Analysis on Tesla Model S Plaid (2023) Final Project Report

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Abstract — **Tesla Model S Plaid** is one of the variants of Tesla Model S series, and it is also the ultimate speed machine which has re-defined speed and acceleration to the entire automotive industry. Originally, we chose Faraday Future 91 as our target vehicle, we then realized a lot of vehicle motor information is not published as our research period progresses. We later decided to switch to Tesla model S Plaid as two vehicles have similar battery parameters. Such as nominal battery voltage of 407V, and it produces a 1,020HP. In this report, we will walk through several topics with concerns like verifying mileage evaluation, approaching the design of its traction inverter, and also introducing our own EV (Electric Vehicle) charger for the vehicle.

Part 1 – Mileage Evaluation

Every year, EPA (Environmental Protection Agency) shares their tested data on every new vehicle available on the US market, including patrol machine drives and electric machine drives, to the public, and the agency will test every model under two conditions, urban and highway. In this part, we would make a comparison among the EPA tested result, the Manufacturer's (Tesla) result, and our Simulink simulation with all the physical and dynamic parameters we have studied.

Choice of BEV: **Tesla Model S Plaid (19inch)**

Vehicle Parameters [1]

	Symbol	Value	
EPA test weight	m	$2267kg$ $(5000\ lb)$	
Rated power	Pr	$761.92\ kW$	
Axle ratio	ng	7.57	
Target Coeff A	A	$29.64\ lbf$	$131.85\ N$
Target Coeff B	B	$0.6164\ \frac{lbf}{mph}$	$6.13318 N/(\frac{m}{s})$
Target Coeff C	C	$0.01\ \frac{lbf}{mph^2}$	$0.2226\ N/\left(\frac{m}{s}\right)^2$

* Target Coeff B is negative, but our model didn't accept any negative input. We adapted $C_B \approx 0$, for the closest estimation.

Additional Parameters [1][2]

	Symbol	Manufacturer Data	EPA Data
Rated torque	Tr	$1{,}977\ Nm$	-
Wheel radius	r	$0.2794\ m$	-
Peak power	P_peak	$1{,}050\ hp$	$1{,}050\ hp$

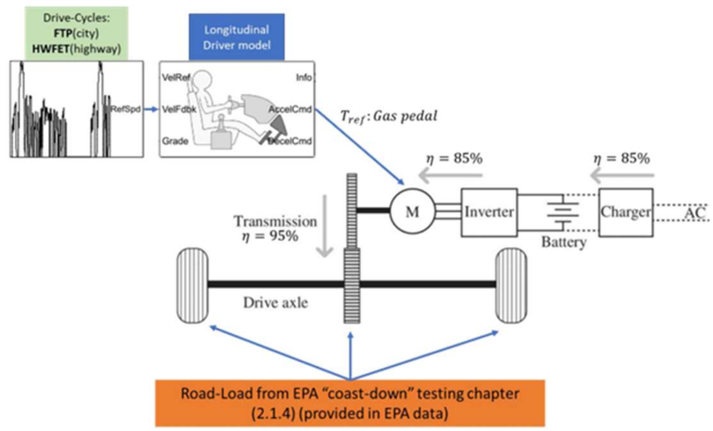

Fig. 1 Demonstration of our mpge simulation

We collected and ran the simulation with EPA collect parameters and obtained fuel efficiency in mpge.

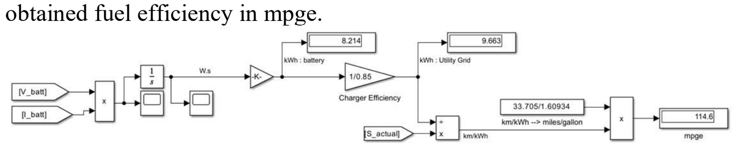

Fig. 2 Estimated fuel combustion at 114.6 mpge (in HWFET, hwy conditions)

On the other hand, the manufacturer didn't release the branded fuel consumption of the model, but we can track it back from its EPA range posted on the website. According to notes from EPA, EPA considers every 33.7 $kWhr$ used is equivalent to 1 gal of fossil gas [3] for every 100 miles drive. Therefore, we can derive the estimated mpge by:

$$mpge = \frac{S_{EPA}}{E_{bat}} * \frac{33.7kWhr}{100mi}$$

Based on the Manufacture's Info [2]

	Value
EPA Range	$381\ mi$
Battery Pack Energy	$142\ kWh$
Estimated mpge (hwy)	$90.42\ mpge$

Overview:

We observed that our results from three different sources have certain amounts of variations, and it could result by multiple factors, like test conditions, chassis efficiencies, marketing strategies from the brand, etc. Especially, we currently do not allow negative inputs of coasting coefficients, and our assumed number could make the final number look different from the real-world data.

Fuel Consumption Comparison among EPA, Manufacturer, and MATLAB Simulink

	EPA	Manufacturer	MATLAB
Fuel Eff	101.14 mpge	90.42 mpge	114.6 mpge

Part 2 – Traction Inverter

In this part of the report, we try to modulate a three-phase inverter on MATLAB Simulink using circuit parameters from hands calculation with known vehicle information. The TESLA model S Plaid uses a tri motor, but here we are only performing one of the motors' simulations. From the database, we know that the line-to-line rms voltage of the motor is 350V [4]. Therefore, we can calculate the phase voltage using this value which gives us:

$$V_{LL} = V_{ph} \cdot \sqrt{3}$$

$$V_{PH} = \frac{350}{\sqrt{3}} = 202.1V$$

The rated power is given by 205kW which corresponds to the real power of the regular RL load [4]. Using the calculated phase voltage, we can also find the desired phase current and line current of the WYE load by:

$$P_{rated} = 3 \cdot I_{ph} \cdot V_{ph} \cdot \cos\phi$$

$$I_{ph} = I_L = 338.3A$$

Now we consider the **modulation index (m)** value which is given by the equation:

$$m = \frac{2\sqrt{2} \cdot V_{ph}}{V_{dc}}$$

A typical modulation index value falls in the range between 0.3 to 0.9. Therefore, we pick 0.9 to determine the minimum V_{dc}value which is calculated to be 634V. It is also the voltage applied to the input of inverter. We know that from data base, the nominal battery voltage is 407V [4]. This means a boost converter is needed for this voltage increment, which will be modulated and presented in simulation in later section. We choose 800V as our desired input voltage applied at the inverter input. Then we have a **duty cycle (D)** of:

$$D = 1 - \frac{V_L}{V_H} = 0.49$$

In Simulink, we simulated the circuits under 100% load, 50% load and 25% load. We measure the boost converter output voltage and phase current of the inverter output load. Then we compare the results with hands calculation to estimate design errors. The results are shown below:

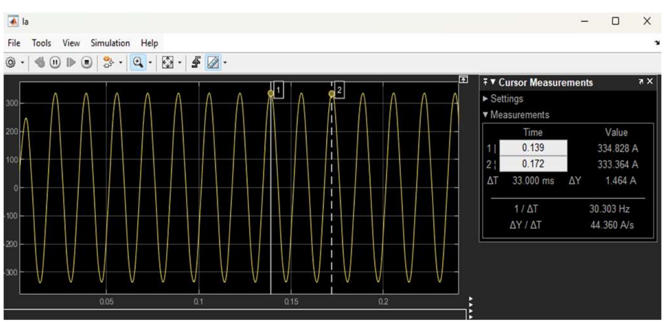

Fig. 3 Phase current (100% load)

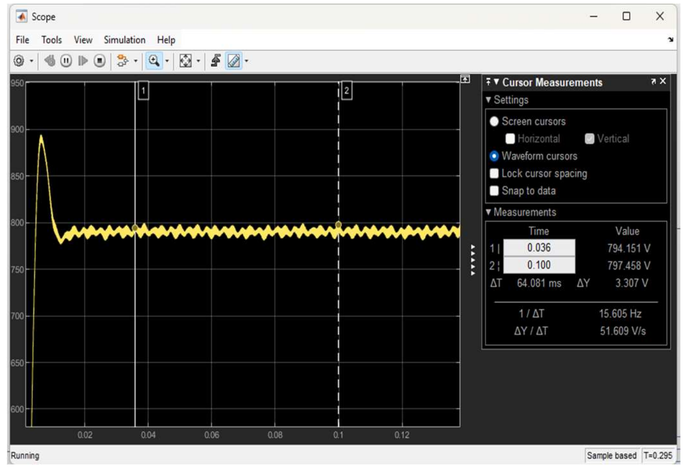

Fig. 4 Boost converter output voltage (100% load)

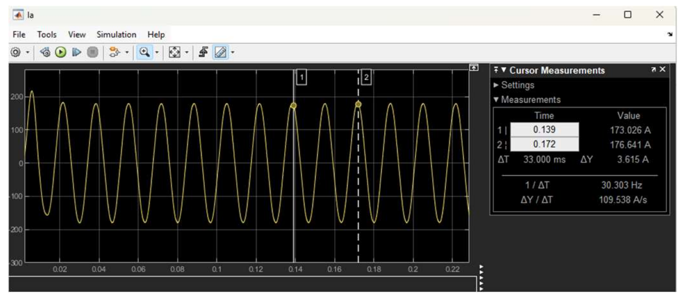

Fig. 5 Phase current (50% load)

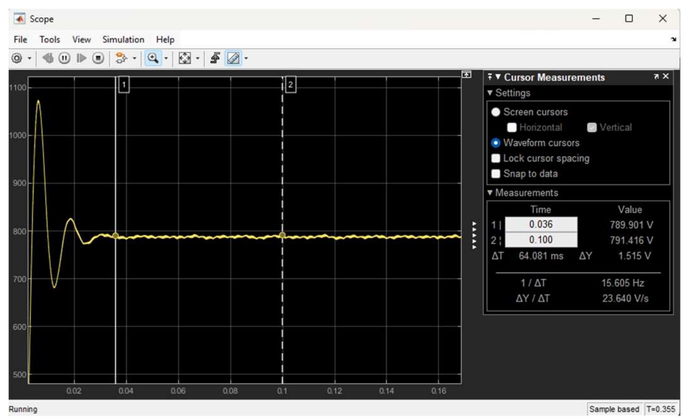

Fig. 6 Boost converter output voltage (50% load)

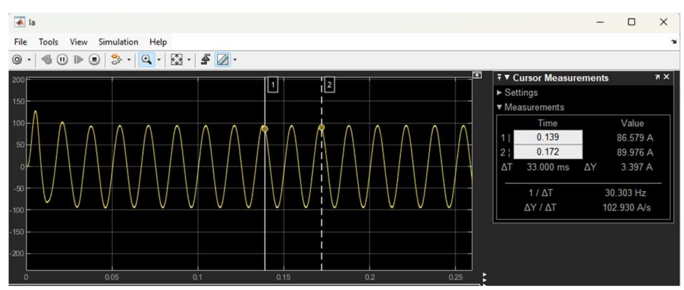

Fig. 7 Phase current (25% load)

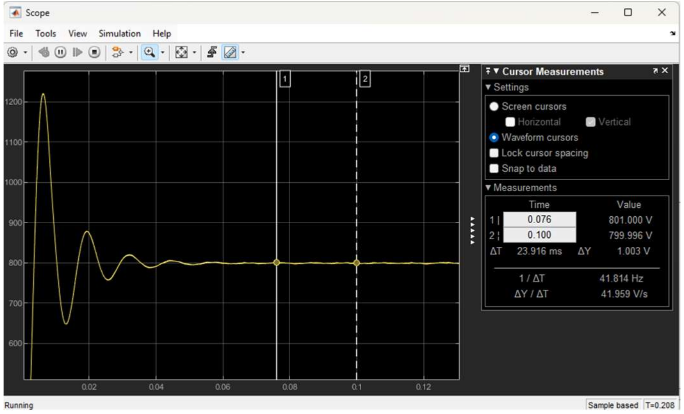

Fig. 8 Boost converter output voltage (25% load)

Results and Comparison:

	Calculated	Simulated	Error
@ 100% Load			
D	0.49	0.55	10%
M	0.71	0.9	27%
@ 50% Load			
D	0.49	0.52	5%
M	0.71	0.72	1%
@ 25% Load			
D	0.49	0.52	4%
M	0.71	0.65	9%

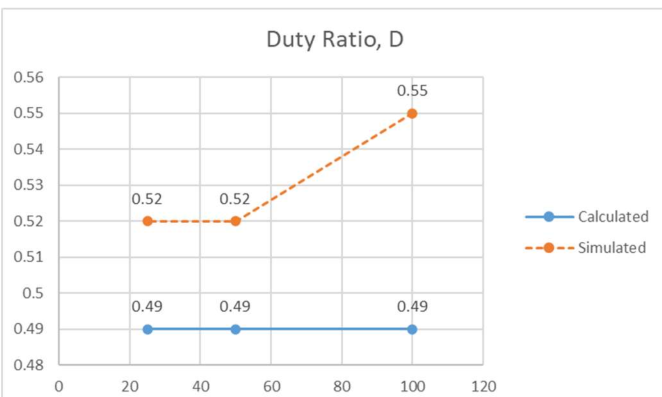

Fig. 9 Duty Ratio (D) various against loads

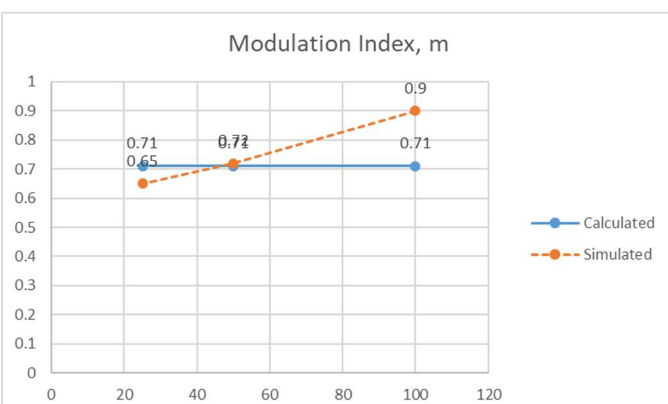

Fig. 10 Modulation Index (m) various against loads

Conduction Loss Analysis

IXYS IXXX140N65B4H1 [8]

	Value
IGBT saturation voltage	Vec = 2.3V
IGBT on-resistance	Rce = 0.013Ω
Diode forward voltage	Vf = 2.1V
Diode forward resistance	Rf = 0.021 Ω

For evaluating the power performance while the inverter is fulling conducting, we calculated the conduction losses of all 6 IGBTs with the approach with various currents flowing through the devices [5].

$$I_{Q(dc)} = I_{ph}\left(\frac{1}{\sqrt{2}\pi} + \frac{V_{ph}}{2V_{dc}}\right)$$

$$I_{D(dc)} = I_{ph}\left(\frac{1}{\sqrt{2}\pi} - \frac{V_{ph}}{2V_{dc}}\right)$$

$$I_{Q(rms)} = I_{ph}\sqrt{0.25 + \frac{4\sqrt{2}}{3\pi} * \frac{V_{ph}}{V_{dc}}}$$

$$I_{D(rms)} = I_{ph}\sqrt{0.25 - \frac{4\sqrt{2}}{3\pi} * \frac{V_{ph}}{V_{dc}}}$$

And the conduction power dissipations are:

$$P_{Q(cond)} = V_{CE0}I_{Q(dc)} + r_{CE}I_{Q(rms)}^2$$

$$P_{D(cond)} = V_{f0}I_{D(dc)} + r_f I_{D(rms)}^2$$

$$P_{total} = 6 * (P_{Q(cond)} + P_{D(cond)})$$

$P_{q(cond)}$	1096.5W
$P_{d(cond)}$	184.8W
P_{total}	5.53kW

The total power in a three-phase Wye-connected system is recalled as [5]:

$$P_{total} = 3 * V_{phas} * I_{phase} * cos\phi$$

where $cos\phi$ = power factor ≅ 1

Furthermore, we can derive the overall conducting efficiency of the design by [5]:

$$\eta = \frac{P_o}{P_o + P_{loss}} = \frac{205kW}{205kW + 5.53kW} = 98.4\%$$

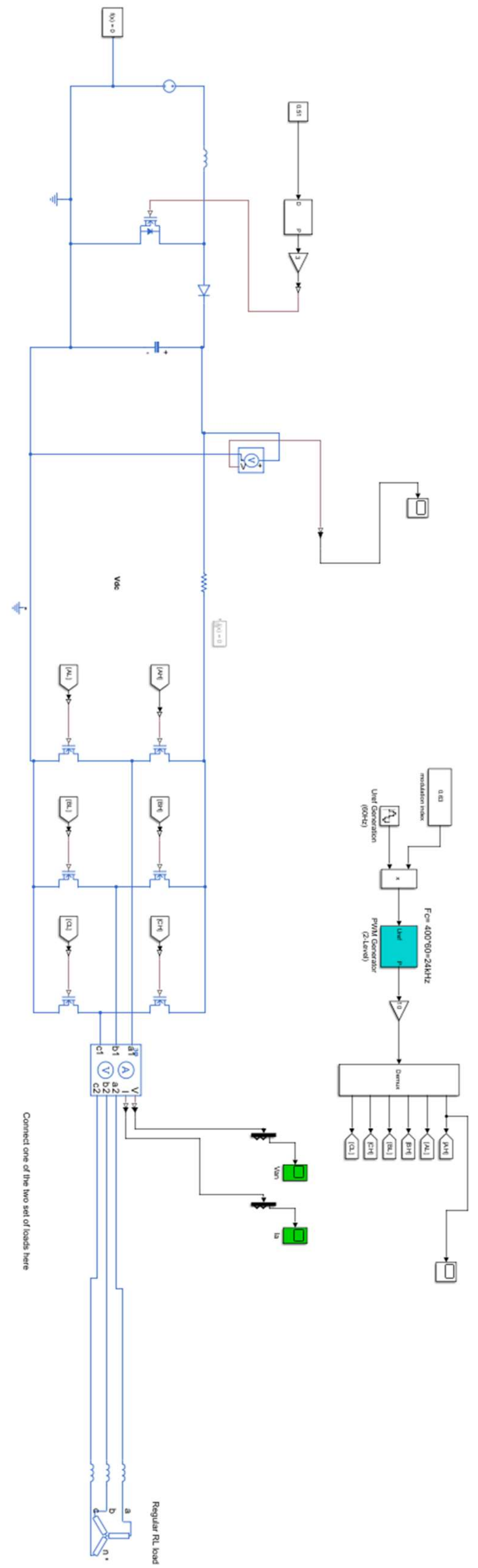

Fig. 11 Simulation of Traction Inverter

Part 3 - EV Charger

In this section, we designed an EV charger targeting the EV model we chose, Tesla Model S – Plaid; moreover, we simulated the design in MATLAB Simulink for exploring the possibility of deployment of our design in the real-life.

The charger was inspired by the standard level 2 AC charger, which is the most common method in the US market [1]. It runs at $7.7kW$ from a single-phase AC power supply which is $240V_{rms}$ $(line\ to\ line)$, $50Hz$. The attached figure shows the approaches by blocks [2][3]:

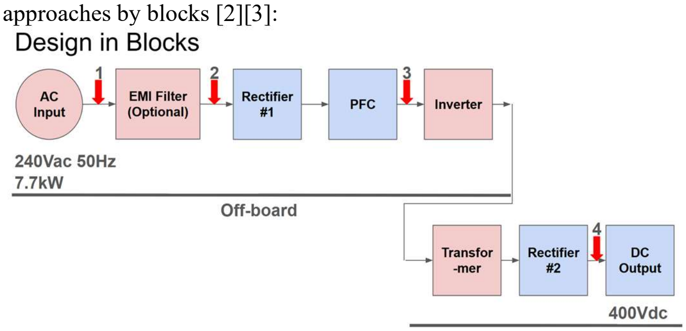

Fig. 10 Designing by Blocks (EV charger)

*All the AC components are noted in Red, and the DC components are noted in Blue.

* The numerical indicators states for the following voltage measurements, it was found very helpful to monitor the performance of the entire design.:

1. V_{AC} is the trace of phase voltage, V_{ph}.
2. V_{DC} is the trace of the rectified DC voltage before being boosted by PFC.
3. V'_{DC} is the trace of the boosted DC voltage after being powered by PFC.
4. V_{load} is the race of battery voltage, $V_{battery}$.

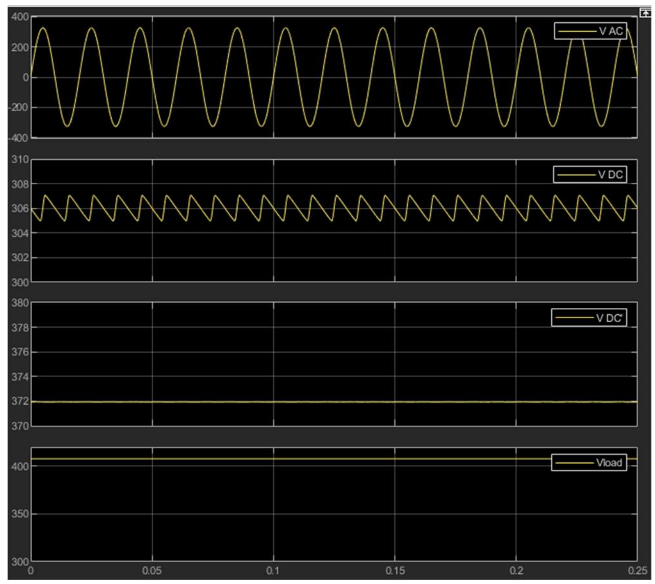

Fig. 12 The voltage performance across the application

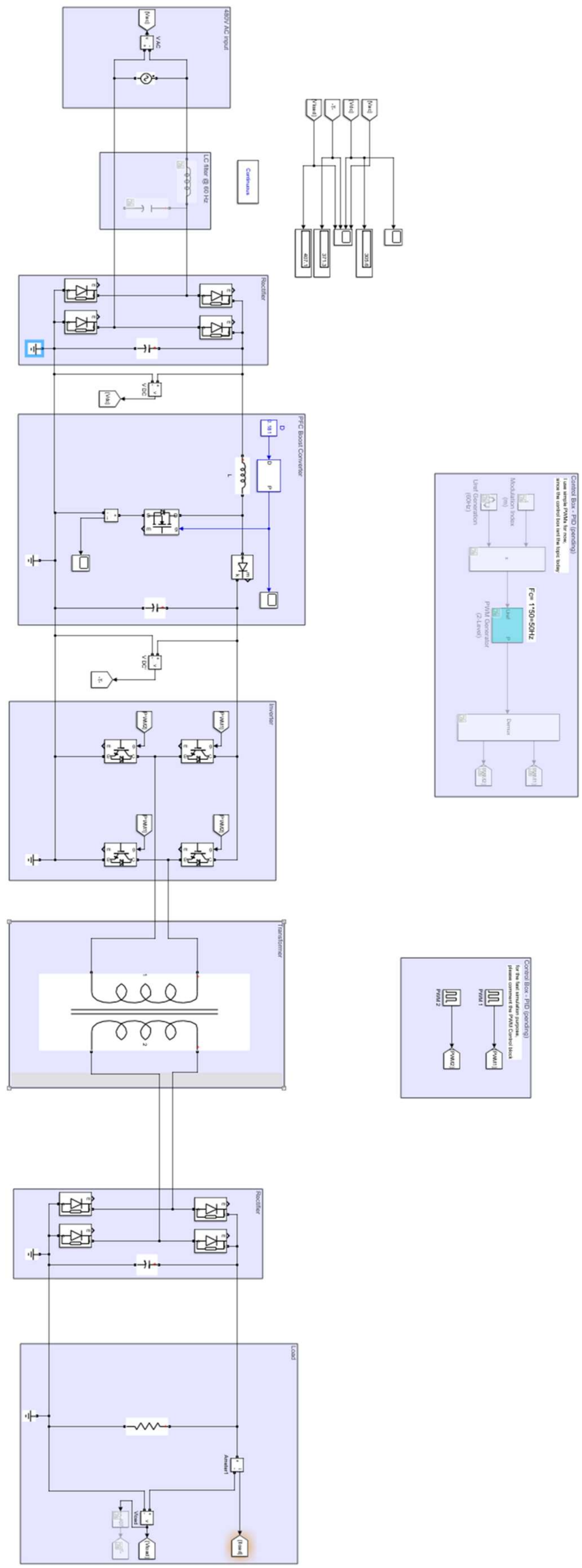

Fig. 13 Designing by Schematics (EV charger)

Designing and Losses Estimation:

- Recitifer#1 & PFC Boost Converter

This **AC-to-DC** rectifier and the **Boost** converter are designated to set up the AC energy into DC form, reducing harmonics and EMI effects, and get ready for the incoming inverter (AC) applications. The application would take $240V_{rms}$ input, and output at approximately $370V_{dc}$. Meanwhile, the switching frequency is set at $40kHz$, and the design is considered to take at the maximum at 10% current ripple. Therefore, for selecting the sizing of the inductor in the Boost topology, the number could be derived by [5]:

$$\Delta I = \frac{P}{V_L} * 10\%$$

$$d(0) = 1 - \frac{\sqrt{2}V_{ph}}{V_{dc}}$$

$$L \geq \frac{\sqrt{2}V_{ph}}{f_{sw} * \Delta I} d(0) = 277.866uH$$

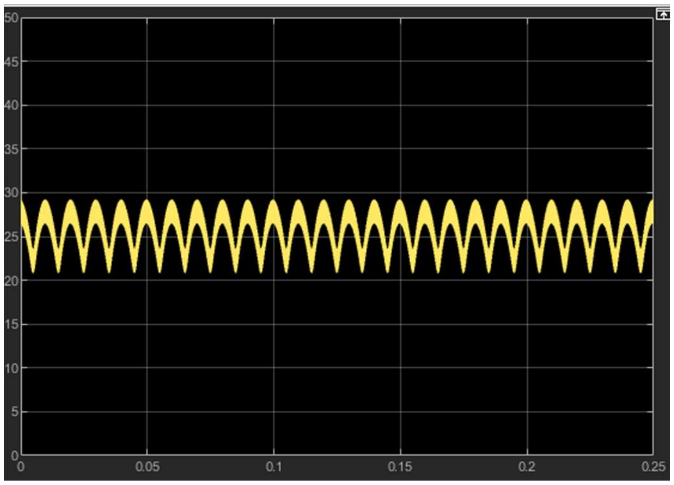

Fig. 14 The current flew though the inductor L

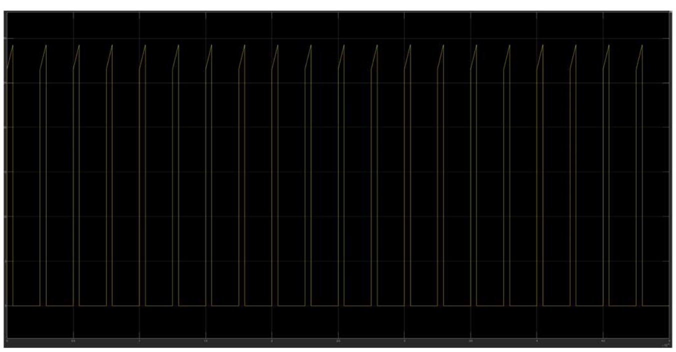

Fig. 15 The current flew though the MOSFET (t=5e-4s)

For power loss analysis, we selected several parts currently available in the market (Digikey.com). For considering and selecting rated parameters (voltages and currents), we consider **at least 25% bigger** than the numerical results we had:

Rectifier#1

R_Diode: GBPC3504A-ND [9]

V_{DS}	V_{f0}	$R_{DS}(on)$	r_f
-	0.77V	-	4.852mΩ

PFC

MOSFET: STB47N50DM6AG [10]

V_{DS}	V_{f0}	$R_{DS}(on)$	r_f
2V	-	71mΩ	-

Diode

VS-HFA135NH40PBF [11]

V_{DS}	V_{f0}	$R_{DS}(on)$	r_f
-	1.1V	-	7.857mΩ

Furthermore, the relevant currents and the conduction losses of the diodes and the MOSFET could be found by [5]:

Rectifier:

$$I_{R(dc)} = \frac{\sqrt{2}}{\pi} I_{ph}$$

$$I_{R(rms)} = \frac{1}{\sqrt{2}} I_{ph}$$

$$P_{RB} = 4P_B = 4V_{f0}I_{R(dc)} + 4r_f I_{R(rms)}^2$$

PFC:

$$I_{D(dc)} = \frac{V_{ph}I_{ph}}{V_{dc}}$$

$$I_{Q(rms)} = I_{ph}\sqrt{1 - \frac{8\sqrt{2}V_{ph}}{3\pi V_{dc}}}$$

$$I_{D(rms)} = I_{ph}\sqrt{\frac{8\sqrt{2}V_{ph}}{3\pi V_{dc}}}$$

$$P_{Q(cond)} = R_{DS(on)} I_{Q(rms)}^2$$

$$P_{D(cond)} = V_{f0}I_{D(dc)} + r_f I_{D(rms)}^2$$

Noted that if the information is unclear or very subjective, we considered and chose the constants in the ***worst-case scenario*** from the datasheet, and here are the conduction losses attached below:

Stage	Type	Part #	P_{cond}
Rectifier#1	R_Diode	GBPC3504A-ND	$46.906W$
PFC	MOSFET	STB47N50DM6AG	$17.4085W$
	Diode	VS-HFA135NH40PBF	$35.5818W$

- Inverter

The approach in this section is similar to Part 2, Traction Inverter, even though this is a single-phase **Full-Bridge Inverter**, and the various currents go through the diodes and IGBTs are [5]:

$$I_{Q(dc)} = I_{ph}(\frac{1}{\sqrt{2}\pi} + \frac{V_{ph}}{2V_{dc}})$$

$$I_{D(dc)} = I_{ph}(\frac{1}{\sqrt{2}\pi} - \frac{V_{ph}}{2V_{dc}})$$

$$I_{Q(rms)} = I_{ph}\sqrt{0.25 + \frac{4\sqrt{2}}{3\pi} * \frac{V_{ph}}{V_{dc}}}$$

$$I_{D(rms)} = I_{ph}\sqrt{0.25 - \frac{4\sqrt{2}}{3\pi} * \frac{V_{ph}}{V_{dc}}}$$

And the conduction power dissipations are [5]:

$$P_{Q(cond)} = V_{CE}\ I_{Q(dc)} + r_{CE} I_{Q(rms)}^2$$

$$P_{D(cond)} = V_{f0}I_{D(dc)} + r_f I_{D(rms)}^2$$

$$P_{total} = 2 * (P_{Q(cond)} + P_{D(cond)})$$

Inverter

IGBT: STGSB200M65DF2AG [12]

V_{CE0}	V_{f0}	r_{CE}	r_f
2.1V	1.55V	0.0105Ω	7.75 mΩ

Stage	Type	Part #	P_{cond}
Inverter	IGBT	STGSB200M65DF2AG	$618.854W$

- Transformer

The transformer is designed to level-up the AC voltage and get ready to be final rectified before charging the battery at 407V. The turn ratio should be adjustable or alternative depending on the actual performance of the devices.
Furthermore, we would like to use its characteristics of "wireless" to specify our design into two parts, **Off-board and On-board**. The Off-board sections would start from the $240V_{AC}$ source to the inverter, and the On-board sections will start after the transformer, we hope it would be implemented on the vehicle. Moreover, it will be general design since the charger now satisfies different battery voltages depending on the different specifications of vehicles in the US market.

- Rectifier#2

In this part, the design and part selection are very similar to the previous part (Rectifier#1). Since we have considered enough electrical tolerance for using duplicate parts, we will keep using the same rectifier diode.

R_Diode: GBPC3504A-ND [9]

V_{DS}	V_{f0}	$R_{DS}(on)$	r_f
-	0.77V	-	4.852mΩ

Even though they are the same parts, but the current flew through were different; then the power dissipation during conduction is calculated by the same approach in Rectifier#1:

Stage	Type	P_{cond}
Rectifier#1	R_Diode	$29.4611W$

<u>Total Conduction Loss and Overall Efficiency</u>

Stage	Type	P_{cond}
Rectifier#1	R_Diode	$46.906W$
PFC	MOSFET	$17.4085W$
	Diode	$35.5818W$
Inverter	IGBT	$618.854W$
Rectifier#1	R_Diode	$29.461W$
-	Total	$748.208W$

Therefore, we can find the conduction efficiency by [5]:

$$\eta = \frac{P_o}{P_o + P_{loss}} = \frac{7700W}{7700W + 748.208W} = 91.15\%$$

<u>Potential Optimizations:</u>

- Introducing an AC filter at the source.

In real life, there will be a lot of challenges in filtering out the noises from the transmission lines, and those unexpected ripples will lower the electrical performance of our application. Therefore, we proposed a low-pass filter, which would cut-off $(-3dB)$ around $60Hz$. Even though there are different choices of topologies, we chose an RC filter, which is the simplest and most practical design for filtering out the high frequency components, which are most of the noises. The relationship between the resistor and capacitor is derived by:

$$f_c = \frac{1}{2\pi * R * C}$$

where $f_c \cong 50Hz$.

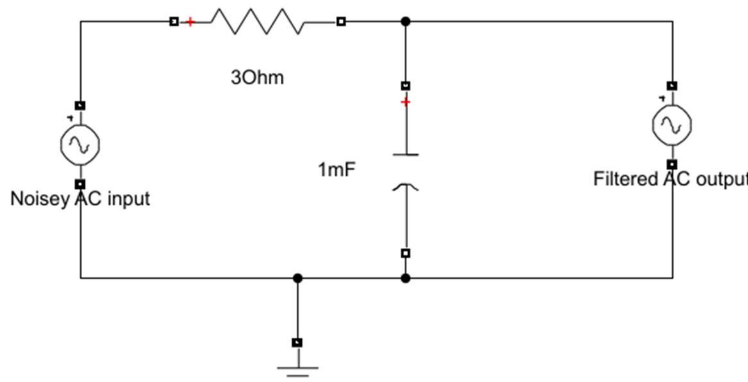

Fig. 16 Low-pass Filter Schematic

- Power Efficiency

There are numbers of factors to improve the overall power efficiency of our design. Especially, while we were calculating our power dissipation, we took the constants under the highest temperature (worst usage) conditions (over 125 Celsius or even 175 Celsius, as long as it was available) from the manufacturer's datasheet. Designing **under the worst-case scenario** is the main idea of the operation, and in the real-world it won't happen like that, and the over efficiency may look better than what we presented on the paper.

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