the competition (inquiry #13763), and the judges indicated that the measurements should be taken using the tractive system's negative (*ACC-*) as the reference. This meant that when creating the harness for the board, *DIV-* was spliced into the *ACC-* connection.

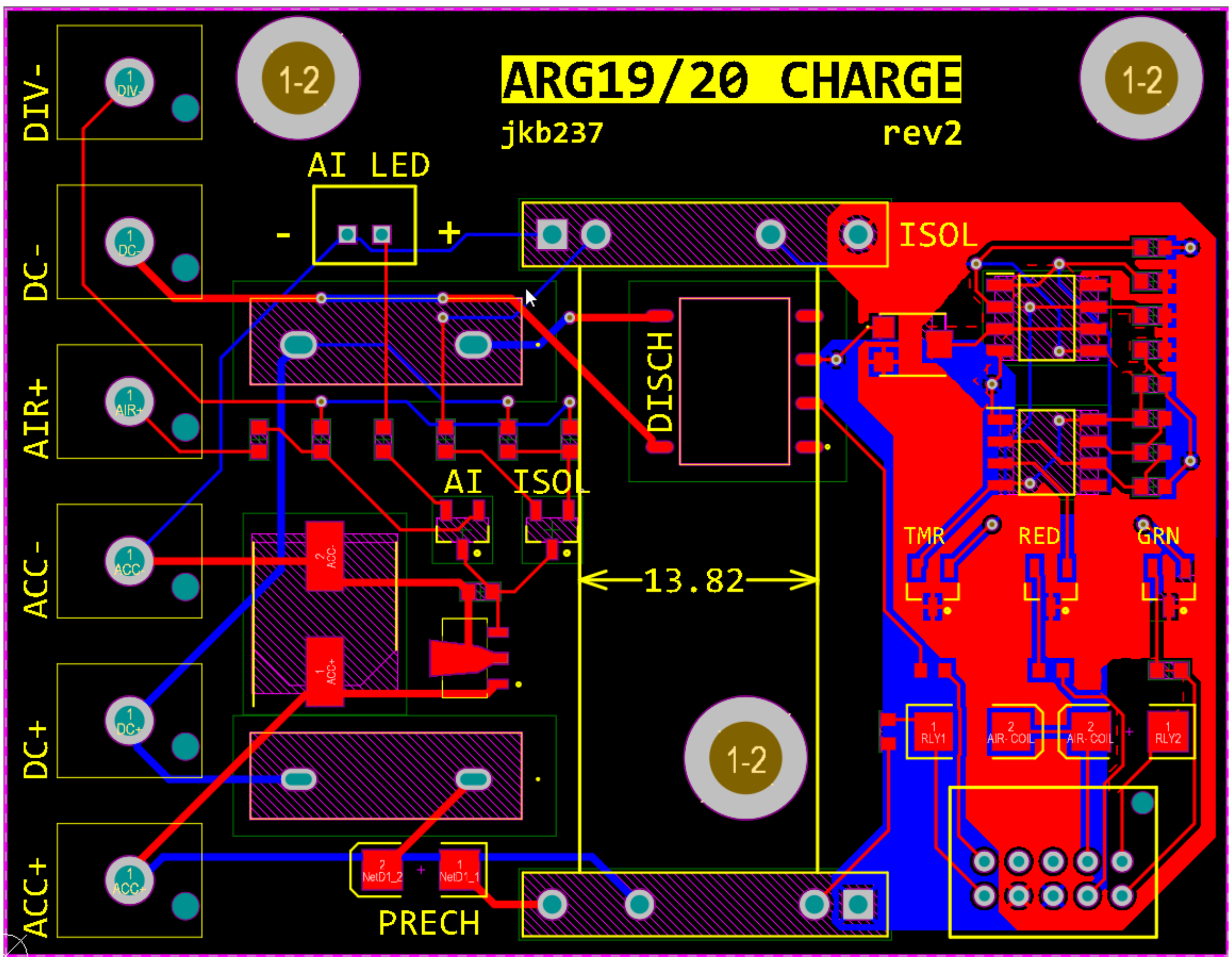

Figure 6: 2D Layout of Charge Circuit Board

Several traces in the layout in Figure 6 were made larger (20mil rather than 10mil) to account for the increased peak current through the pre-charge and discharge paths. 20mil traces will cool faster than 10mil traces because of the increase in convective area. .42A is still within the ampacity of 10mil traces, however this area of the board has plenty of space to expand traces. The dimension shown in the middle of the layout is included to demonstrate adherence to EV.7.1.7, dictating minimum spacing between tractive system and GLV traces on PCBs. The left half of the board contains only tractive system traces, and the right half contains only the GLV traces. On the border are the three optocouplers: the discharge relay, pre-charge relay, and isolation relay used to pass the *>60V* signal to the GLV portion of the board.

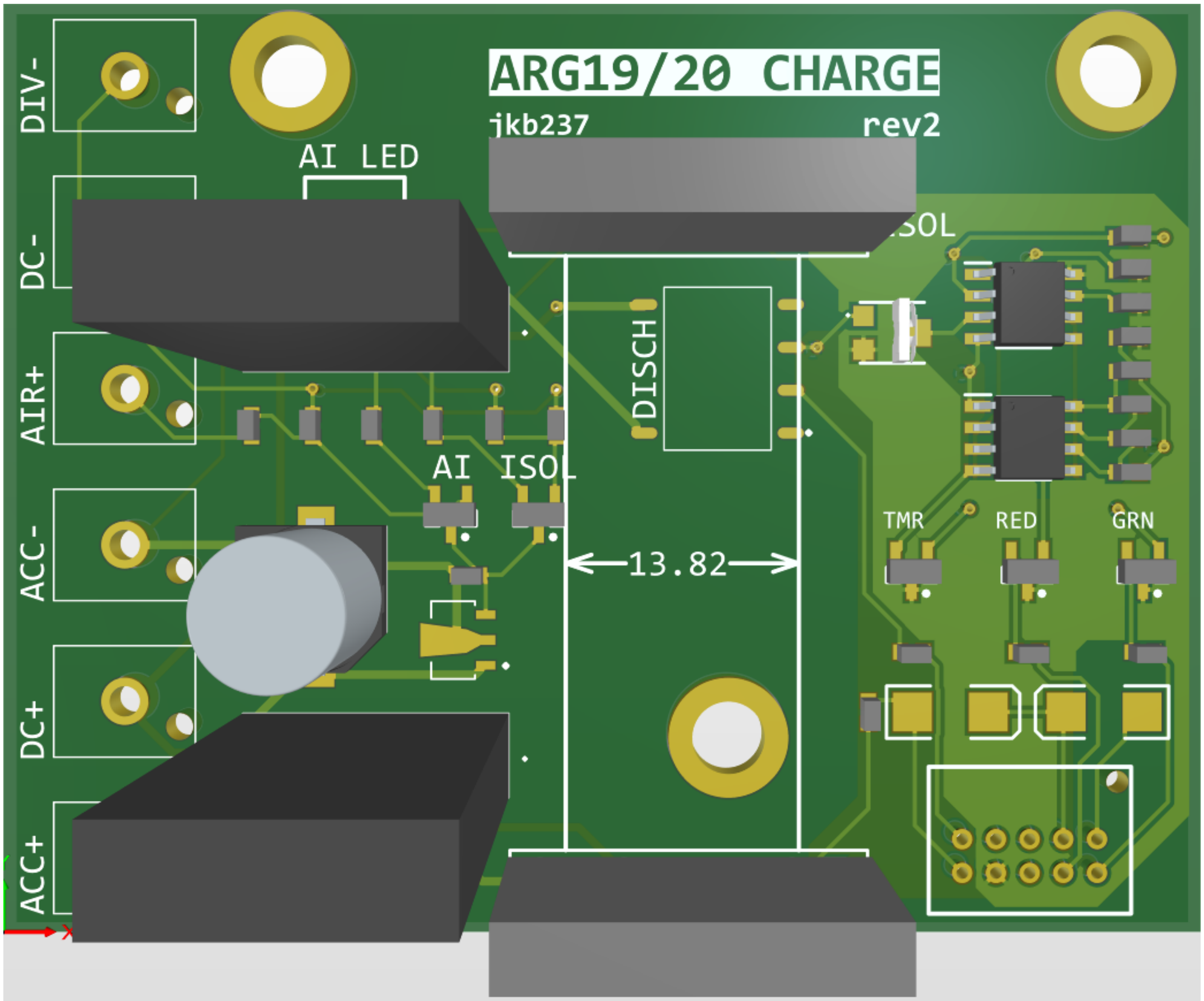

Figure 7: 3D Layout of Charge Circuit Board

Table 1: Bill of Materials

Description	MPN	Manufacturer	Price ($)	Quantity
Pre-Charge Resistor	LTO150F10000JTE3	Vishay Sfernice	11.61	1
Discharge Resistor	AP101 5K6 J	Ohmite	8.04	1
NC Discharge Relay	PLB171P	IXYS Integrated Circuits Division	4.94	1
NO Precharge Relay	CPC1983Y	IXYS Integrated Circuits Division	4.03	2
555 Timer	TLC555CDR	Texas Instruments	0.75	1
12V Regulator	NCP785AH120T1G	ON Semiconductor	0.85	1
TSAL Selector	LM393DT	STMicroelectronics	0.37	1
LV LED/-Timer FET	DMN53D0LQ-7	Diodes Incorporated	0.38	5
10p Header	B10B-PUDSS	JST	0.45	1
10p Header Mate	PUDP-10V-S	JST	0.40	1
10p Header Terminal	SPUD-001T-P0.5	JST	0.10	10
2p Header	B2B-EH-A(LF)(SN)	JST	0.14	1
2p Header Mate	EHR-2	JST	0.10	1
2p Header Terminal	SEH-001T-P0.6	JST	0.10	2
1p HV Connector	DF63M-1P-3.96DSA	Hirose Electric Co Ltd	0.38	5
1p HV Mate	DF63-1S-3.96C	Hirose Electric Co Ltd	0.19	5
1p HV Terminal	DF63-1618SCF	Hirose Electric Co Ltd	0.17	5
50 kOhm Pot	TC33X-2-503E	Bourns Inc.	0.28	1

Description	MPN	Manufacturer	Price ($)	Quantity
200 pF Cap	CC0603JRNPO9BN201	Yageo	0.12	1
.01 uF Cap	CC0603KPX7R9BB103	Yageo	0.10	1
1 uF Cap	CC0603KRX5R8BB105	Yageo	0.10	1
2.2 uF HV Cap	ULH2W2R2MNL1GS	Nichicon	0.92	1
22 uF Cap	CL10A226MO7JZNC	Samsung Electro-Mechanics	0.66	1
100 Ohm Res	PCAN0603E1000BST5	Vishay Thin Film	1.31	2
2.2 kOhm Res	SR0603FR-7T2K2L	Yageo	0.57	5
51 kOhm Res	RT0603BRD0751KL	Yageo	0.10	2
240 kOhm Res	ERJ-PA3J244V	Panasonic Electronic Components	0.10	1
1.96 MOhm Res	CRCW06031M96FKEA	Vishay Dale	0.10	2
50V Diode	S1AB-13-F	Diodes Incorporated	0.33	2
600V Diode	ES3JBHR5G	Taiwan Semiconductor Corporation	0.55	1

6 Spring Recommendations

Changes to the design made in the process of assembling the board within the tractive system are outlined above, however some issues remain present, including:

- The TSAL begins to flash red when appropriate, but occasionally momentarily returns to the green state before continuing to flash red. This could not be investigated in the short period of time we had between March 13th and 16th before being kicked from campus, but a potential cause for this may be the 12V regulator on the HV side of the board. The maximum current to be sourced from the regulator is 10mA, and in theory the ISOL relay should only require around 5mA. However, if the regulator's output is being overdrawn, this can be easily discovered by increasing the capacitance of the decoupling capacitor on the $VOUT$ pin of the 12V regulator, or increasing the size of the current-limiting resistor (R14 in Figure 2). If the period of switching between flashing red and solid green decreases, this is likely to be the cause. Solve the problem by either increasing the size of the limiting resistor, or adding a second 12V regulator in parallel. The latter option may be necessary regardless, in order to account for the lack of a functioning Accumulator Indicator LED on the system when we first drove. Adding the AI LED as a load may saturate the singular 12V regulator, necessitating the addition of a second. Other regulators may also exist with higher peak current, although 450V-12V regulators can be difficult to come by.

- It is still necessary to pass the ESF with this design. The one time we submitted the ESF, one issue related to the Charge Board came back from the judges, which was the power ratings of the resistors on the board. Specifically, the 15s continuous power rating of the discharge resistor was a concern. Either testing to prove the viability of the selected resistor, or changing to a much larger resistor (chassis mounted models, for example) may be necessary in order to pass this requirement. One other option may be to simply search harder for a resistor whose datasheet explicitly says the power rating is satisfactory. Unfortunately, the resistor currently chosen does not have an extremely detailed data-sheet. Perhaps contacting the manufacturer for these specifications will solve the issue.

7 References

[1] SAE International, 'Formula SAE Rules 2020 Version 2.0,' 2019. Available: https://www.fsaeonline.com/. [Accessed: 1 Dec 2019]

[2] Cascadia Motion, 'RMS PM/RM Hardware User Manual,' 2019. Available: https://www.cascadiamotion.com/documentation.html. [Accessed: 9 November 2019]

[3] IXYS Integrated Circuits Division, "CPC1983 Single-Pole, Normally Open OptoMOS® Power SIP Relay" CPC1983Y datasheet, Jun. 2018.

[4] IXYS Integrated Circuits Division, "PLB171 Single-Pole, Normally Closed 800V, 80mA OptoMOS® Relay" PLB171 datasheet, Jun. 2018.

[5] Texas Instruments, "TLC555 LinCMOS™ Timer," TLC555 datasheet, Sep. 1983 [Revised Jul. 2019].

[6] ST Microelectronics, "LM193, LM293, LM393 Low-power, dual-voltage comparators," LM393DT datasheet, Jul. 2002 [Revised Feb. 2016]

8 Appendix

8.1 MATLAB Code

```
clear;clc;close all
textsize = 18;figwidth = 1200; figheight = 900; linewidth=2;

V.max = 420; %max voltage
C.mc = .000440; %farad, internal capacitance of PM100DX
C.dcdc = .0000033;
C.tot = C.mc+C.dcdc;
minR = 400;
maxR = 5000;
dissipativeR = minR:1:maxR; %ohms
I.max = V.max./dissipativeR; %A
P.max = I.max.^2.*dissipativeR;
tauspan = 3*dissipativeR*C.tot;

figure('pos',[75 75 figwidth figheight])
yyaxis right
plot(dissipativeR,I.max,'linewidth',linewidth);hold on
plot(dissipativeR,tauspan,'--','color',[0.9100 0.4100 0.1700],'linewidth',linewidth);
ylabel('Inrush Current (A) and RC Constant (s)')
yyaxis left
plot(dissipativeR,P.max,'linewidth',linewidth);
ylabel('Peak Power Dissipation in Precharge Circuit (W)')
xlabel('Precharge Resistor Resistance (Ohm)')
legend({'Power Dissipation (W)','Inrush Current (A)','3 Time Constants (s)'})
xlim([minR maxR])
set(gca,'FontName','Times New Roman','FontSize',textsize)

%% Precharge
R.pre = 1000; %ohms
I.precharge = V.max/(R.pre); %amps
t = 0:.01:20;
pchargeV = V.max*(1-exp(-t/(R.pre*C.tot)));
pchargeP = (V.max-pchargeV).^2/R.pre;
threetau = 3*R.pre*C.tot;
p.passrulesV = .9*V.max;
p.passrulesT = -log(-p.passrulesV/V.max+1)*R.pre*C.tot;

fprintf('3 Time Constants: %.2f seconds\n',threetau)

figure('pos',[75 75 figwidth figheight])
subplot(2,1,1)
yyaxis left
plot(t,pchargeV,'linewidth',linewidth)
yline(p.passrulesV,'--','linewidth',linewidth);
```

```
xline(p.passrulesT,'--','linewidth',linewidth);
ylabel('Tractive System Voltage')
linelabel = sprintf('Time to Precharge to 90%% of Nominal Voltage: %.2f seconds', ...
    ... p.passrulesT);
text(p.passrulesT+.03,p.passrulesV-40,linelabel,'FontSize',textsize, ...
    ... 'FontName','Times New Roman')
yyaxis right
plot(t,pchargeP,'linewidth',linewidth)
xlabel('Time (s)')
ylabel('Pre-Charge Power (W)')
xlim([0 12])
% title('Voltage and Power in Precharge Scenario vs Time')
set(gca,'FontName','Times New Roman','FontSize',textsize)

%% Discharge
R.dis = 5600;
dchargeV = V.max*exp(-t/(R.dis*C.tot));
dchargeP = dchargeV.^2/R.dis;
d.passrulesV = 60;
d.passrulesT = -log(d.passrulesV/V.max)*R.dis*C.tot;

fprintf('Discharges to <60 volts in %.2f seconds\n',d.passrulesT)

subplot(2,1,2)
yyaxis left
plot(t,dchargeV,'linewidth',linewidth)
xline(d.passrulesT,'--','linewidth',linewidth);
yline(60,'--','linewidth',linewidth);
ylabel('Tractive System Voltage (V)')
linelabel = sprintf('Time to Discharge to <60V: %.2f seconds',d.passrulesT);
text(d.passrulesT+.25,d.passrulesV+40,linelabel,'FontSize',textsize, ...
    ... 'FontName','Times New Roman')
yyaxis right
plot(t,dchargeP,'linewidth',linewidth)
ylabel('Discharge Power (W)')
xlabel('Time (s)')
xlim([0 12])
% title('Voltage and Power in Discharge Scenario vs Time')
set(gca,'FontName','Times New Roman','FontSize',textsize)

%% Voltage Sensing
Rsensing = 10000:1:3000000;
for i = 1:length(Rsensing)
    sensloss(i) = (V.max^2/Rsensing(i));
    senscurrentsixtyw(i) = 60/Rsensing(i);
    senscurrentmax(i) = V.max/Rsensing(i);
end
```

```
figure('pos',[75 75 figwidth figheight])
yyaxis left
plot(Rsensing,sensloss,'linewidth',linewidth)
ylabel('Power Dissipated by Sensing Divider (W)')
yyaxis right
plot(Rsensing,senscurrentsixtyw,'linewidth',linewidth);hold on
plot(Rsensing,senscurrentmax,'linewidth',linewidth)
ylabel('Control Current Available from Equivalent Bridge')
xlabel('Voltage Divider Resistance (Ohm)')
legend({'Power Dissipated at 420W','Current Through Divider at 60V', 'Current ...
    ... Through Divider at 420V'}, 'FontSize',textsize,'FontName','Times New Roman')
% title('Power Dissipated Through Voltage Dividing Resistors vs. ...
    ... Resistance of Voltage Dividing Resistors')
set(gca,'FontName','Times New Roman','FontSize',textsize)
```