Electric Car Battery Charger
ECE3503 Project 2017

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1 INTRODUCTION

The focus of this project is to research and design an efficient battery charger for an electric vehicle. According to a survey[1] performed by the UBS global autos, consumer interest in electric vehicles is on the rise, and it is expected that about one in every sixth car sold in the world will be electric by 2025.[2] For this to happen without error, it is important that electric vehicle systems are efficiently charged and powered which is what this report will encompass.

This report will detail the method and reasons for selecting each component in the battery charger design. Using proper modeling and computation, this report will also further prove that the design functions properly and as expected.

1.1 Problem Statement

Problem is to design a battery charger for an electric vehicle and meeting most to all of the requirements below:

1. Available Voltages
   120 / 240 V, 60Hz, Single Phase or
   440 V, 60Hz, 3-Phase
2. The battery is (Choose Battery Type) with 200*ϵ Ah. The Battery rated voltage is 24 V for $\epsilon < 11$, 48 V for $11 < \epsilon < 21$ and 96 V for $\epsilon > 20$
3. The battery charger has to have efficiency better than 85%, a power factor better than 95%, and a total distortion factor of the current better than 10%.
4. The +/- terminal that are connected with the battery terminals must be floating
5. The charging should be performed with a constant current with a ripple less than 10%. Once the full charge is reached the battery is disconnected or a trickle current is continuously supplied.
6. The charger should operate silently. Lights should indicate the stage of operation and the approximate amount of charge stored.
7. The system should fail safe (no fire, no arc escalation)
8. The system should be immune to voltage surges of 2000 V peak, lasting 2 us.
9. The charger will operate in a room with a temperature in the range of -20 ℃ to 40 ℃ and very dusty air.
10. You should determine what quality assurance tests the charger should pass
11. You should determine the cost of the charger (materials, labor, overhead)

**Note, ϵ should be the student number. However, because the specifications for e in the voltage ratings are low, I chose a value of 25.*

[1] https://neo.ubs.com/shared/d2NY9OkeKUpBxTw/
[2] https://www.bloomberg.com/news/articles/2017-11-28/rise-of-electric-cars-quickens-pace-to-tesla-s-benefit

2 METHODOLOGY

This section outlines the steps taken into designing this battery charger. In order to design it, it is necessary to have a battery in mind - this project will use a lithium ion battery rated at 96 volts with a charge capacity of 5000 Ah. From there, information on the charging specifications, the circuit protection, the quality assurance tests, and the power specifications are listed. After all specifications were researched and designed, the cost of the charger is estimated and a prediction is set as to how it will do in the market.

2.1 Battery Specifications

2.1.1 Three-Phase Alternating Current Input Power

Out of the two choices in the specification #1 of the project guidelines, the chosen AC power for this charger is a three-phase alternating current. Initially, this product was going to utilize single phase AC power as the targeted customer was going to be for homeowners who would prefer charging their electric vehicles at home rather than at a charging station. However, upon further research, the three-phase was more suitable for this application as in the long run it would be deemed more efficient for high powered electric applications. As of now, three phase power is most commonly used in industrial, commercial and professional sites, but because of its continuous and smooth flow of power, and greater efficiency, three-phase AC power has a much greater potential to be used in residential settings as electrical vehicular systems are on the rise.[3][4]

For a 440 volt 3 phase input, at a frequency of 60 Hz, it was calculated that each input source should have an amplitude of 208 V_{RMS}.

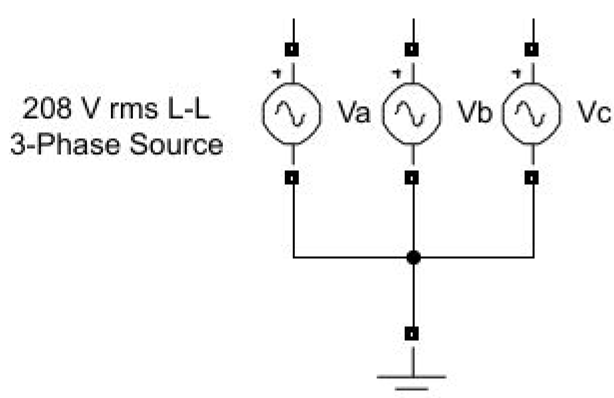

Figure 1. Simulink Model of a 3-phase source

[3] https://www.otterbine.com/resource-center/articles-and-press/single-phase-vs-three-phase-power/
[4] https://blog.tripplite.com/single-phase-vs-three-phase-power-explained/

2.1.2 Lithium Ion Battery

The battery that was chosen for this application was a lithium ion battery due to its vast applications in the recent and upcoming years. Usually, rechargeable car batteries are made of lead-acid, however, Tesla and Nissan, both leading automakers in electric vehicles[5], are using and improving lithium ion batteries for their needs.

Although the technology is new, it is on the rise. Therefore it is a good idea to come to the market without as many competitors. Li-on batteries are lightweight, fast and efficient in charging, high in energy density, and can self discharge at a much lower rate than other types of rechargeable batteries. However, unlike its counterparts, if overcharged, or over-discharged, it may have negative effects on the battery. These will be further looked over in the next section.

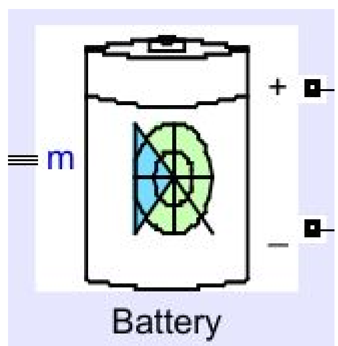

Figure 2. Simulink Model of a Lithium Ion Battery with Floating Terminals

As seen in the figure above, this is the model in Simulink for the the lithium ion battery. This meets specification #4 as it has floating terminals. The battery that will be used will have a nominal voltage rating of 96 volts, and will hold a charge capacity of 5000 amp hours[6].

2.2 Charging Specifications

This section focuses on the charging specifications from #5 and #6 on product requirements. Because the battery chosen was a lithium ion battery, it will need a constant current and voltage charge, thus the ripple of the charge will have to be heavily reduced. Once the charge of the battery reaches 100%, a breaker will be activated to stop the battery from overcharging. With the concept of hysteresis, once the battery reaches a certain percent of charge, it should begin to charge again. To visualize the charge in the battery, LED indicators will be used.

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[5]https://www.forbes.com/sites/bertelschmitt/2017/05/01/who-is-the-worlds-leading-ev-marker-no-its-not-tesla/#708dce513912

[6] This value was not chosen by my ECE number of 347. It was quite high. So I chose a value of 25, giving me 96V and 5000 Ah as said in the specifications.

2.2.1 Constant Current Charge

The figure below shows the battery voltage and charge capacity as a function of time when charging the lithium ion. To make this more basic, the lithium ion will be supplied a constant charge with a constant voltage. This can be done by rectifying the 3-phase signals from AC to DC, and then filtering it.

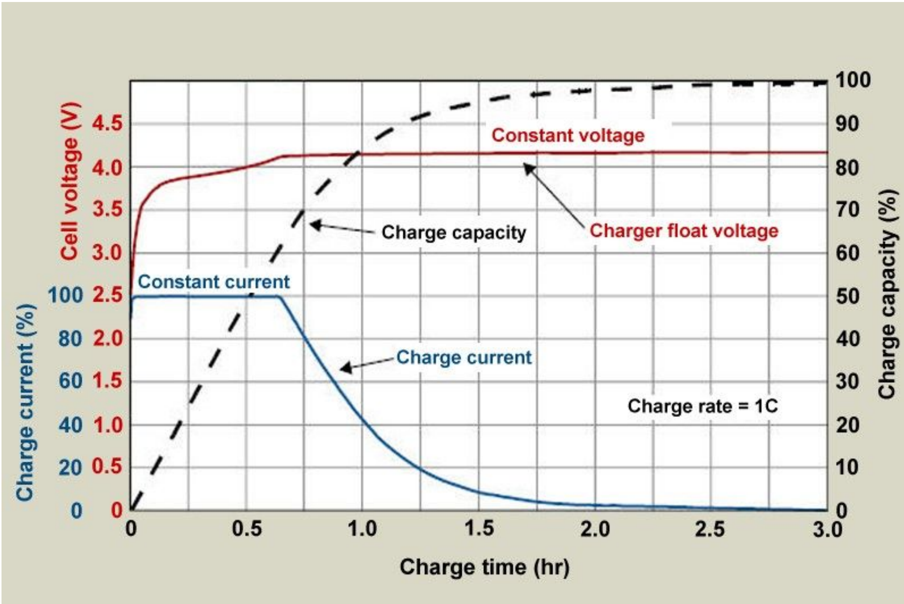

Figure 3. Volts/Capacity vs. time when charging lithium ion[7]

In Figure Y, to model the rectifier a thyristor bridge was utilized. The PID control for the thyristor bridge can be seen in the figure below.

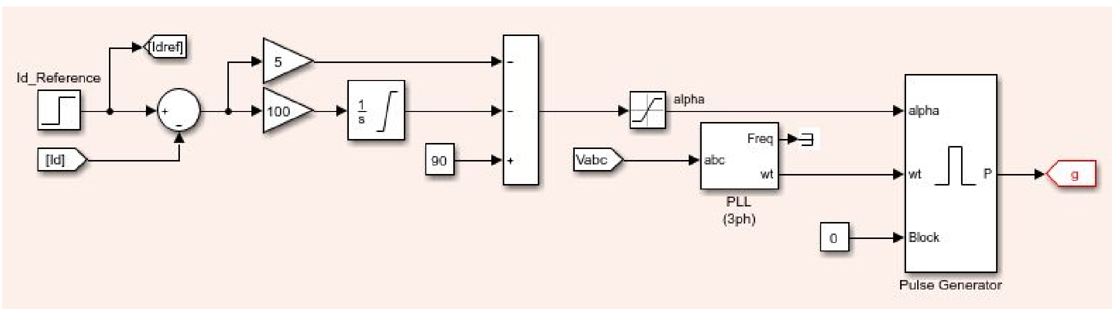

Figure 4. PID control for Thyristor Bridge

To make the rectified output a constant DC voltage, an LC filter was used. Considering a voltage ripple of 0.01, the inductance and capacitance values were obtained. Derived from the fourier series and the output voltage, the ripple factor is:

[7] http://batteryuniversity.com/_img/content/new.jpg

$$\gamma = \frac{V_{rms}}{V_{dc}} = \frac{\sqrt{2}}{3} \cdot V_{dc} \cdot \frac{X_C}{X_L} = \frac{\sqrt{2}}{3} \cdot \frac{1}{4\omega^2 CL} \qquad \text{Eq 1}$$

$$CL = \frac{\sqrt{2}}{3} \cdot \frac{1}{4\omega^2 \gamma} \qquad \text{Eq 2}$$

$$CL = 0.0008292\, FH$$

From there, the values of the inductor and the capacitance were chosen on whether they existed they were available from distributors.

L_1 = 82 mH[8]
C_1 = 1000uF[9]

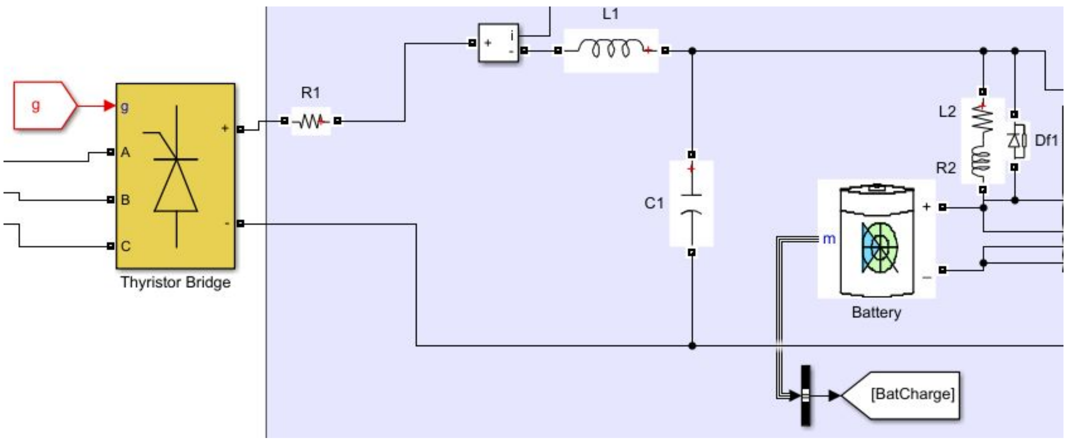

Figure 5. Simulink Rectified and Filtered 3-phase input for constant current and voltage charge

2.2.2 Full Charge Disconnection

Unlike lead acid batteries, lithium ion does not need to be trickle charged once it reaches its full capacity. The moment the battery charge is met, the battery should stop charging. As seen in the figures below, once the charge of the battery reaches 98% of its total charge, it will send a signal to the three-phase breaker to open it. Opening it will cause the circuit to stop charging the battery. If the battery were to discharge to 96% of its capacity while attached to the charger, it should begin charging again. The battery should not reach its full potential as lowering the end charge voltage and accepting a shorter runtime leads to prolonging the service life of a Li-ion battery[10].

[8] https://www.mouser.com/Passive-Components/Inductors-Chokes-Coils/Fixed-Inductors/_/N-wpcz?P=1z0wpwe
[9]https://www.mouser.com/Passive-Components/Capacitors/Aluminum-Electrolytic-Capacitors/Aluminum-Electrolytic-Capacitors-Leaded/_/N-75hqw?keyword=100v%201000uf&P=1z0z819
[10] http://batteryuniversity.com/learn/article/charging_lithium_ion_batteries

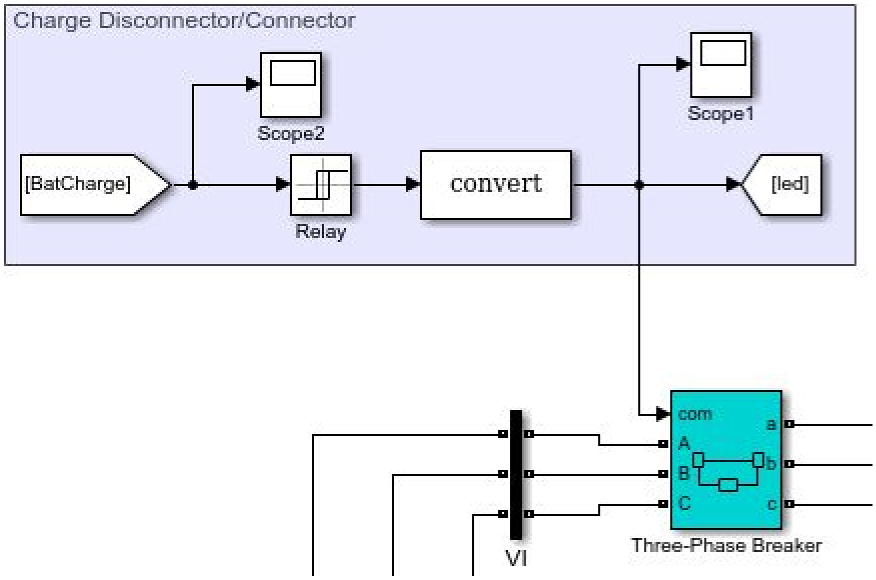

Figure 6. Simulink Model of Charge Disconnector/Connector using Hysteresis

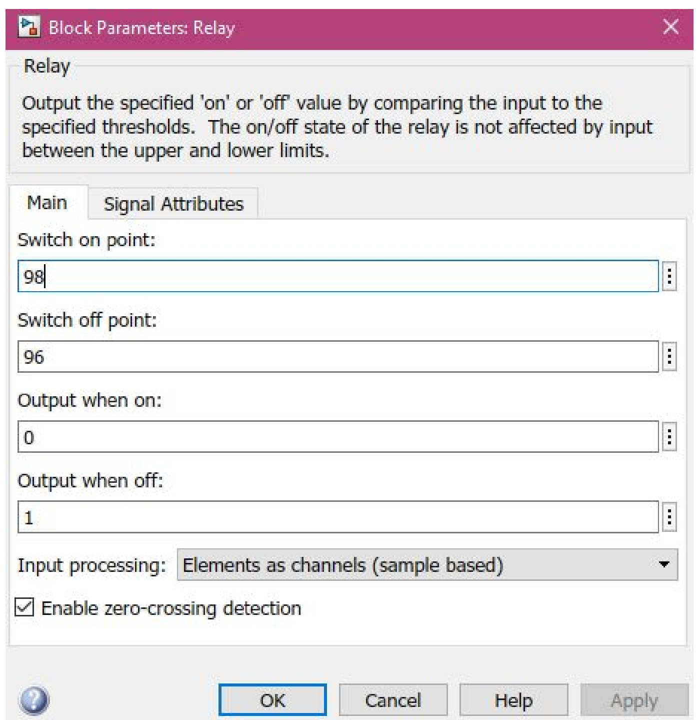

Figure 7. Relay Hysteresis Logic

2.2.3 Visualizing Charge

To visualize the charging of the battery, the state of charge (SoC) will be used to light up the different stages of charging. As seen below, the model shows a single LED charge indicator, with a switch controlled by the SoC which has been previously shown in Figure Z2.

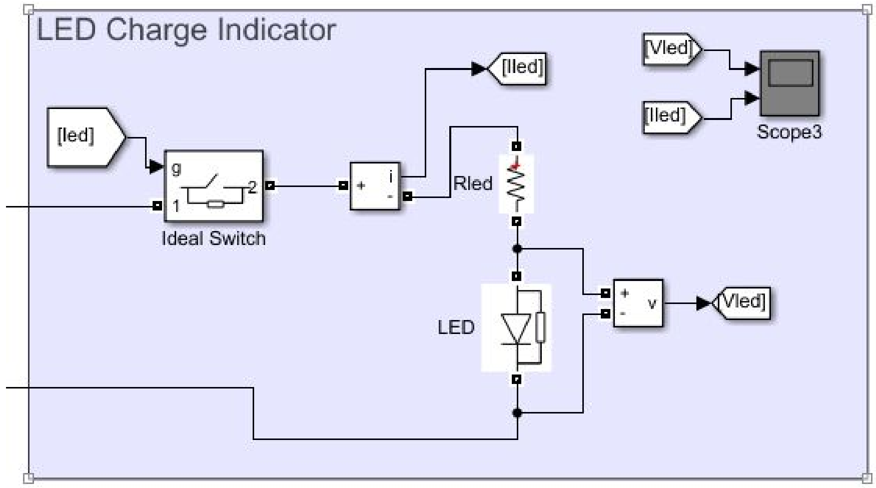

Figure 8. Simulink Model of Single LED Charge Indicator

The same model for the Single LED charge indicator can be stacked in order to include more stages of lighting for the SoC visualization.[11]

2.3 Circuit Protection

In any circuit, it is very important that the components are protected from damage which can come from voltage spikes, heat, faulty connections, and much more. This section will specify how the system will be immune to voltage surges of 2000 V peak that last 2 microseconds, and how the system will fail safe. These will meet the specifications for #7 and #8 on the product requirements.

2.3.1 Surge Protection

There are many types of surge protectors, however for this design, because it is using high powered components, a metal oxide varistor (MOV) will be used. A MOV is a bidirectional semiconductor voltage transient suppressor which behaves as voltage sensitive variable resistors.[12] It's advantages are that its low cost, fast acting, easy to use, bidirectional, and that it fails short circuited - however it isn't good to use for applications that demand continuous power dissipation as it can only dissipate a small amount of power.

The varistor should be placed in parallel to any circuit that needs to be protected and also in switching applications. In the circuit, the best place to place them Arresters were parallel to the load, and near switches.[13]

[11] I did not have the time to test this out, however I believe it can function using the same concept of relays.
[12] https://www.allaboutcircuits.com/technical-articles/transient-voltage-suppressors-tvs-an-introduction/
[13] http://www.electronics-tutorials.ws/resistor/varistor.html

2.3.2 Fail Safe

If a customer were to use this charger and have a much smaller voltage rating, their battery could most possibly catch on fire. In order to fail safe, one suggestion would be to add a thermistor in close proximity to the battery and the charger. If the thermistor "senses" a temperature that is dangerous for a battery, it should fail short circuited in order for the charging to halt.[14]

Freewheeling diodes were also added to the system, in order to eliminate flyback which is a sudden voltage spike which can be seen across an inductive load when the supply current is suddenly changed.[15] Such a case was added in series with the Battery as seen in the figure below.

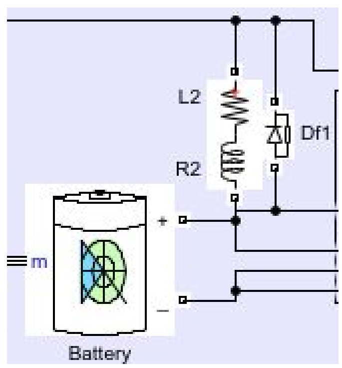

Figure 9. Free wheeling diode in parallel with LC load

2.4 Quality Assurance Tests[16]

Quality assurance tests are ways of preventing mistakes or defects in the the product and its a way of avoiding problems when delivering solutions or services to customers.[17] Here are the steps to take in order to make sure that this charger works as expected:

- ❏ Circuit and Components Check
  Check that all instruments, and components are correctly rated and located with specific labeling.
- ❏ Sequence Test
  Circuitry is functionally tested. Acceptance criteria are schematic diagrams.
- ❏ Temperature Test
  Battery Charger must be able to perform even at its max temperature ratings
- ❏ Controls Test
  Test that all controls specifications function as specified, with correct responses. Tests are acceptable if operate correctly based on reference document and schematics.

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[14] http://www.resistorguide.com/thermistor/
[15] https://en.wikipedia.org/wiki/Flyback_diode
[16] http://www.inspection-for-industry.com/third-party-inspection-for-battery-charger.html
[17] https://en.wikipedia.org/wiki/Quality_assurance

- ❑ Performance and Functional Test
  - ❑ Voltage Accuracy: By applying different input voltages, the output should correspond accordingly.
  - ❑ Voltage Surge: Check whether the circuit can be protected from voltage surges
  - ❑ Efficiency: Must be better than 85%
  - ❑ Power Factor: Must be better than 95%. Measure with a P.F. meter
  - ❑ Total Distortion Factor of Current. Must be better than 10%
  - ❑ Ripple Voltage is measured at 1% and full load (peak to peak with the battery, RMS. with resistive load)
- ❑ Verify Packaging Materials
  Check if it conforms to specifications and accepted practice for the mode of transport
- ❑ Verify Protection against Damage
  Against Humidity, Temperature, Distortion, Heat, and other damage.

2.5 Charger Cost

A rough estimate was done of the simulated model in simulink.

Item	**Cost per item ($)**	**Number of items**	**Total ($)**
3-phase outlet	16.95	1	16.95
1-phase breaker	10.50	3	31.5
Thyristor	3.52	6	21.12
$0.1\,\Omega$ resistor	0.68	1	0.68
83 mH inductor	0.78	1	0.78
$1000\,\mu F$ capacitor	1.00	1	1.00
$0.2\,\Omega$ resistor	0.21	1	0.21
20 mH inductor	6.00	1	6.00
Red LED	1.00	5	5.00
$10\,\Omega$ resistor	0.49	5	2.45
Comparator	0.84	5	4.20
Total			**89.89**

With the unit cost of $89.89, the selling price should be four to five times the unit cost, hence $449.45. Considering a fixed cost of $200,000

3 RESULTS

Using Simulink, the circuit/blocks were tested.

3.1 AC to DC using Thyristor Bridge Rectification

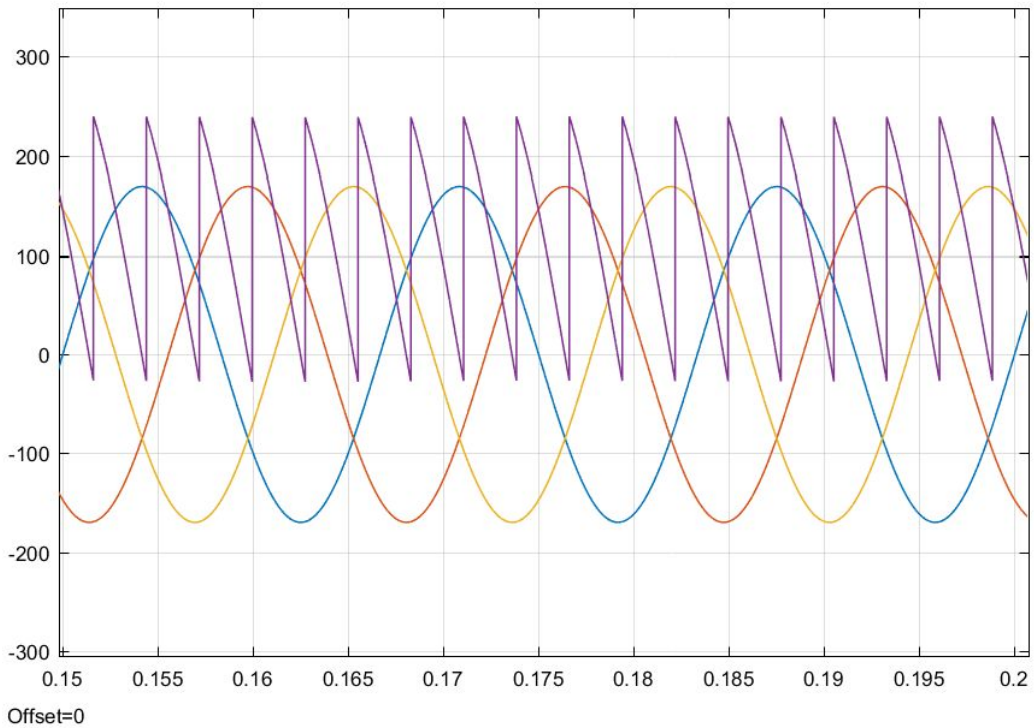


Figure 10. Input AC Signal vs. (Purple) Rectified Signal

3.2 Constant Current, Constant Voltage, and Ripple

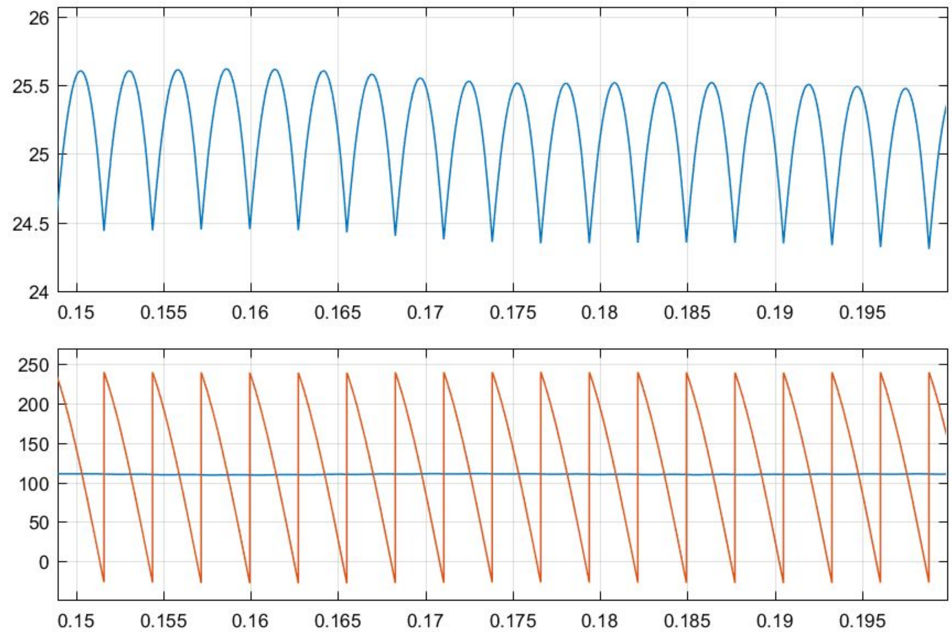


Figure 11. (TOP) Id Current Filtered, (BOTTOM RED) Vd3 Voltage Rectified, (BOTTOM BLUE) Vd Voltage Filtered

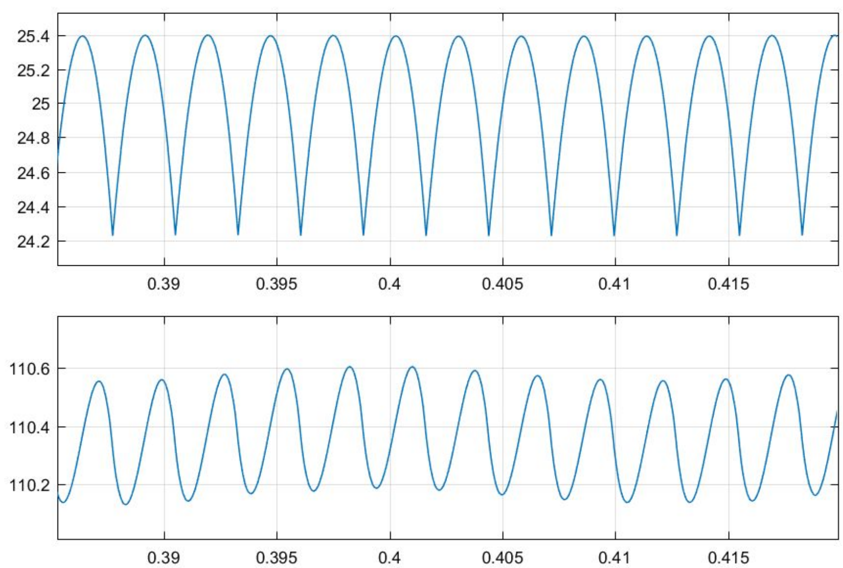
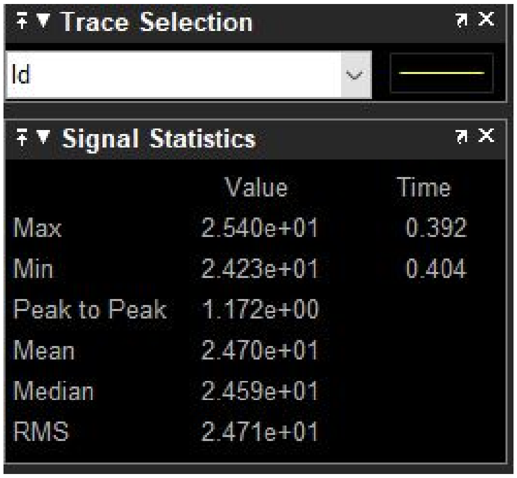
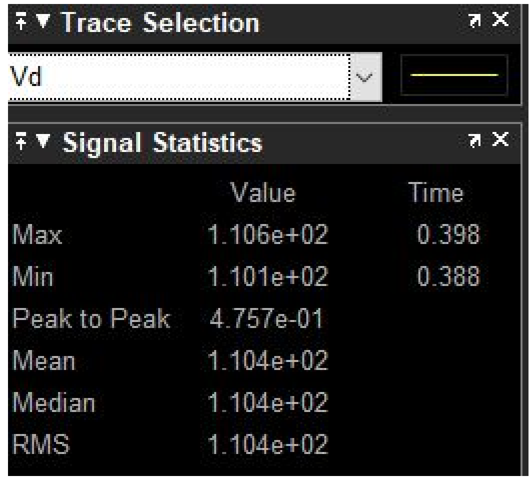


Figure 12. (TOP) I_D Current Rectified, (BOTTOM) V_D Voltage Rectified





Looking at the values taken the voltage ripples can be found using the mean and the peak to peak values of the V_d signal.[18]

$$\gamma = \frac{\Delta V_o}{V_o} = \frac{4.757E{-}1}{1.104E{+}2} = 0.43089\ \%$$

This value is within range of the specified ripple voltage.

3.3 Battery Fully Charged

To simulate that the battery gets fully charged, and gets disconnected, the battery was set to be at an initial charge of 94%. As mentioned before, Lithium Ion Batteries can't be charged fully, so the breaker was set to activate at 95% SoC. These first figure below shows the effect of the circuit breaking, while the second figure shows the rise of the SoC.

[18] http://www.visionics.a.se/html/curriculum/Experiments/FW%20Rectifier/Full%20Wave%20Rectifier1.html

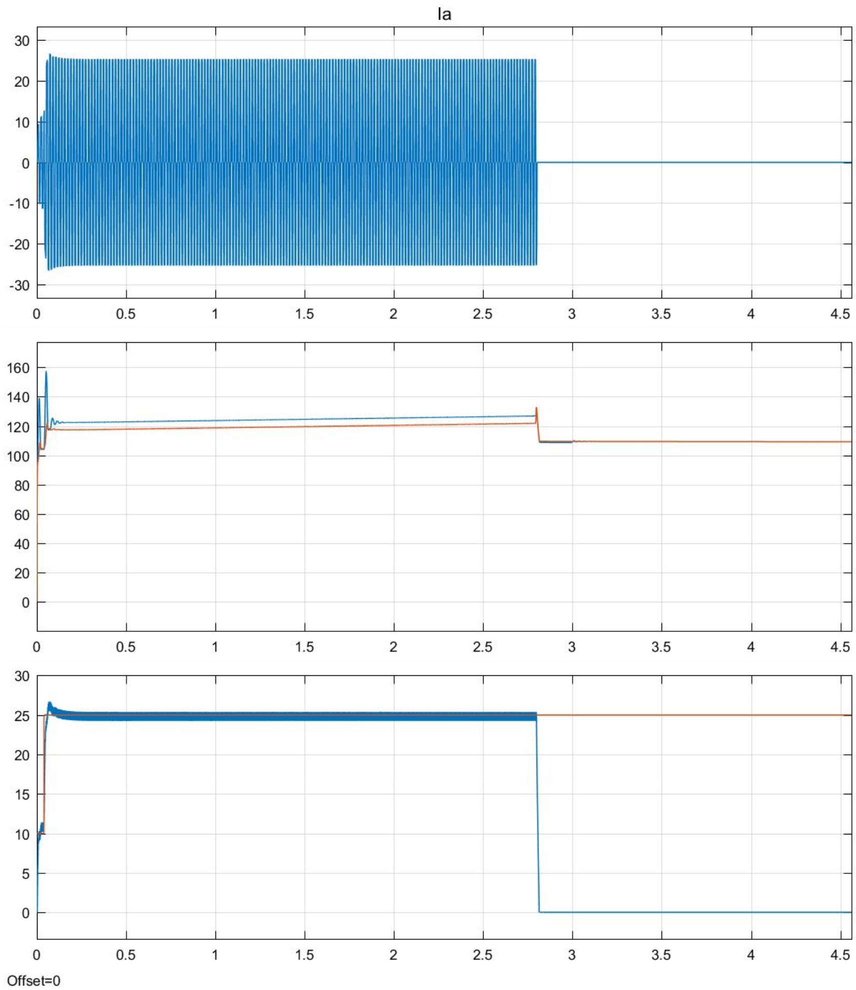


Figure 13. Charging Battery To full Capacity (95% SoC)
(TOP)3-Phase AC Current
(MIDDLE) Blue. Rectified/Charging Voltage, Orange. Battery Voltage
(BOTTOM) Orange. Reference Current (Pulse), Blue. Rectified Current

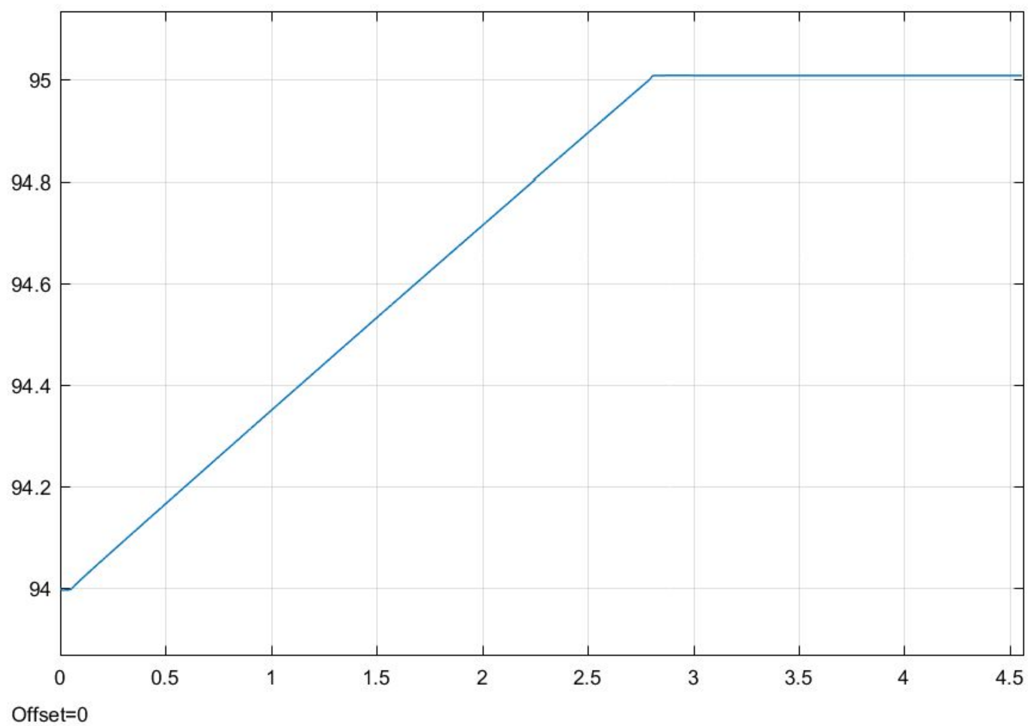


Figure 14. Battery Stops charging at 95% SoC

Although there is a set value for when the battery should start charging, Simulink wasn't able to discharge the battery fast enough to get it to that specified SoC.

3.4 LED Indicator

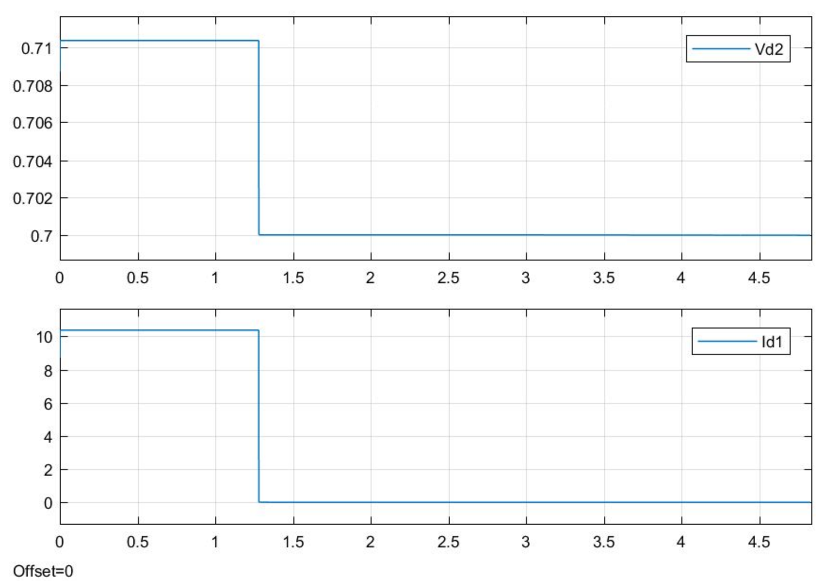


Figure 15. Simulation of LED light On then Off at Charge Complete

Using the state of charge SoC that was used to turn off the charging circuit, the same was for the LED indicator. The LED would be on whilst the battery was charging, but the moment it would reach the specified SoC, it would shut off to indicate a completed charge.

3.5 Power Computations

To calculate for efficiency, as specified the efficiency has to be greater than 85%.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{DC,rns}}{P_{ac,rns}} = \frac{1.092E{+}2 \cdot 2.475E{+}1}{1.209E{+}2 \cdot 1.929E{+}1 \cdot \sqrt{\frac{3}{2}}} = 0.9462234 = 94.622\%$$

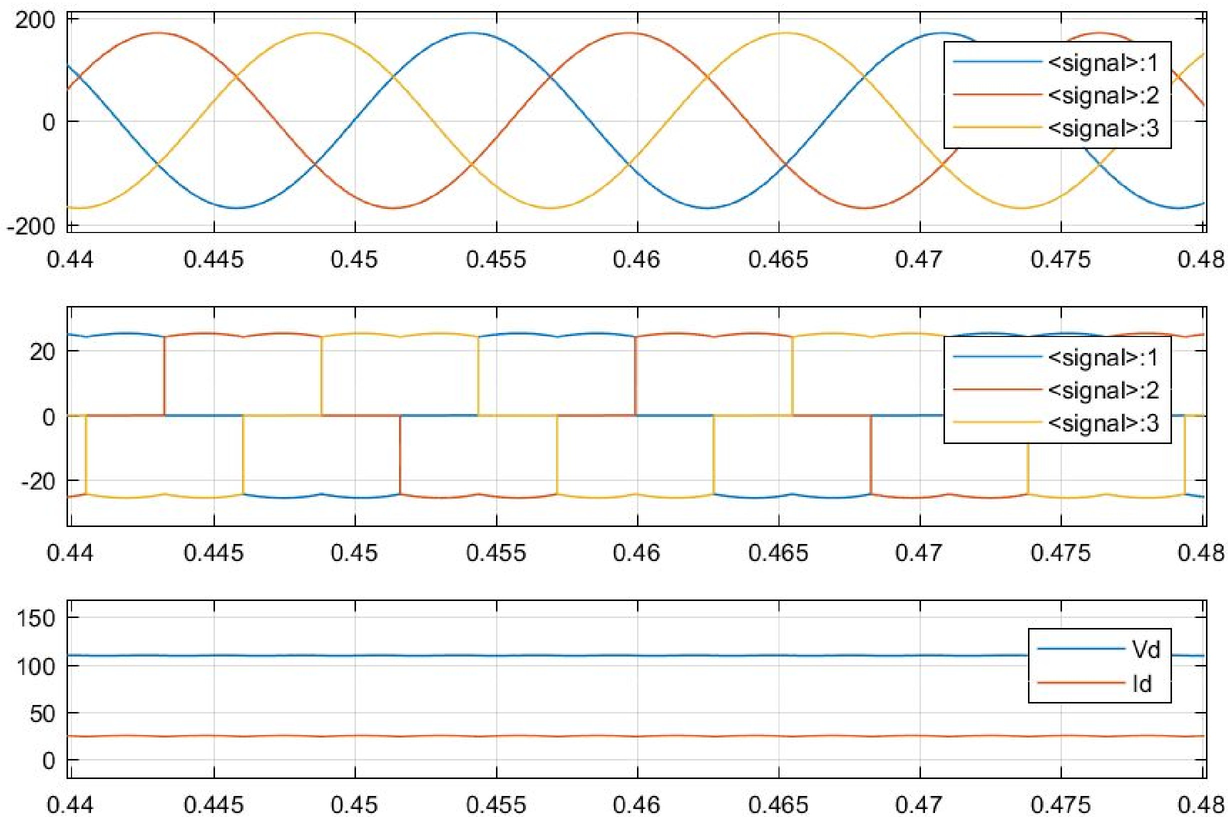
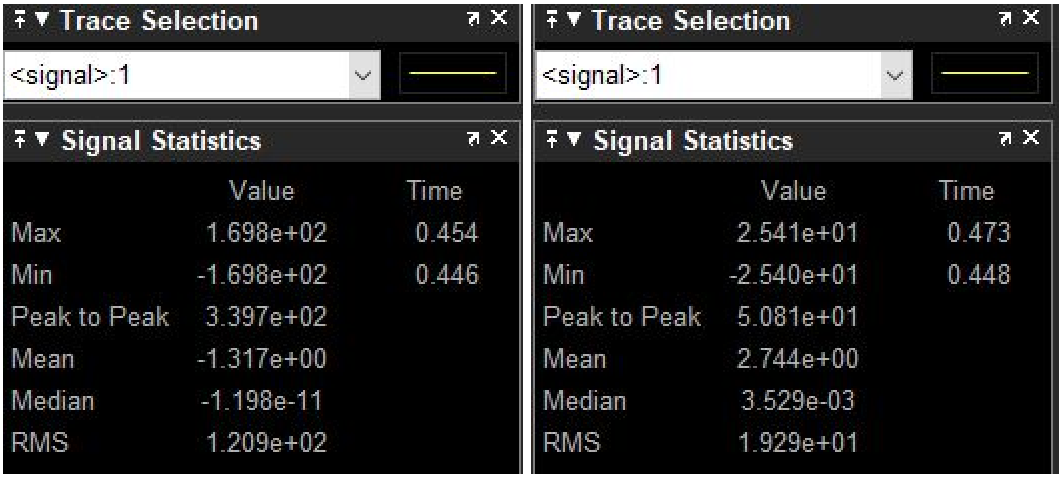


Figure 16. (TOP) 3-Phase Input Voltage, (MID) 3-Phase Input Current, (BOT) Output Current and Output Voltage



Trace Selection: <signal>:1

Signal Statistics

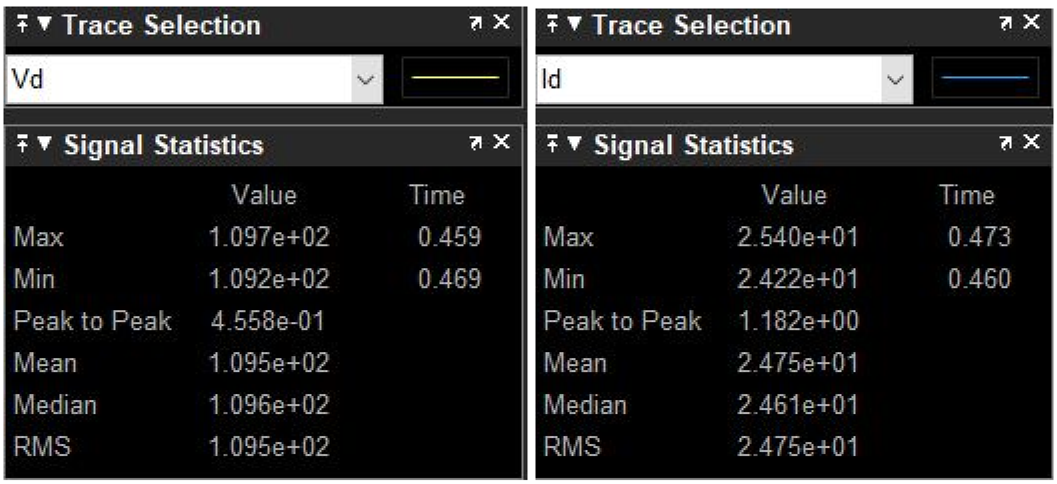
	Value	Time
Max	1.698e+02	0.454
Min	-1.698e+02	0.446
Peak to Peak	3.397e+02	
Mean	-1.317e+00	
Median	-1.198e-11	
RMS	1.209e+02	

Trace Selection: <signal>:1

Signal Statistics

	Value	Time
Max	2.541e+01	0.473
Min	-2.540e+01	0.448
Peak to Peak	5.081e+01	
Mean	2.744e+00	
Median	3.529e-03	
RMS	1.929e+01	

L: Single 3-phase voltage; R: Single 3-phase Current



Trace Selection: Vd

Signal Statistics

	Value	Time
Max	1.097e+02	0.459
Min	1.092e+02	0.469
Peak to Peak	4.558e-01	
Mean	1.095e+02	
Median	1.096e+02	
RMS	1.095e+02	

Trace Selection: Id

Signal Statistics

	Value	Time
Max	2.540e+01	0.473
Min	2.422e+01	0.460
Peak to Peak	1.182e+00	
Mean	2.475e+01	
Median	2.461e+01	
RMS	2.475e+01	

L: Output Voltage; R: Output Current

To calculate the Power Factor:

$$PF = \frac{P_{ac}}{S} = \frac{P_{ac}}{V_p I_p} = \frac{1.097E{+}2 \cdot 2.540E{+}1}{1.209E{+}2 \cdot 1.929E{+}1 \cdot \sqrt{3}} = 0.94$$ [19]

[19] Didn't have enough time to calculate the power factor or the Distortion Factor. Not sure if this is correct. THD values were wanky in the simulations.

3.6 Simulink Schematic

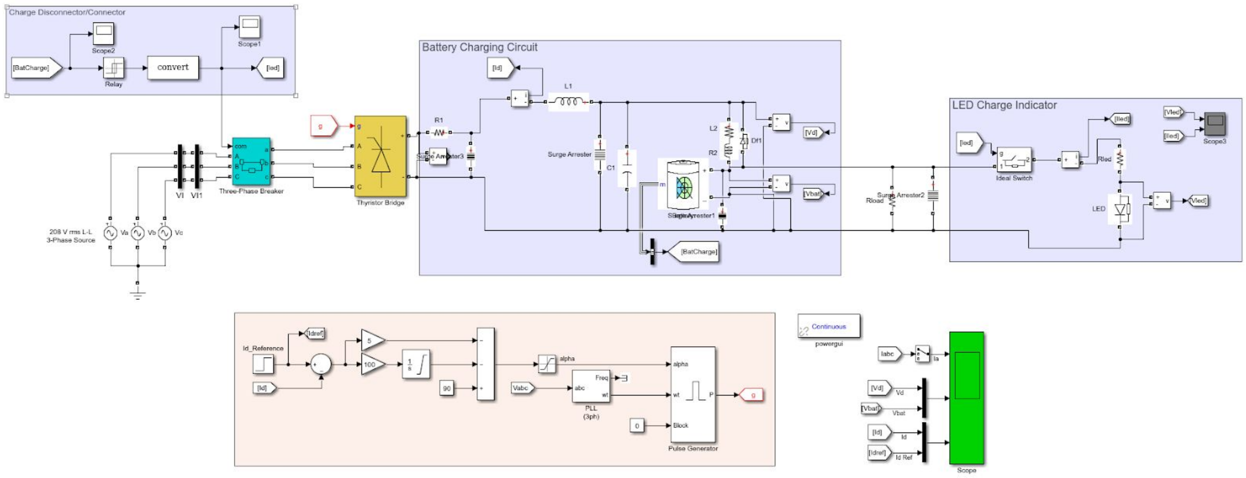


Figure 17. Full Schematic

Model Parameter Values:

R1 = 0.1 ohms

L1 = 82 mH

C1 = 1000 uF

L2 = 20 mH

R2 = 0.2 ohms

R_{led} = 10

Diodes → Forward Voltage 0.7V

R_{load} = 1k ohm

This schematic was based of the Current Controlled Thyristor Rectifier[20] with a few modifications.

[20] https://www.mathworks.com/help/physmod/sps/examples/current-controlled-thyristor-rectifier.html

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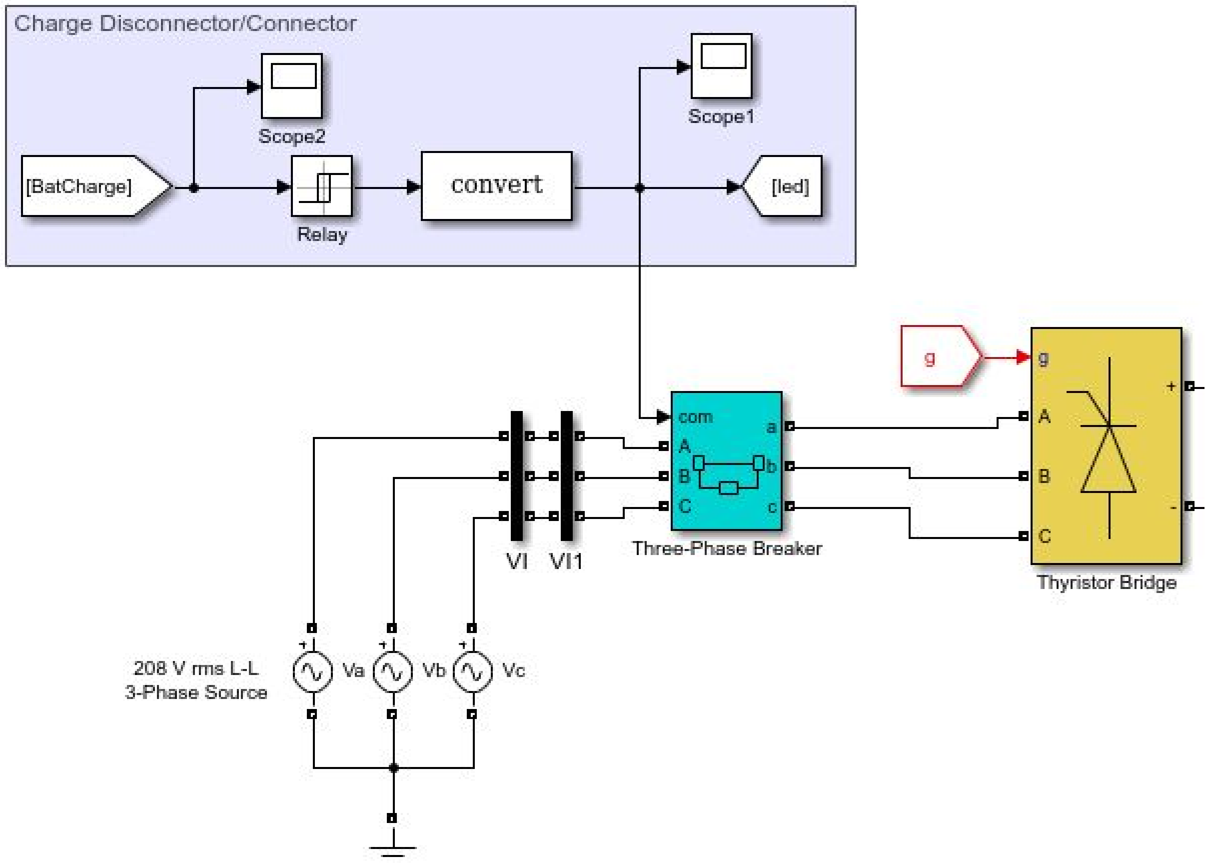
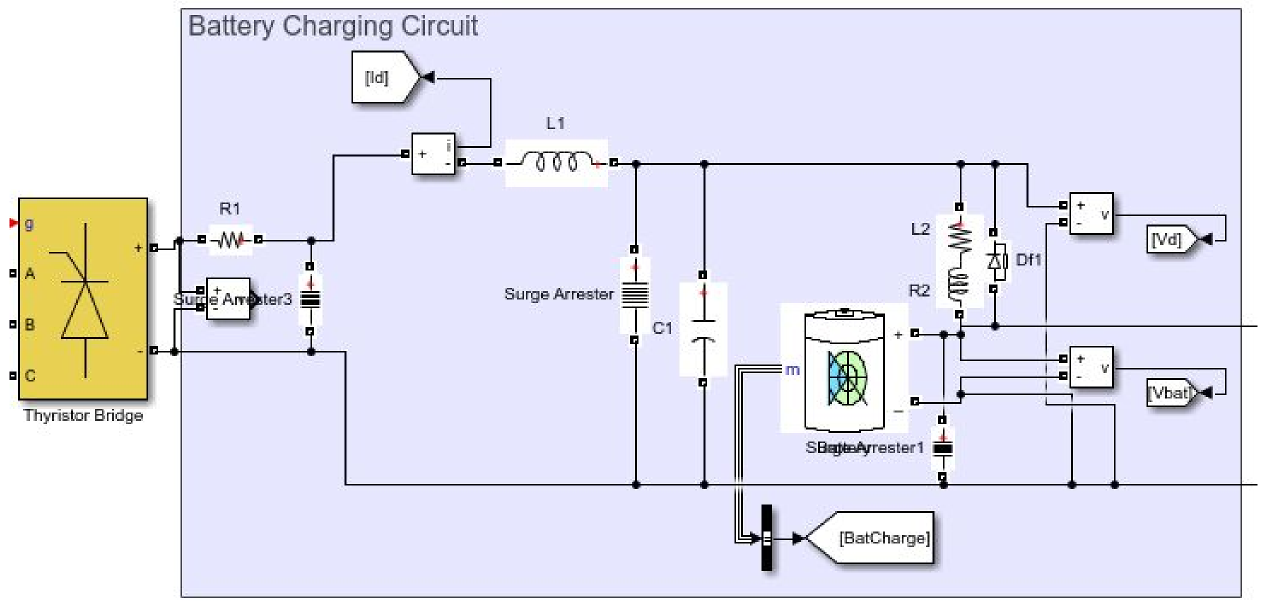
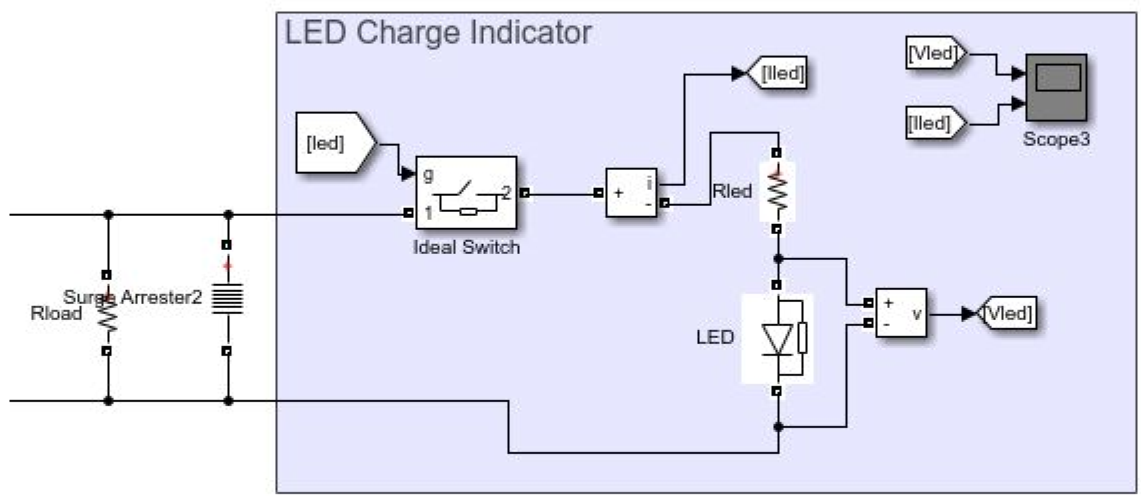
13. (n.d.). Flyback diode - Wikipedia. Retrieved December 16, 2017, from https://en.wikipedia.org/wiki/Flyback_diode
14. (n.d.). Third Party Inspection for Battery Charger - Inspection-for-Industry.com. Retrieved December 16, 2017, from http://www.inspection-for-industry.com/third-party-inspection-for-battery-charger.html

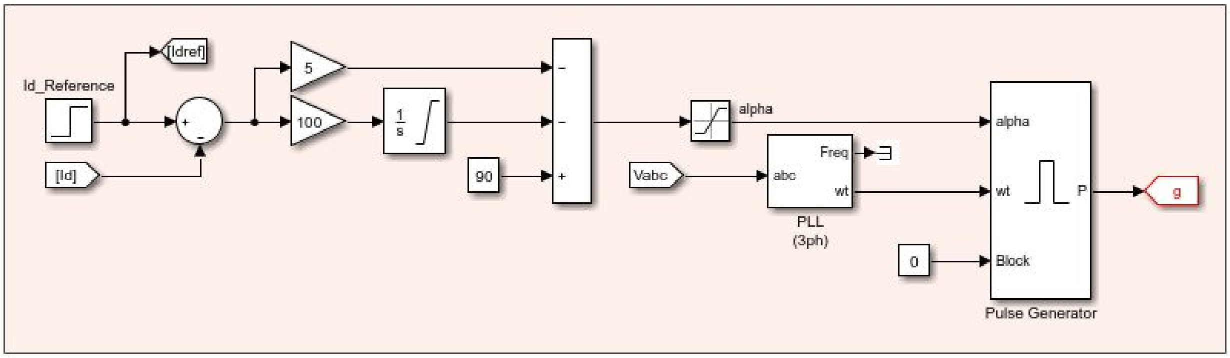
15. (n.d.). Quality assurance - Wikipedia. Retrieved December 16, 2017, from https://en.wikipedia.org/wiki/Quality_assurance
16. (n.d.). Current-Controlled Thyristor Rectifier - MATLAB & Simulink - MathWorks. Retrieved December 17, 2017, from https://www.mathworks.com/help/physmod/sps/examples/current-controlled-thyristor-rectifier.html

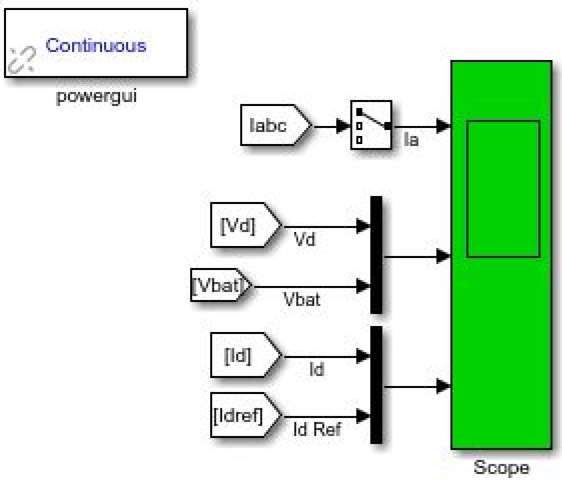
APPENDIX: Broken Down Schematic




Battery Charging Circuit
[Id]
L1
R1
Thyristor Bridge
g
A
B
C
Surge Arrester3
Surge Arrester
C1
L2
R2
Df1
[Vd]
[Vbat]
Surge Arrester1
Battery
m
[BatCharge]


LED Charge Indicator
[Vled]
[Iled]
[Iled]
Scope3
[Ied]
Ideal Switch
Rled
LED
[Vled]
Surge Arrester2
Rload


Id_Reference
[Idref]
[Id]
5
100
1/s
90
alpha
Vabc
abc
Freq
wt
PLL
(3ph)
0
alpha
wt
Block
P
Pulse Generator
g


Continuous
powergui
Iabc
Ia
[Vd]
Vd
[Vbat]
Vbat
[Id]
Id
[Idref]
Id Ref
Scope