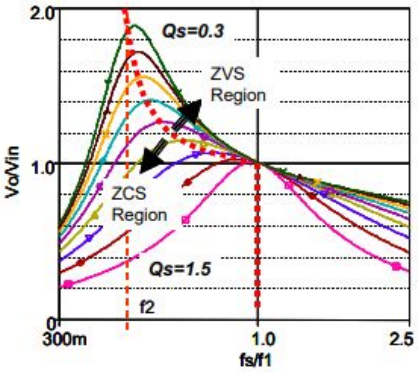
LLC Resonant Converter: Operation and Application

By: Noah Bean and Cade Tillema

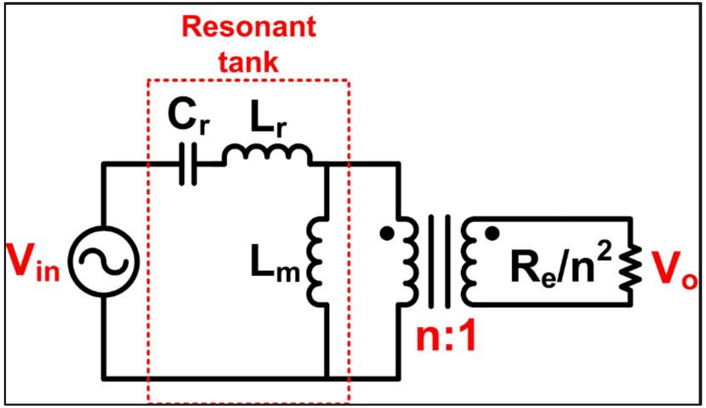
Circuit Functionality

-Makes use of inherent transformer properties

-Resonance



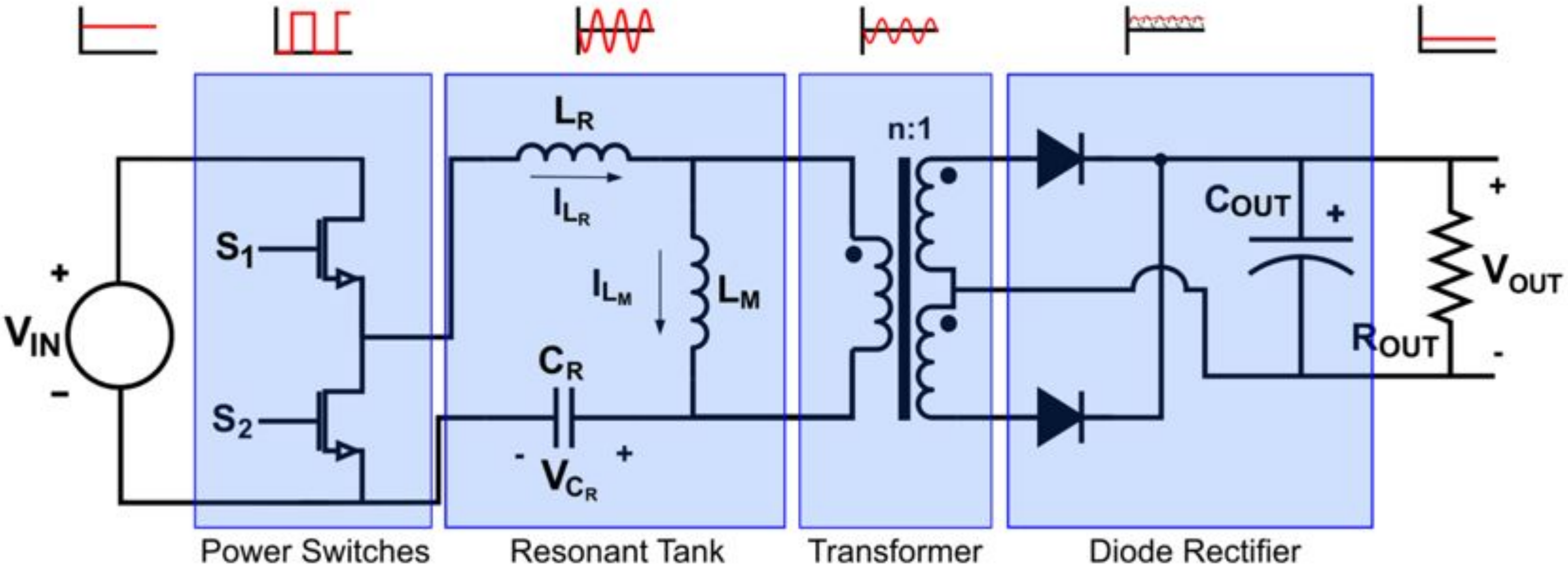
Soft-switching regions [1]



$$f_R = \frac{1}{2\pi\sqrt{L_R \times C_R}}$$

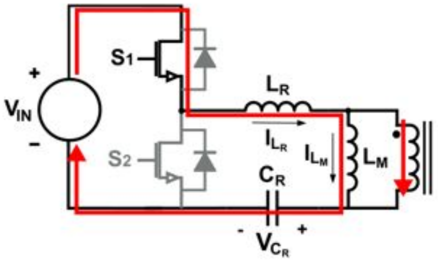
$$f_M = \frac{1}{2\pi\sqrt{L_M + L_R \times C_R}}$$

Circuit Functionality

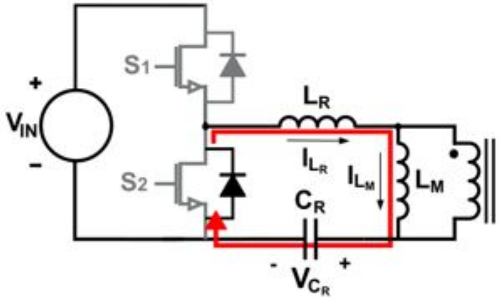


LLC Modes of Operation [1]

Mode 1

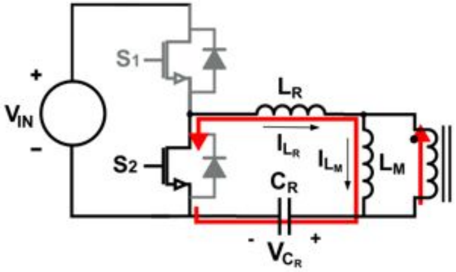


Mode 2

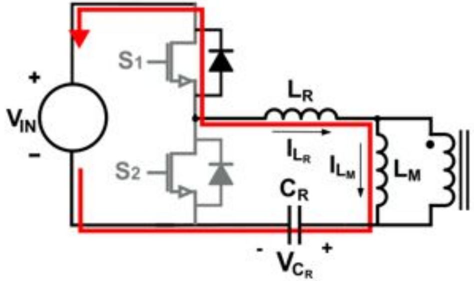


“Dead Period”

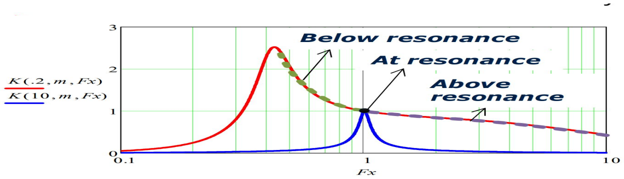
Mode 3



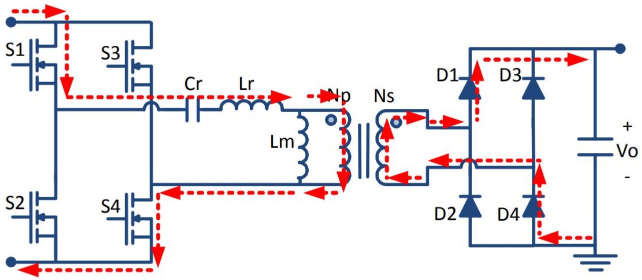
Mode 4

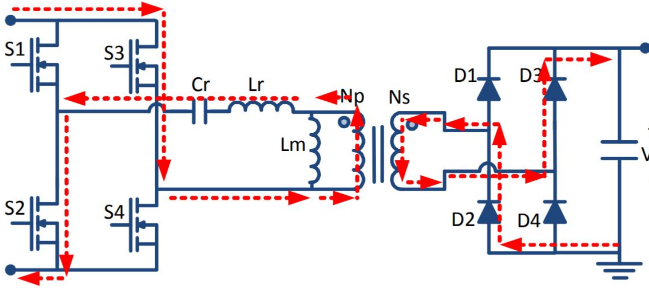


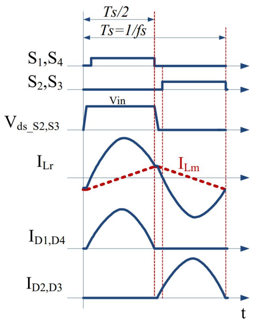
“Dead Period”



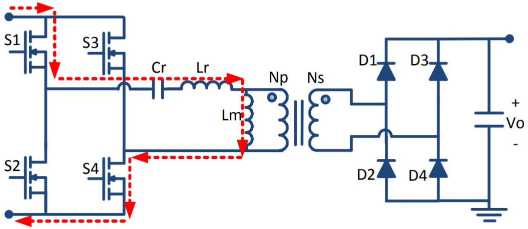
Power Delivery (fs = fr)

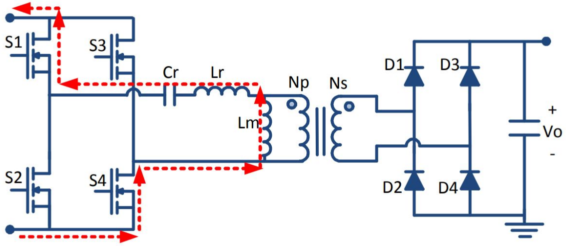


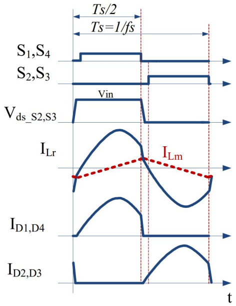




Free Wheeling (fs > fr)

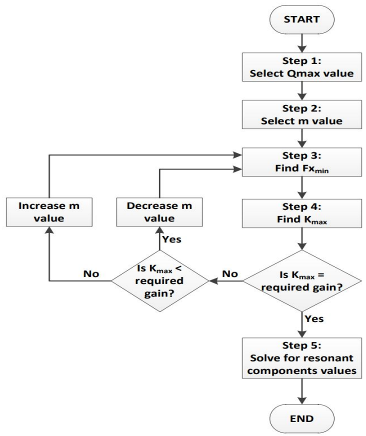






Design Considerations

- Choose Half-Bridge or Full Bridge
- Choose Mode of Operation
  fs = fr -> full power
  fs> fr -> partial power (buck)
  fs < fr (boost)
- Choose values for the Lm, Lr, and Cr
- Chose a control strategy for inverter
- Manage heat dissipation in diodes and MOSFETs



$$Q = \frac{\sqrt{L_r / C_r}}{R_{ac}}$$ Quality factor

$$R_{ac} = \frac{8}{\pi^2} \cdot \frac{N_P{}^2}{N_S{}^2} \cdot R_o$$ Reflected load resistance

$$F_x = \frac{f_s}{f_r}$$ Normalized switching frequency

$$f_r = \frac{1}{2\pi\sqrt{L_r \cdot C_r}}$$ Resonant frequency

$$m = \frac{L_r + L_m}{L_r}$$ Ratio of total primary inductance to resonant inductance

$$K(Q,m,F_x) = \left|\frac{V_{o\_ac}(s)}{V_{in\_ac}(s)}\right| = \frac{F_x{}^2(m-1)}{\sqrt{(m \cdot F_x{}^2 - 1)^2 + Fx^2 \cdot (F_x{}^2 - 1)^2 \cdot (m-1)^2 \cdot Q^2}}$$

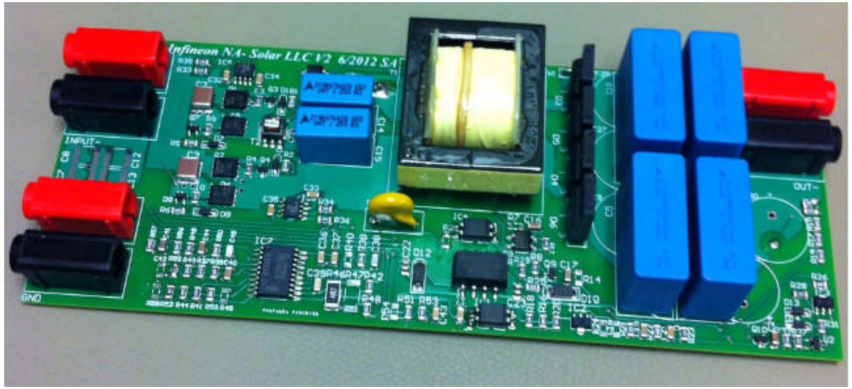
Advantages and Disadvantages

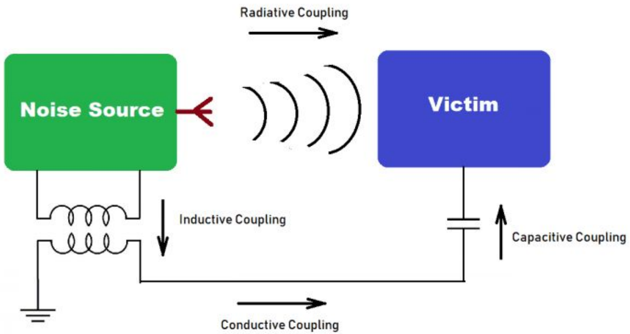
Advantages

- High efficiency (soft switching: ZVS, ZCS)
- Reduced component size (high frequency)
- Wide input voltage range (robust input)
- Reduced electromagnetic interference (EMI)
- Isolated input and output (transformer)

Disadvantages

- Load sensitivity (non-linear)
- Control complexity (inverters)
- System and component cost





Applications

- LED lighting (efficiency)
- Photovoltaic inverters (efficiency)
- Electric vehicle chargers (compact system size)
- Telecommunications (low EMI)
- Data center servers (low EMI)

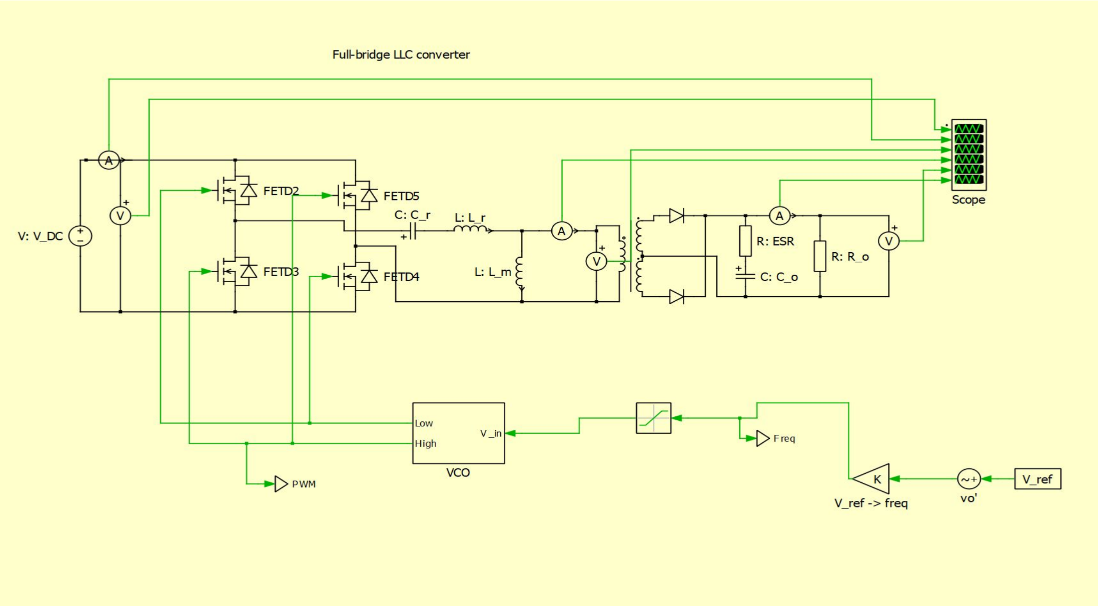
Models

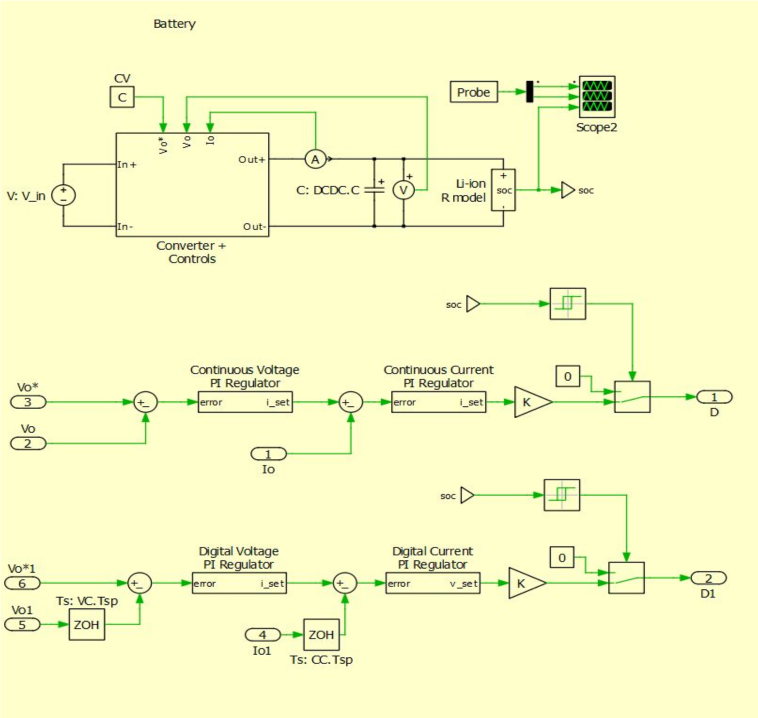
This project aims to design and simulate an LLC resonant converter for an electric car battery

Design Requirments
input voltage vdc = 80 v
output voltage v0 = 22.8 v
switching frequency fs = 100 khz
rated power pr = 5.3 kw
Efficiency n > .9
Iout = 190 A

Component Specifications
lm = 1.4e-4 H
lr = 2.79e-5 H
cr = 9.09e-9 F
Q = 0.5
m = 6
Q_max = 0.4
Rac_min = 35 ohms
N = 10:1

Batttery Specifications for Tesla Model S LithiumIon Battery
Capacity: 232Ah, 5.3kWh,
Voltage nominal: 3.8V/Cell, 22.8V/Module
Charge voltage cut-off: 4.2V/Cell, 25.2V/Module
Discharging cut-off: 3.3V/Cell, 19.8/Module
Maximum Discharging Current (10 sec.):750 Amps

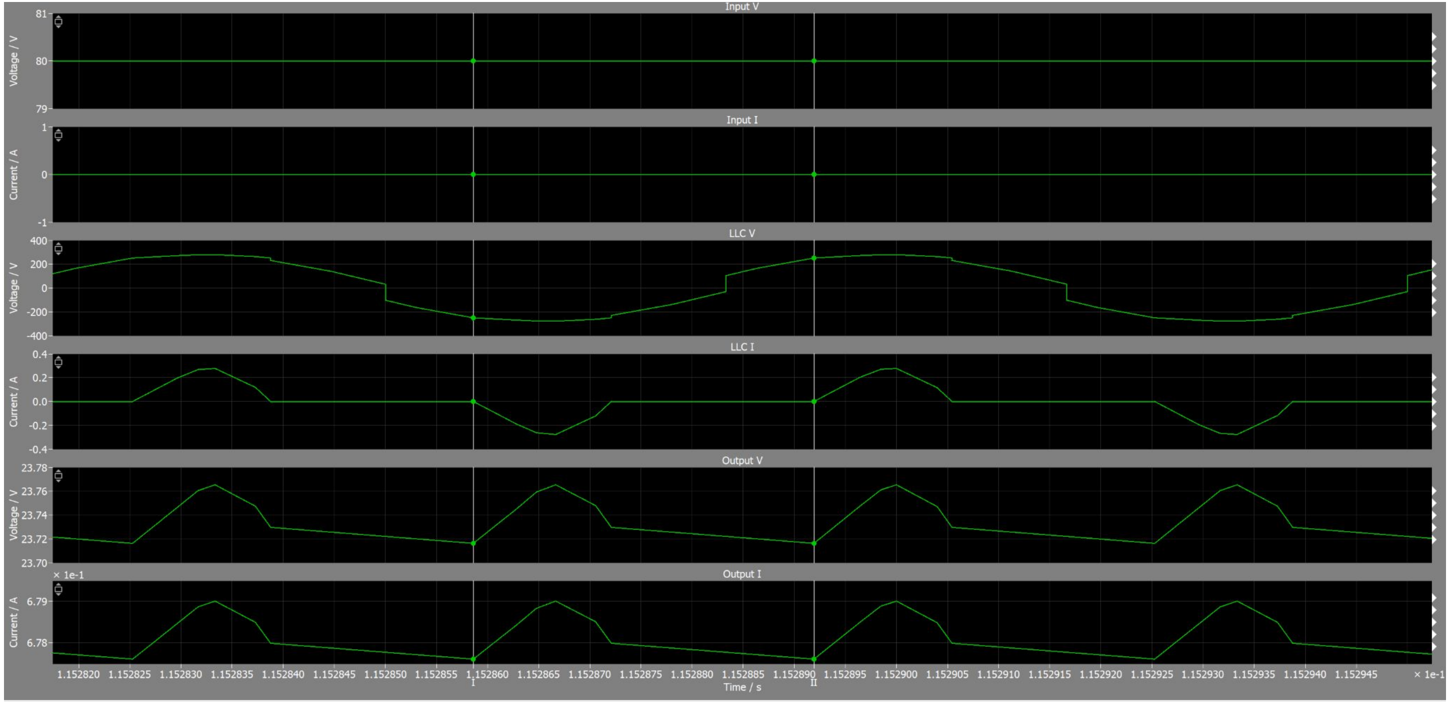




Simulation Results (LLC Converter)

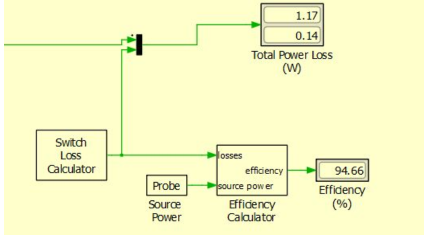
THD of input current
THD meets IEEE 519

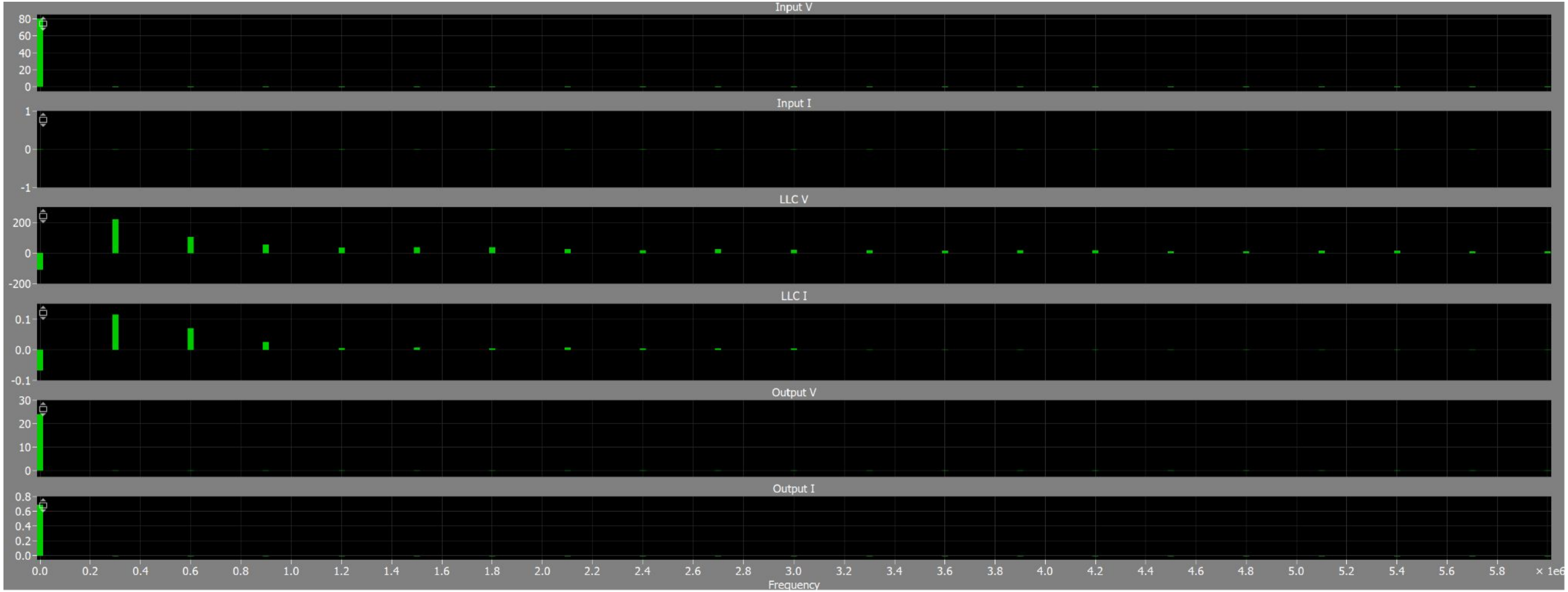
Bus voltage V at PCC	Individual harmonic (%)	THD (%)	Individual harmonic (%)	THD (%)
V ≤ 1.0 kV	5.0	8.0	7.5	12



Data

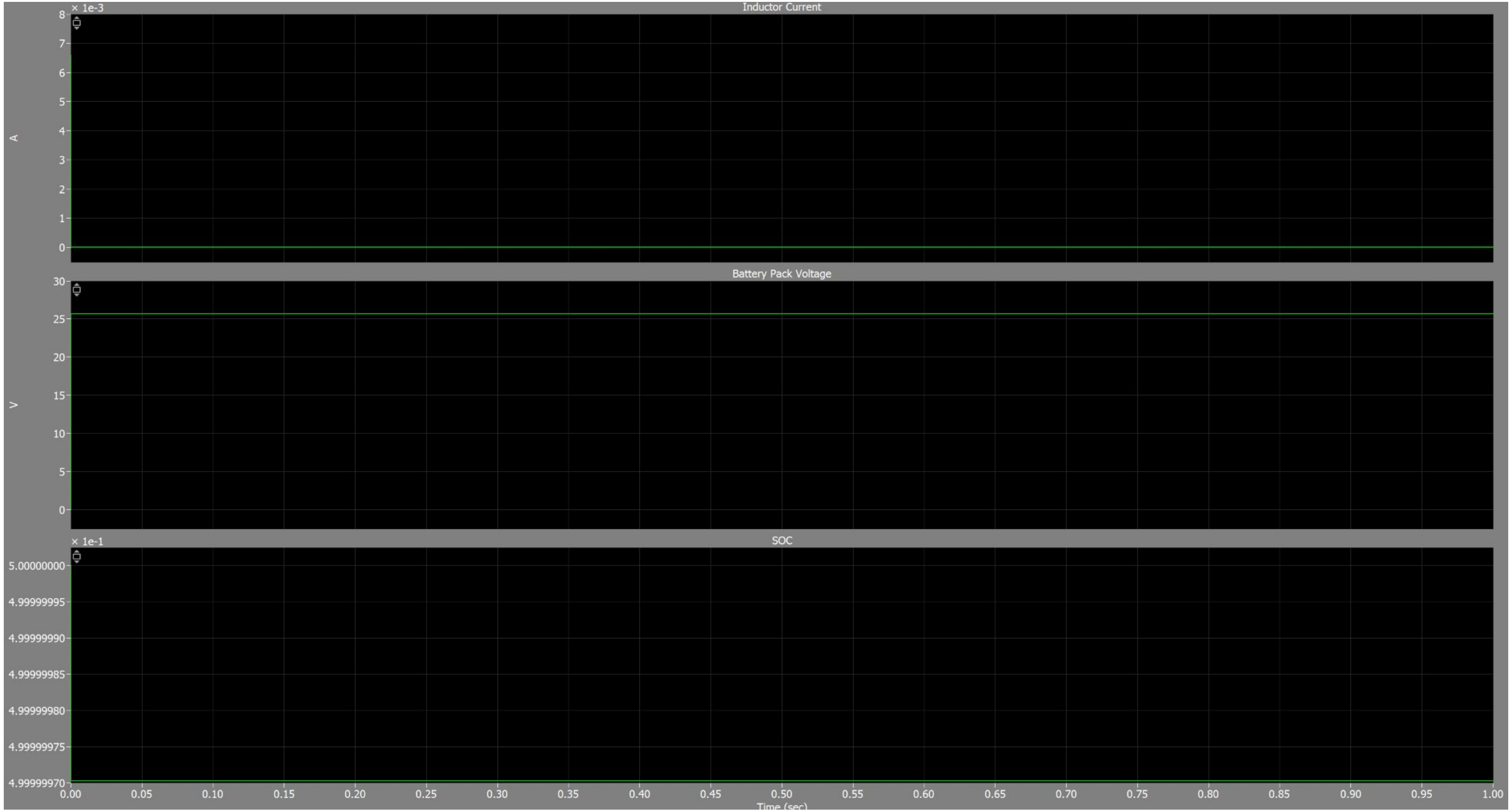
Name	Cursor 1	Cursor 2	Delta	THD
Vm3:Measured voltage	23.7162	23.7162	-1...e-06	0.614303
Output I				
Am2:Measured current	0.677605	0.677605	-3...e-08	0.614303



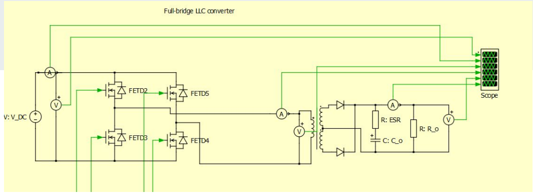


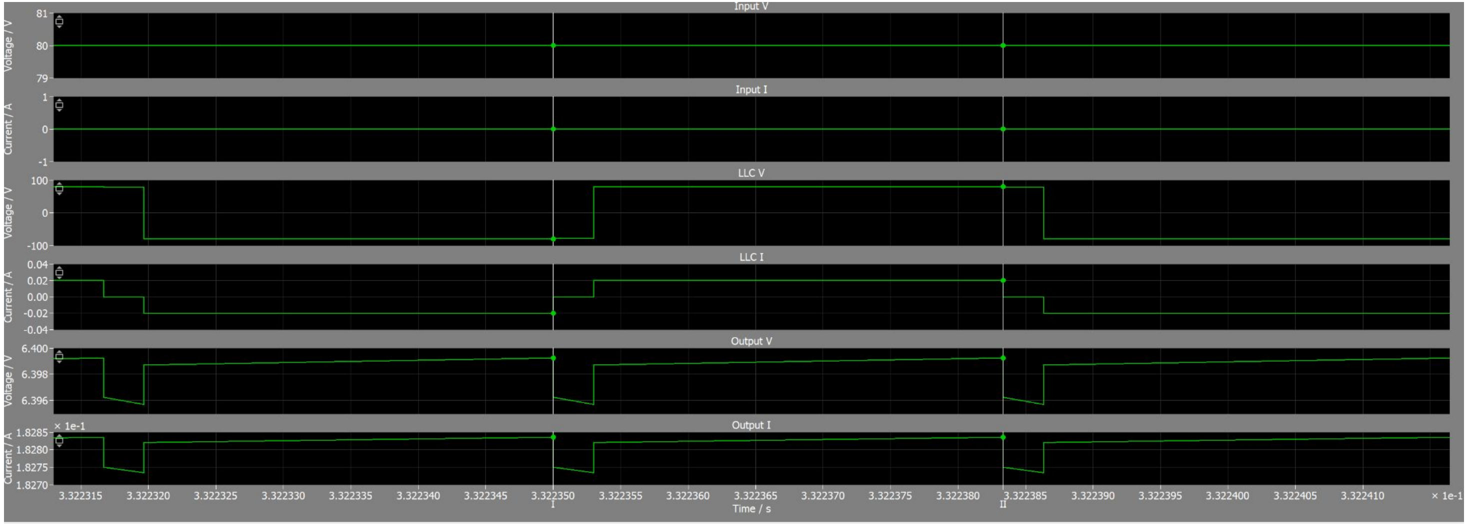
Input V
80
60
40
20
0
Input I
1
0
-1
LLC V
200
0
-200
LLC I
0.1
0.0
-0.1
Output V
30
20
10
0
Output I
0.8
0.6
0.4
0.2
0.0
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0 3.2 3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8 5.0 5.2 5.4 5.6 5.8
× 1e6
Frequency

Simulation Results (Electric Car Battery)



Simulation Results (Without resonant tank)

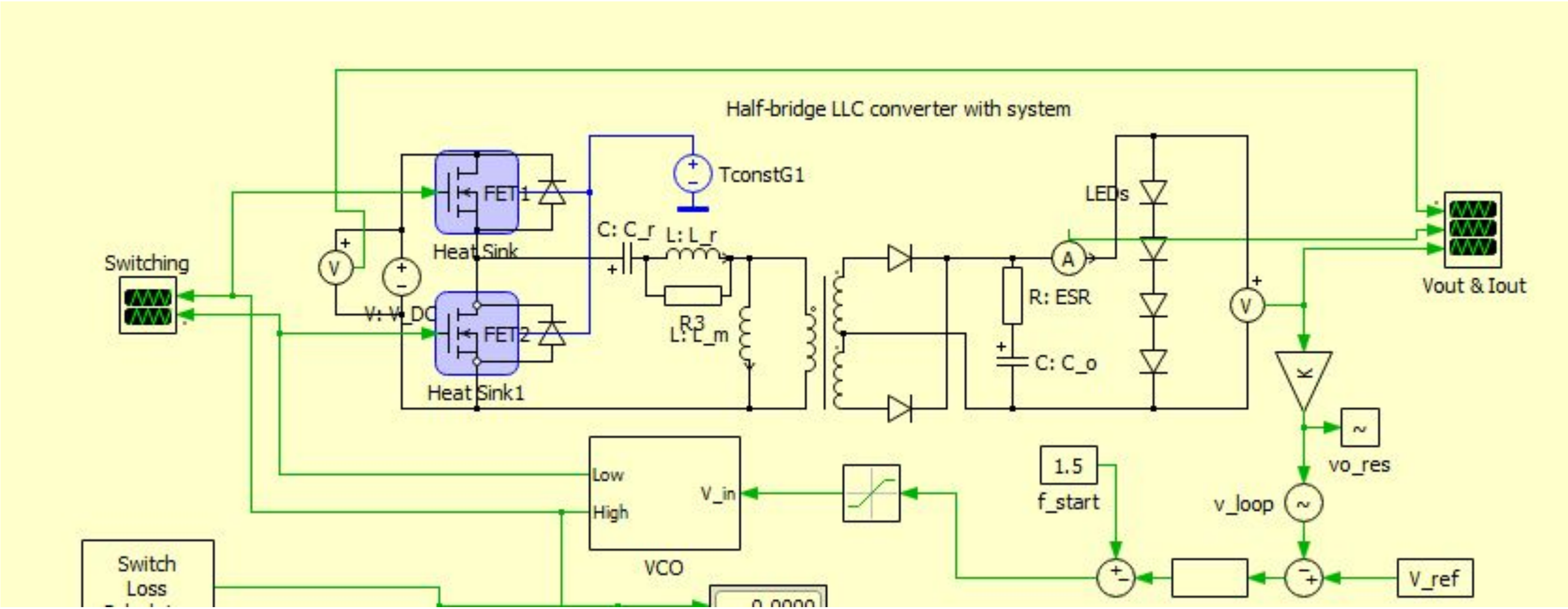




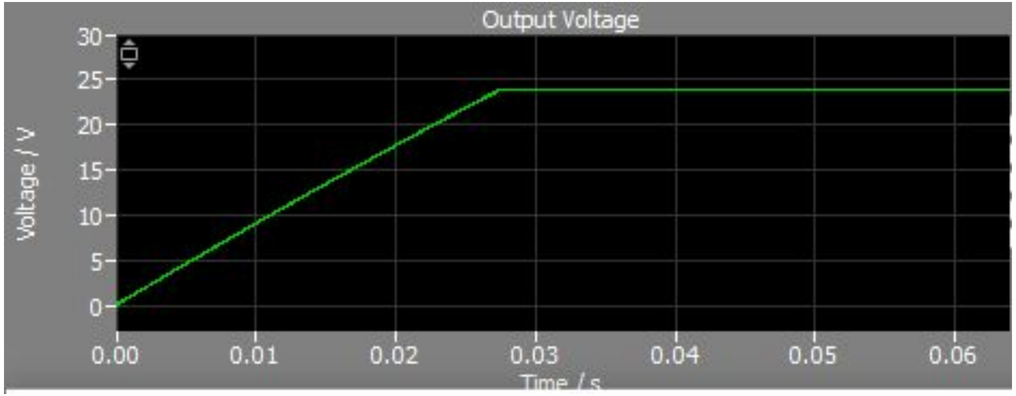
Data

Name		Cursor 1	Cursor 2	Delta	THD
Time		0.332235	0.332238	...e-06	
Input V					
VCO Input Voltage		80	80	0	0
Input I					
Output Current		0	0	0	0
LLC V					
Vm4:Measured voltage		-79.9988	79.9988	-159.998	2.04755
LLC I					
Am1:Measured current		-0.0200...	0.02006...	-0.0401...	2.04757
Output V					
Vm3:Measured voltage		6.39925	6.39925	-8...e-15	1.94208
Output I					
Am2:Measured current		0.182836	0.182836	-2...e-16	1.94208

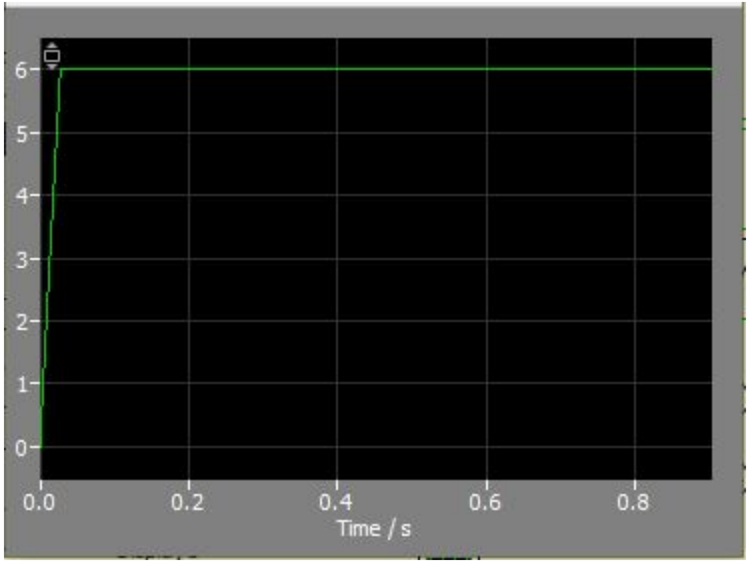
LED Driver Application - Cade



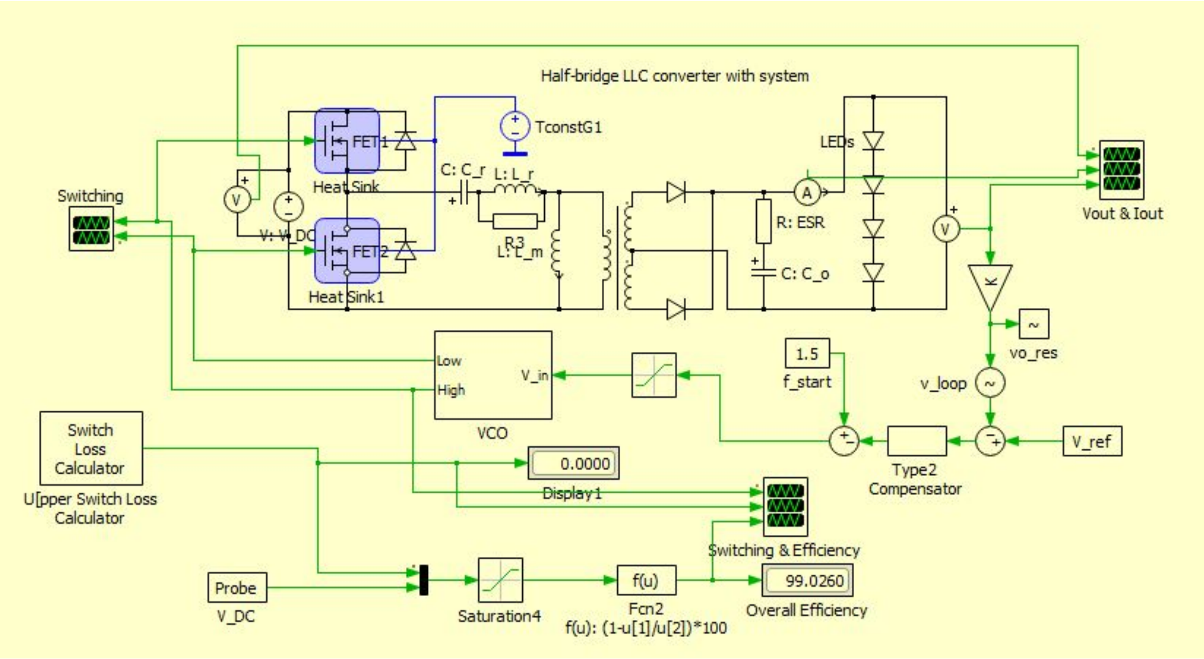
Output Voltage



Voltage across single Diode



LED Driver Application - Cade



Switching Waveform

Conclusion

Noah:

Objective evaluation:

- Design for LLC Resonant converter was successful (THD, output voltage, efficiency)
- Battery Model was successful (SOC, output voltage)
- Integration with battery model and converter was unsuccessful (required changing Matlab Code)

Lessons:

- Learn how to use Matlab for system integration with PLECS initialization
- Learned more about designing circuits and using PLECS

Future Efforts:

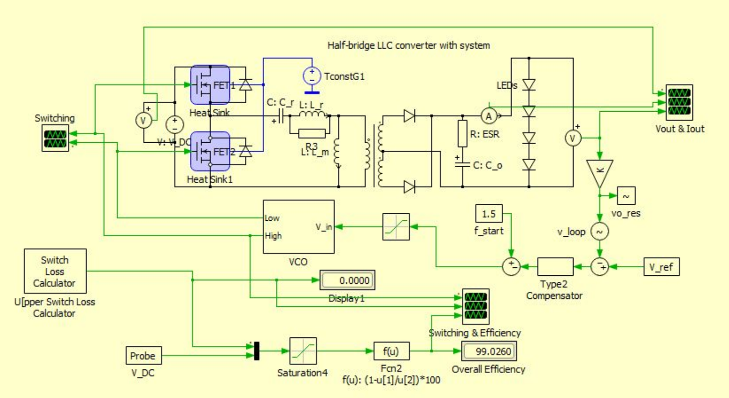
- Investigate control systems
- Investigate magnetic circuit considerations

Conclusion - Cade

-Achieved very high efficiency

-Needed more realistic load

-Learned how to use many different resources



References

[1] Bo Yang, F. C. Lee, A. J. Zhang and Guisong Huang, "LLC resonant converter for front end DC/DC conversion," APEC. Seventeenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.02CH37335), Dallas, TX, USA, 2002, pp. 1108-1112 vol.2, doi: 10.1109/APEC.2002.989382

[2]“Understanding LLC Operation (Part I): Power Switches and Resonant Tank | Article | MPS,” *Monolithicpower.com*, 2022. https://www.monolithicpower.com/understanding-llc-operation-part-i-power-switches-and-resonant-tank

References

[3] S. Abdel-Rahman, “Resonant LLC Converter: Operation and Design 250W 33Vin 400Vout Design Example,” 2012. Available: https://www.infineon.com/dgdl/Application_Note_Resonant+LLC+Converter+Operation+and+Design_Infineon.pdf?fileId=db3a30433a047ba0013a4a60e3be64a1

[4] J. Deng, S. Li, S. Hu, C. C. Mi and R. Ma, "Design methodology of LLC resonant converters for electric vehicle battery chargers", IEEE Trans. Veh. Technol., vol. 63, no. 4, pp. 1581-1592, May 2014

[5] Y. Wei, Q. Luo, Z. Wang and H. A. Mantooth, "A complete step-by-step optimal design for LLC resonant converter", IEEE Trans. Power Electron., vol. 36, no. 4, pp. 3674-3691, Apr. 2021.