LLC Resonant Converter for Electric Car Battery Charger

Noah Bean

## I. Introduction:

The electric vehicle (EV) is a popular transportation option and it requires battery charging systems that can meet novel demands. This project aimed to design and simulate an LLC resonant converter for an electric car battery charger. The LLC resonant converter was invented in 1988 in order to take advantage of softswitching [9]. Some advantages for this topology include high efficiency from softswitching by using zero voltage switching and zero current switching, high energy density through reduced component size, low electromagnetic interference (EMI), wide input voltage range, electrical isolation due to the transformer, and high frequency operation [9]. However, some disadvantages of this converter topology include complicated parameter design due to load sensitivity and complex control design when compared to other converters [9]. Consequently, some novel applications for this technology include electric vehicle (EV) charging due to high energy density, photovoltaic systems due to high efficiency, LED lighting due to high efficiency, LCD TV power supplies, and data center servers due to the low EMI [8] [9].

## II. Proposed Converter and System:

The high-level technical tasks included designing the LLC resonant converter topology and designing a model for the EV battery.

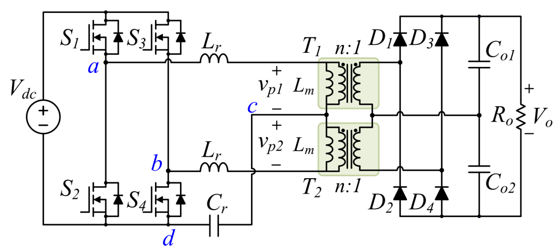


Fig 1: A Diagram of the Proposed LLC Resonant Converter [5]

The LLC converter consists of an inverter, an LLC resonant tank, and a diode bridge rectifier as seen in Fig 1. The switching behavior can be seen in Fig 2 and Fig 3. In maximum power mode, the current flows through the inverter, then through the resonant tank, thus generating alternating current that is rectified by a diode bridge [11]. By containing the resonant tank, the square waves generated by the inverter are smoothed out, thus lowering the THD and increasing the efficiency of the system [11].

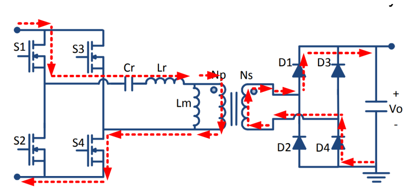


Fig 2: Fs = Fr Full Power Delivery Mode Forward [11]

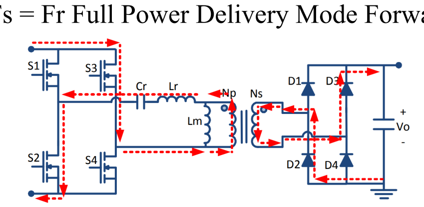


Fig 3: Fs = Fr Full Power Delivery Mode Backward [11]

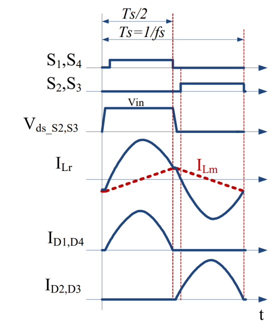


Fig 4: Graph of Full Power Mode Waveforms [11]

This system was optimized for high efficiency, correct output voltage, and compliance with IEEE 519. The efficiency of the system was calculated in PLECS by analyzing the thermal losses of the diodes and MOSFETS. The C4D40120D diodes and C2M0025120D MOSFETS were used due to familiarity and their high quality. The IEEE 519 standard requires that for voltage buses less than or equal to 1 kV, the weekly 95th percentile short time is no more than 8%, and the daily 99th percentile short time is no more than 12% [13]. A full-bridge inverter will be selected since this option reduces current through each individual MOSFET which decreases power consumption when compared to a half-bridge inverter. Compared with other converters, the LLC resonant converter can act in both Buck mode and Boost mode depending on the frequency [4]. if switching frequency is higher than resonant frequency, voltage gain is always less than one, ZVS can be used. When the switching frequency is lower than resonant frequency, both ZVS and ZCS could be achieved [4]. A Full power mode (Fs = Fr) will be used in order to increase the efficiency of the system [4]. A control algorithm for power delivery and battery management was developed by analyzing prefabricated plecs models. Finally, the correct output voltage was designed by using mathematical formulas associated with the LLC resonant converter in order to compute the capacitance and inductance of the resonant tank, the turn ratio of the transformer, and the gain of the resonant tank. The flow chart for this process can be seen in Fig 5.

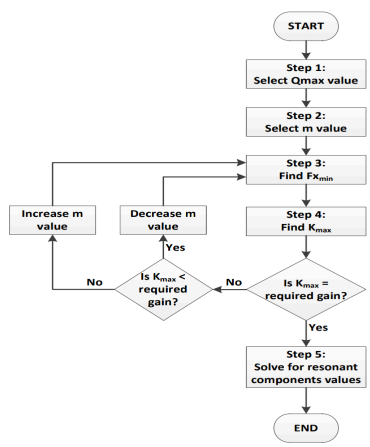


Fig 5: Flow Chart for LLC Resonant Converter Design Process [11]

Fundamentally, the goal of designing the resonant tank is to ensure that the tank gain is appropriate for output voltage consideration.

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

Fig 6: Resonant Tank Gain Equation [11]

The reflected load resistance was calculated as follows with a turns ratio of 100:1 assumed initially:

$$R_{ac} = \frac{8}{\pi^2}\frac{N_p^{\,2}}{N_s^{\,2}} v_0^{\,2} / p_{max}$$

Next, the quality factor was assumed to be Qmax = 0.5 as a standard. The normalized switching frequency was calculated by assuming Fs = Fr for delivering maximum power.

$$F_x = \frac{f_s}{f_r}$$

The quality factor formula in conjunction with the resonant frequency formula, allowed for the computation of Lr and Cr:

$$Q = 0.5 = \frac{\sqrt{L_r/c_r}}{R_{ac}} -> C_r$$

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} -> L_r =$$

Finally, the ratio of total primary inductance to resonant inductance was calculated to find Lm by assuming m = 6 [11]:

$$m = \frac{L_r + L_m}{L_r} -> Lm$$

**III. Example Design and Simulation Results:**

The final design specifications for the LLC converter include an input voltage Vdc = 80 V, an output voltage v0 = 22.8 V, a switching frequency fs = 100 KHz, a rated power pr = 5.3 kw, an Efficiency n > .9, and output current Iout = 190 A. Consequently, component Specifications were decided to be 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 and N = 10:1.

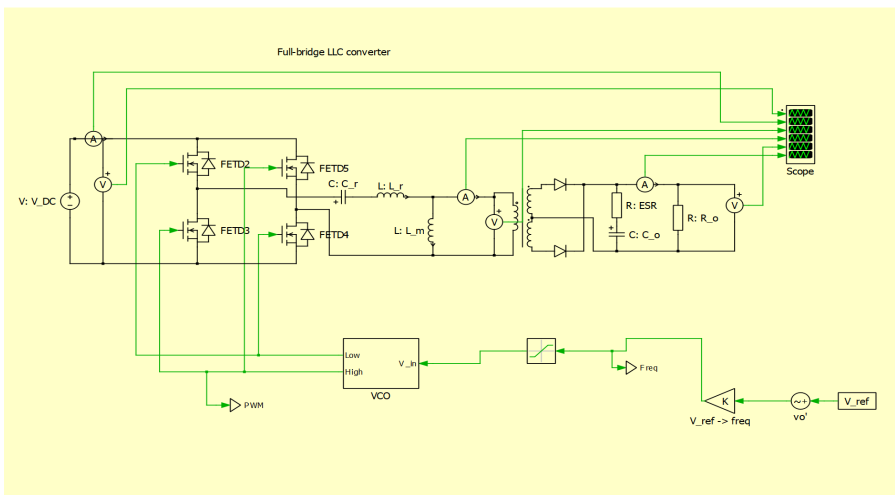


Fig 7: An Image of the LLC Resonant Converter

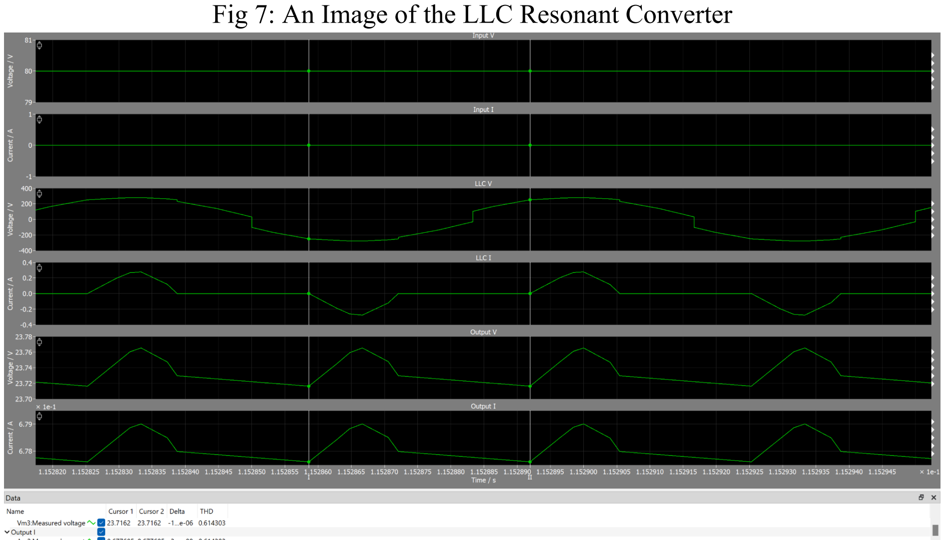


Fig 8: Graph of Converter waveforms

The design specifications for the Tesla Model S Lithium Ion Battery include a capacity of 5.3kWh, a nominal voltage of 3.8V/Cell, 22.8V/Module, charge voltage cut-off of 4.2V/Cell, 25.2V/Module, discharging cut-off of 3.3V/Cell, 19.8/Module, maximum discharging current of 10 seconds, and maximum current of 750 Amps [12]. Therefore, the final component selection included: 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, and N = 10:1.

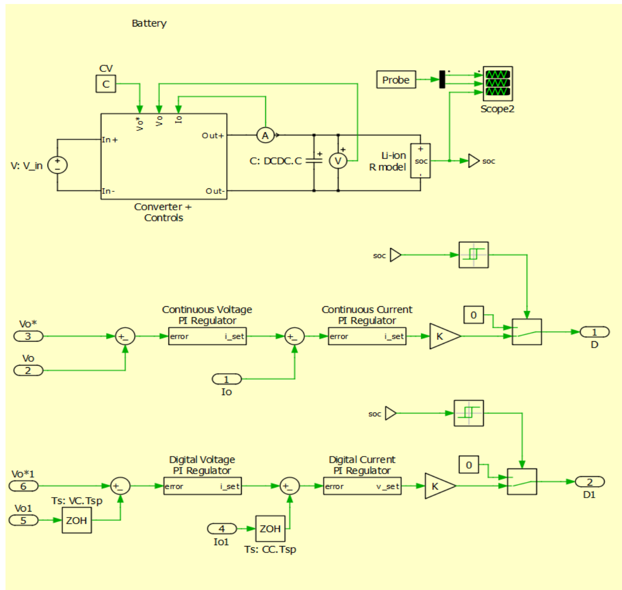


Fig 9: An Image of the Tesla Model S Lithium Ion Battery


Fig 10: Graph of Battery waveforms

**IV. Analysis and Discussion:**

The primary advantages of the LLC resonant converter include reduced EMI, reduced component size, and high efficiency. In order to demonstrate the effectiveness of the resonant tank on THD, the same circuit was developed without the tank. The THD was calculated at the output. This THD was measured as 1.94208 (compared to .641303 with the tank). The waveforms appear to be less smooth and this will affect the EMI rating of the circuit [11].

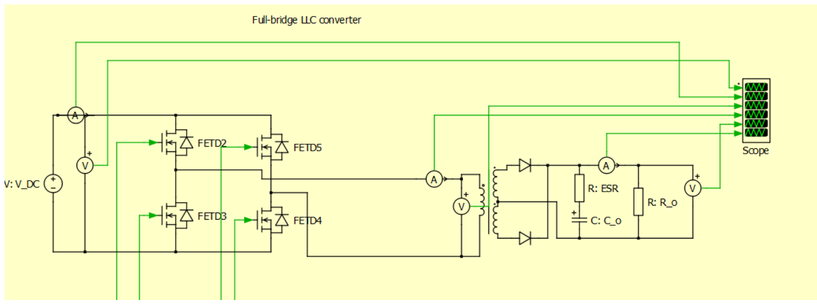


Fig 11: Converter Without the Resonant Tank

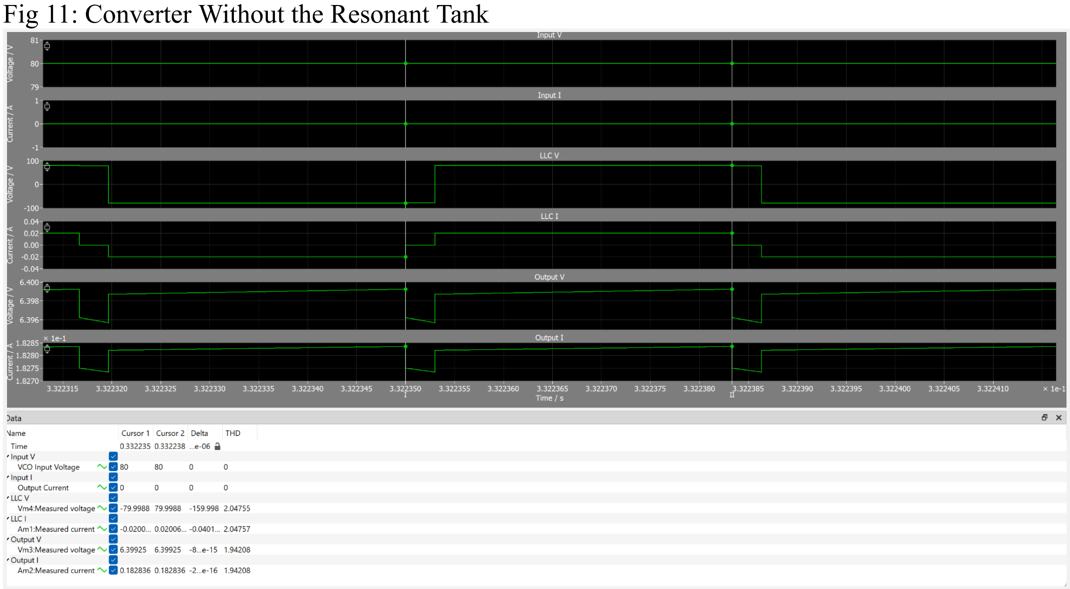


Fig 12: Waveforms for the Converter Without the Resonant Tank

Another usage for this converter is the high efficiency. From the temperature calculations of the model, the converter with the resonant tank was 94.66% efficient, while the converter without the tank was only 31.63% efficient. The converter also had a wide input voltage range with a difference of 10 V yielding appropriate output. The battery model demonstrated acceptable performance for voltage and current levels that would not break the system. However, the power rating was not particularly high, which was disappointing.

**- V. Conclusion:**

In conclusion, the design for LLC Resonant converter was successful with a THD of .61 at the output which complies with IEEE 519, the correct output voltage of 22.8 V to charge the Tesla battery, and an efficiency of 94.66%. The battery Model was partially successful by demonstrating the correct output voltage and power requirement to charge. However, integration between the battery model and the converter was unsuccessful due to difficulties with Matlab initialization code in PLECS. Therefore, some lessons learned from this experience include using Matlab for system integration with PLECS initializations, designing circuits, and using PLECS software. Some future efforts to improve this project include investigating control system design and investigating magnetic circuit considerations.

**References**

[1] F. Musavi, M. Craciun, D. S. Gautam, W. Eberle and W. G. Dunford, "An LLC resonant DC–DC converter for wide output voltage range battery charging applications", IEEE Trans. Power Electron., vol. 28, no. 12, pp. 5437-5445, Dec. 2013.

[2] 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.

[3] X. Fang, H. Hu, Z. J. Shen and I. Batarseh, "Operation mode analysis and peak gain approximation of the LLC resonant converter", IEEE Trans. Power Electron., vol. 27, no. 4, pp. 1985-1995, Apr. 2012.
[4] B. Lu, W. Liu, Y. Liang, F. C. Lee and J. D. van Wyk, "Optimal design methodology for LLC resonant converter", Proc. IEEE 21st Annu. Appl. Power Electron. Conf. Expo., 2006.
[5] L. A. D. Ta, N. D. Dao and D.-C. Lee, "High-efficiency hybrid LLC resonant converter for on-board chargers of plug-in electric vehicles", IEEE Trans. Power Electron., vol. 35, no. 8, pp. 8324-8334, Aug. 2020.
[6] B. Yang, F. C. Lee, A. J. Zhang and G. Huang, "LLC resonant converter for front end DC/DC conversion", Proc. 17th Annu. IEEE Appl. Power Electron. Conf. Expo., vol. 2, pp. 1108-1112, 2002.
[7] 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.
[8] F. C. Lee, Q. Li and A. Nabih, "High-frequency resonant converters: An overview on the magnetic design and control methods", IEEE J. Emerg. Sel. Topics Power Electron., vol. 9, no. 1, pp. 11-23, Feb. 2021.
[9] J. Zeng, G. Zhang, S. S. Yu, B. Zhang and Y. Zhang, "LLC resonant converter topologies and industrial applications—A review", Chin. J. Electr. Eng., vol. 6, no. 3, pp. 73-84, Sep. 2020.
[10] J. Jung and J. Kwon, "Theoretical Analysis and Optimal Design of LLC Resonant Converter", 2007 European Conference on Power Electronics and Applications, 02-05 September 2007.
[11] 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
[12]“Tesla 5.3 kWh Module (85 kWh Pack) | Batteries,” *Stealth EV*. https://stealthev.com/product/tesla-module/

[13] elspec, “Understanding the IEEE 519 – 2014 standard for Harmonics | Elspec,” Jan. 10, 2021. https://www.elspec-ltd.com/ieee-519-2014-standard-for-harmonics/