High Efficiency Battery Charger

A Major Qualifying Project submitted to the Faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Undergraduate Degree of Bachelor of Science in Electrical and Computer Engineering

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Abstract

This project investigates the construction of a high efficiency battery charger, focusing on the implementation of a resonant converter topology, specifically an LLC configuration, to enhance efficiency. It will detail their utility, the three distinct phases that comprise such a converter and their individual functionalities. The project will analyze the various simulations through observing the transient and frequency responses of each circuit. Further work is necessary to improve overall performance with a feedback loop and a microcontroller to interpret the feedback for system regulation.

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Background Research

This section provides a background for understanding the inner mechanisms of a battery charger including; general battery technology; the functionality and topology of chargers; and the role current and voltage sensors play in charging regulation. This section will specifically highlight the benefits lithium iron-phosphate (LiFEPO4) batteries offer when compared to other batteries on the market, such as environmental, safety, reliability, etc. This section investigates key elements found in chargers, and how these elements function individually and interact with the system as a whole. Since a resonant converter was chosen as the project's energy converter, it is fundamental to this project and is heavily detailed throughout this section. Finally, this section aims to detail the importance of voltage and current sensors, and the role they play in charging regulation.

Battery Technology

Battery Types

LiFePO4 Batteries: Why is important for us focusing on this type of lithium battery

Lithium iron phosphate battery technology (LiFePO4 batteries, also abbreviated as LFP batteries) is growing in our day markets, so this would be an interesting type to use in our project since is less popular than other lithium technologies and is newer compared to them.

Other lithium batteries include:

Lithium Cobalt Oxide (LiCoO22)

Lithium Nickel Manganese Cobalt Oxide (LiNiMnCoO2)

Lithium Titanate (LTO)

Lithium Manganese Oxide (LiMn2O4)

Lithium Nickel Cobalt Aluminum Oxide (LiNiCoAlO2)

A brief history

LiFePO4 battery was first discovered in 1996, at the University of Texas Austin by Arumugam Manthiram and John B. Goodenough first identified the polyanion class of cathode materials for lithium-ion batteries. LiFePO4 is a natural mineral of the olivine family (triphylite). Because of its low cost, non-toxicity, the natural abundance of iron, and its thermal stability and safety characteristics this type of battery has gained a considerable market. It has a great electrochemical performance with specific capacity of 170 mA·h/g, or 610 C/g (Coulomb/gram).

Now LiFePO4 ranks top and is known as the safest, most stable and most reliable lithium battery.As of today there are rechargeable LiFePO4 batteries in many applications. LiFePO4 are used in boats, solar systems, electric vehicles, hybrid and non-electric vehicles and more.

LiFePO4 batteries are better for the environment as they are cobalt-free, and cost less than most of its alternatives in the duration of time as they last longer. For these reasons and also the abundance of iron and phosphate, it is believed that this type of battery will have a very bright future.

Advantages/Disadvantages

The LiFePO4 battery has a lower energy density compared to other lithium-ion batteries, that is why it isn't great for smaller applications such as wearable devices like watches. It is best used for applications like solar energy systems, RVs, golf carts, boats, semi-trucks and electric motorcycles and is challenging other technologies by far. This comes as LiFePO4 battery has more than 4x cycle life compared to other lithium-ion batteries. It is also safer than lithium ion and other battery types.

Another big advantage is that LiFePO4 batteries can not only reach 3,000-5,000 cycles or more (usually a rated at 5000 cycles), they can reach 100% depth of discharge (DOD). This is a great advantage when compared to other batteries because there is no need to worry about over-discharging the battery. This also adds to its usage capacity. It can be used. for a longer period of time as a result. In fact, you can use a quality LiFePO4 battery for many years longer than other battery types. It's rated to last about 5,000 cycles. That's roughly 10 years. So the average cost over time is much better.

Safe, Stable Chemistry

Another important viewpoint of comparison when it comes to Lithium batteries is safety. We know that lithium is a very unstable element and also there are many cases when explosions or fires have been caused by lithium-ion laptop or mobile phone batteries. One of the most important advantages LiFePO4 has over other battery types is safety. LiFePO4 is the safest lithium battery type. This is because lithium iron phosphate LifePO4 has better thermal and structural stability. This is something the lead acid battery type and most other battery types don’t have at the level LiFePO4 does. LiFePO4 is incombustible. It can withstand high temperatures without decomposing. It’s not prone to thermal runaway and will keep cool at room temperature. If a LiFePO4 battery is subjected to harsh temperatures or hazardous events (like short-circuiting or a crash) it won’t start a fire or explode, and this makes it very preferable for usage in many applications.

Environmental Safety

A growing demand for protecting our planet makes the LiFePO4 batteries a preferable choice not only because they’re rechargeable, but also because unlike lead acid and nickel oxide lithium batteries, they are non-toxic and do not leak. Also, when it comes to recycling the LiFePO4 batteries don’t need to be recycled as often as other lithium technologies as they last more, a good quality lasts about 5000 cycles compared to lead acid batteries last only 300-400 cycles or other Lithium-ion batteries lasting 500-1000 cycles.

LiFePO4 batteries are also lightweight compared to other battery technologies. They’re almost 50% lighter than lithium manganese oxide batteries and 70% lighter than lead acid batteries. This makes them a perfect choice when it comes to hybrid vehicles as this will mean less gas usage due to less weight.

Comparison to other types of batteries

Lead Acid Batteries

Lead acid batteries may be a bargain at first, but they’ll end up costing you more in the long run. That’s because they need constant maintenance, and you must replace them more often. A LiFePO4 battery will last 2-4x longer, with zero upkeep needed.

Gel Batteries

Like LiFePO4 batteries, gel batteries don’t need frequent recharging. They also won’t lose charge while stored. A big factor in favor of LiFePO4 is the charging process as they charge much faster than Gel batteries. Also, for gel batteries, you must disconnect them when 100% charged to avoid ruining them.

AGM Batteries (Absorbed glass mat)

When compared to AGM batteries LiFePO4 is clearly a winner as they will damage themselves if you drain them past 50% battery capacity. LiFePO4 Ionic lithium batteries can be discharged completely with no risk of damage.

Our battery choice

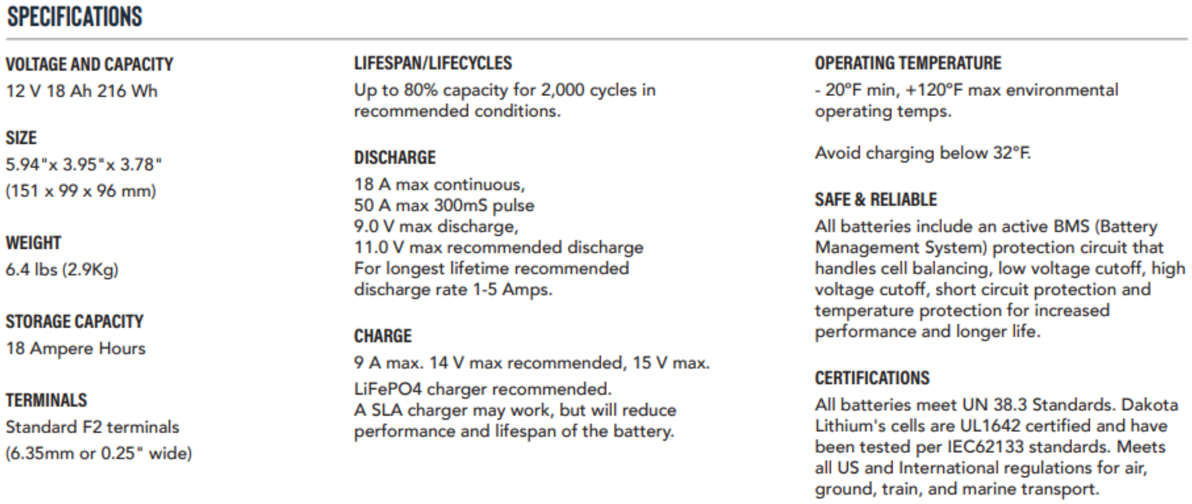
After reviewing many options of LiFePo4 batteries in the market we concluded that for our project would be suitable to use the DAKOTA LITHIUM 12V 18Ah BATTERY. This decision was made due to many reasons taking into consideration that we are doing a scalable project which can be upgraded further in time and compared to the quality and cost this manufacturer was offering the best product for our purpose. Below is an image and some of the specifications of the battery taken from the vendors website.

Figure 1: Selected Dakota 12V LiFePO4 Battery (Dakota Lithium website)

In the website datasheet this battery is described as the following,

> "These 12 Volt 18 Amp Hours lithium battery packs more energy in a small package. Engineered in a 12Ah SLA case, but with 18Ah of Lithium Iron Phosphate (LiFePO4) technology, this battery has three times the power, half the weight, and lasts 4 times longer than a 12Ah sealed lead acid battery – providing exceptional performance and lifetime value. Optimal performance down to minus 20 degrees Fahrenheit (for winter warriors). 18 Amp hours of capacity provides a full day of power for high amp draw electronics like Garmin fish finders, ice augers, or anything where you need a longer run time. Same performance as our legendary 10 Ah battery, but with 80% more capacity. Compared to 12Ah SLA (lead acid) batteries (same size, physical dimensions & terminals) but with three times (3X) longer run time. 12V LiFePO4 charger recommended."

Below are shown some of the specifics from the company website.



SPECIFICATIONS

VOLTAGE AND CAPACITY
12 V 18 Ah 216 Wh

SIZE
5.94"x 3.95"x 3.78"
(151 x 99 x 96 mm)

WEIGHT
6.4 lbs (2.9Kg)

STORAGE CAPACITY
18 Ampere Hours

TERMINALS
Standard F2 terminals
(6.35mm or 0.25" wide)

LIFESPAN/LIFECYCLES
Up to 80% capacity for 2,000 cycles in recommended conditions.

DISCHARGE
18 A max continuous,
50 A max 300mS pulse
9.0 V max discharge,
11.0 V max recommended discharge
For longest lifetime recommended discharge rate 1-5 Amps.

CHARGE
9 A max. 14 V max recommended, 15 V max.
LiFePO4 charger recommended.
A SLA charger may work, but will reduce performance and lifespan of the battery.

OPERATING TEMPERATURE
- 20°F min, +120°F max environmental operating temps.

Avoid charging below 32°F.

SAFE & RELIABLE
All batteries include an active BMS (Battery Management System) protection circuit that handles cell balancing, low voltage cutoff, high voltage cutoff, short circuit protection and temperature protection for increased performance and longer life.

CERTIFICATIONS
All batteries meet UN 38.3 Standards. Dakota Lithium's cells are UL1642 certified and have been tested per IEC62133 standards. Meets all US and International regulations for air, ground, train, and marine transport.

Figure 2: Dakota LiFePO4 Specification Sheet (Dakota Lithium website)

Applications intended to charge will be for Electric vehicles, medical equipment or variety of applications using LiFePO4 battery technology.

Chargers

In this section, the team investigates the key components that comprise a battery charger, detailing their functionality and contributions to the system. Researched components include EMI filters, different DC-DC converters, and microcontrollers. We discuss each module's specific role and significance, and detail how their circuit design allows them to contribute to the overall system. EMI filters are essential for mitigating noise that comes from an AC power supply. This reduces electromagnetic interference that can disrupt the system's stability. DC-DC converters are crucial for stepping-down the supply voltage to the required level for the load. Since different charging systems utilize different DC-DC converters, the team identified two different converters: buck and resonant converters. We evaluated the benefits of each configuration to determine which one is best for our system. The microcontroller and respective feedback loop are key components of the regulation process. The feedback loop collects voltage or current data at the load, and transfers this information to the controller. This feedback is processed by the controller to implement the appropriate charging phase, such as constant current (CC) and constant voltage (CV). It may also serve as a failsafe and shutdown the system if any undesirable conditions are introduced, such as high temperature, overload of current or voltage, etc. This section aims to provide an understanding of how these components allow a system to charge a battery. It will explore the function of each individual component, how they are designed, and the considerations we will make in our own design process.

EMI Filters (Electromagnetic Interference Filters)

EMI Filters are electrical devices or circuits used to diminish the high-frequency electromagnetic noise which is generated from different electronic devices such as electric motors, power supplies, electronic controls, inverters, microprocessors, clock circuits. The frequency range of this electromagnetic noise usually ranges from 9KHz-10GHz which can affect signal transmissions and electronic devices performance. Most electronic devices include an EMI filter or fixed within circuit boards. EMI Filters for power supply includes passive components like capacitors and inductors which are connected to make LC circuits. The inductors allow low-frequency currents or DC to supply through while blocking the unnecessary high-frequency currents. Capacitors provide a low-impedance lane to redirect the noise away from EMI filter into the GND connection.

Applications of EMI filters

- Military or Aerospace systems and subsystems
- Energy Management Systems
- Test Chambers or Shielded Rooms
- Appliances
- MRI Rooms
- Computers
- Automotive Battery Charger
- Factory Automation Equipment
- Exercise Equipment
- Industrial Equipment
- Medical Imaging or Diagnostic/Patient Devices

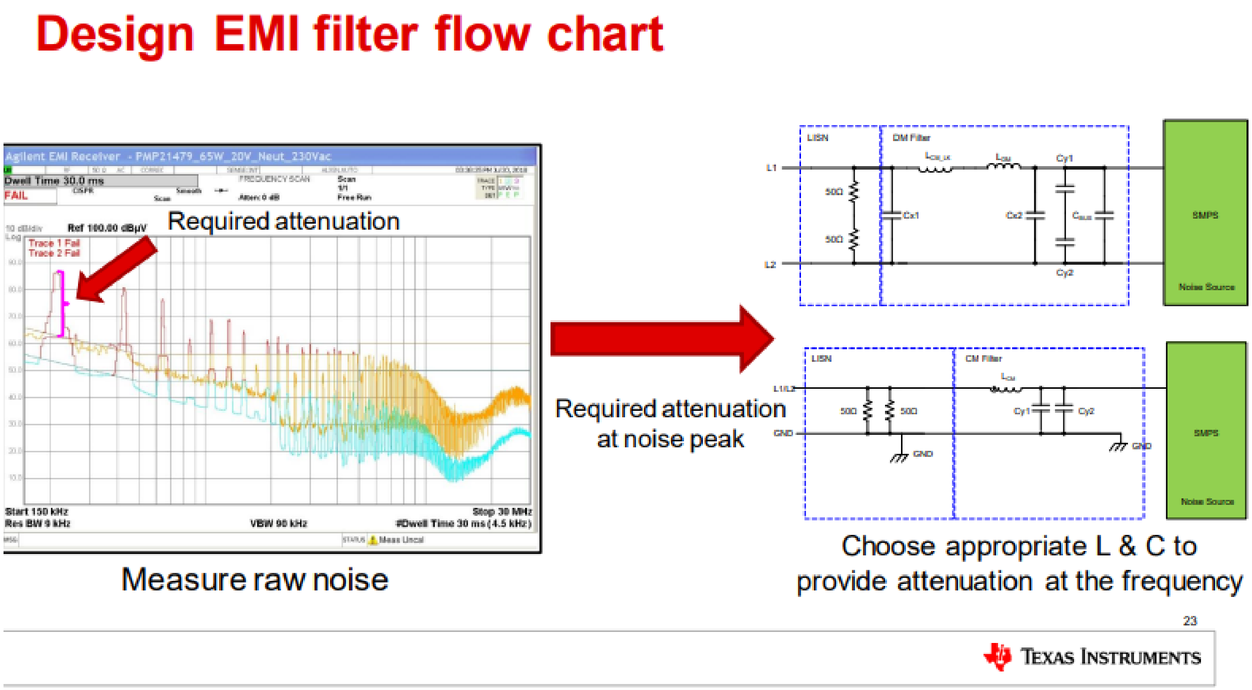
Types of EMI Filters

Active EMI Filters

Active EMI Filters are mainly designed with active components such as op-amps combined with passive components to attenuate low-frequency and achieve desired filtering. Active EMI filter is used to detect the noise from the current transformer and amplifies then injects it back throughout an RC branch coupled to an op-amp circuit. These filters play a key role in low-level circuits as compared to high voltage or high input current AC power circuits. However, the active components can be a limiting factor in governing the EMI suppression as these components have some well-defined bandwidth. The bandwidth effectivity of these filters can be restricted relative to passive filters. This is the main reason why we are choosing to use the other type of EMI filter for our application, which is passive.

Passive EMI filters

Passive EMI filters include capacitors and inductors which are connected circuits to get the desired filtering. Compared to active filters, a passive EMI filter consumes less power, has lower-cost components and when cascaded provides multi-band filtration. Filtering behavior can be easily predicted using basic series and parallel impedance equations. The simplest type of passive EMI filters are L and C filters. These filters can be placed in any critical circuit or on the input of any critical component to remove noise at a broad range of frequencies. There are more complex configurations of passive EMI filters – LC filter, CL filter, T – filter, and Pi filter. Out of these configurations, Pi, and T- filters are best used with low and high-source or load impedances, respectively. Figure 3 shows a Design filter flow chart explained by Texas Instruments.



Design EMI filter flow chart

Required attenuation

Measure raw noise

Required attenuation at noise peak

Choose appropriate L & C to provide attenuation at the frequency

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Texas Instruments

Figure 3:Design flow chart of EMI. (Texas Instruments)

Buck converters

The Buck Converter is a direct current dc-to-dc converter designed for step-down conversion of a given dc input. This means that the fixed dc input applied to the Buck Converter is reduced to a specific dc output voltage, always lower than the input voltage. Hence, the Buck Converter is also referred to as a step-down converter.

Efficient power conversion in the Buck Converter makes it a preferred choice for smaller electronic devices. It finds widespread application in Switched-Mode Power Supplies (SMPS) where the required output dc voltage is less than the input dc voltage.

Various semiconductor devices such as power MOSFET, power BJT, IGBT, and GTO are used as switches in Buck Converter circuits. Power MOSFET or IGBT can be turned off by maintaining zero potential between the gate and the source terminal of power MOSFET or the gate and the collector terminal of IGBT.

Operating Principle of Buck Converter

The operation of the buck converter is based on the principle of storing energy in an inductor. The voltage drop across an inductor is proportional to the change in the electric current flowing through the device. A switching transistor is used in between input and output for continuous switches on and off at high frequency. To maintain a continuous output, the circuit uses the energy stored in the inductor.

The circuit diagram for a typical buck converter is shown in figure 4 below.

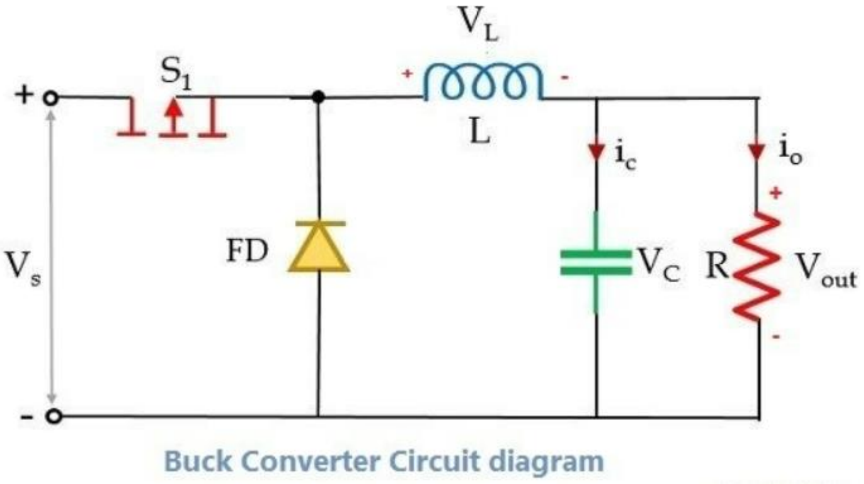


Figure 4:Buck Converter Circuit Diagram (Subedi, 2023)

In this circuit, the input voltage is connected to a controllable solid-state device which operates as a switch. In circuit diagram represent that switch which is power MOSFET. There is another switch used in the circuit which is a diode (FD). The switch and diode FD are connected to a low pass LC filter to reduce current and voltage ripples, which help generate regulated dc output.

Here, the load is purely resistive load. The input voltage and current through load are constant. And the load can be seen as a current source.

The controlled switch is turned on and off by using PWM (Pulse Width Modulation). PWM can be time-based, or frequency based. Time-based Modulation is mostly used for buck converters because it is simple to construct and use. The frequency remains constant in this type of PWM modulation. Whereas Frequency-based modulation has a wide range of frequencies to achieve the desired control of the switch and has a complicated design for the low-pass LC filter.

There are two modes of operation of the Buck converter. They are:

Mode I: Switch1 is ON and Diode FD is OFF

Mode II: Switch1 is OFF and Diode FD is ON

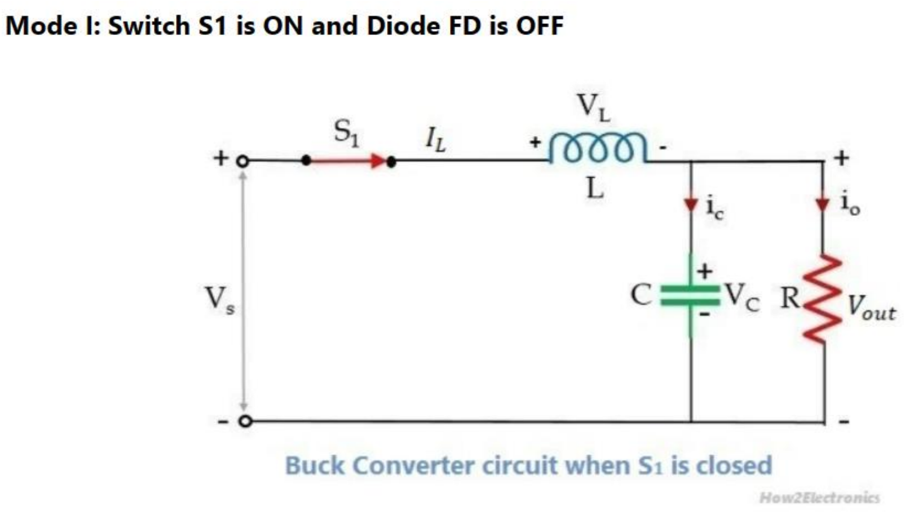


Figure 5:Buck Converter Circuit Diagram (Subedi, 2023)

In first mode the inductor stores energy as the diode does not permit current to flow and acts as an open circuit. The polarity is as shown in figure 5 above.

Mode II: Switch S1 is OFF and Diode FD is ON

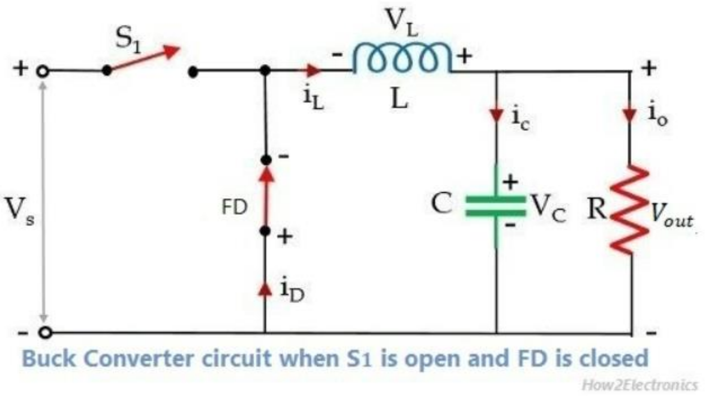


Figure 6: Buck converter switch off state (Subedi, 2023)

On the second mode when the switch is off the current flowing on the inductor will drop and the magnetic field will collapse, and the inductor will switch polarities as shown in figure 6 above acting as a current source. The current will flow through the capacitor and through the load. At this mode the diode will be forward biased and acts as a short circuit. Both the inductor and the capacitor will discharge through the resistor increasing the current.

By analyzing the circuits above, we get that the voltage output is dependent on the duty cycle and the duty cycle is given by time the switch is on over the total time (Subedi, 2023)

$$D = \frac{T_{on}}{T}$$

Applying KVL in the above circuit, we get:

$$D = \frac{V_{out}}{V_s}$$

We know that by controlling the duty cycle D we can hence produce a desired output voltage lower than the input voltage. In this way buck converter steps down the input voltage.

Below is represented the waveforms of a buck converter

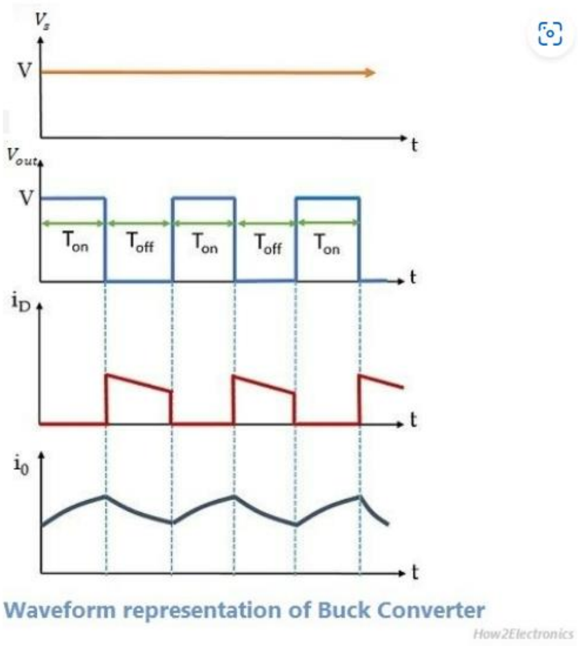


Figure 7:Waveforms of input and output of buck converter (Subedi, 2023)

The 1st graph is the voltage source, the 2nd graph is the voltage in the load Vout as the switch is on and off. The last two represent the current in the diode and the current through the load.

Resonant Converters

Resonant converters are a common DC-DC converter used in various technological applications, including servers, communication systems, consumer electronics, and automotive chargers. Resonant converters are used in this wide array of applications due to their efficiency in high-power and high-frequency operations, and their compact size. A resonant converter is composed of three distinct elements: a switch network, a resonant tank, and a rectifying network. Together, these components produce high-efficiency systems and utilize a technique known as soft-switching. This method is designed to reduce power loss by introducing an intentional overlap during switch network transitions that minimizes energy dissipation and abrupt changes in voltage and current (Ikimi, 2021). For soft-switching, a key condition to understand is circulating current to, “charge or discharge the parasitic capacitors of the switching elements (MOSFET) during switching dead time” (Yu, 2018), which is further discussed in the switch network section. Another attraction to resonant converters is their use of transformers with magnetizing and leakage inductance, as this leads to a lower component count and reduced cost of construction (Huang, 2010). While resonant converters offer advantages such as increased efficiency and lower construction cost, they require a much more complex and demanding design process. Other DC-DC converters, including buck, regulate voltage and current through pulse width modulation (PWM). However, resonant converters achieve regulation through frequency modulation (FM). In a PWM converter, the input-to-output voltage gain can be determined through the inductor volt-second balance. Whereas the gain of an FM converter cannot be determined through the inductor, making them much more complex compared to PWM. Further in the section, we will investigate the logistics of frequency modulation. This section of the report aims to provide a comprehensive analysis on the functionality of resonant converters and their elements.

Resonant converter topology

This section will discuss the three elements that compose a resonant converter: a switch network, resonant tank, and rectifying network. The switch network is responsible for receiving a pulsating DC signal and transforming that into a high frequency square wave that can then be fed into the resonant tank. The resonant tanks, consisting of inductors and capacitors in several unique configurations, adjust the amplitude of its gain by varying the frequency of the pulsating signal the tank receives. The output of the resonant tank is then fed into the rectifying network, which is responsible for rectifying the received signal, that is to transform the received signal into a constant DC voltage.

Figure 8:Resonant Converter Topology Plot (Yu, 2018)

Switch Network

The starting element of a resonant converter, the switch network, plays a critical role as the initial stage of the energy conversion process. Constructed from dual transistors, the switch network acts as a filter for the received pulsating DC signal, manipulating switching frequency to reduce power loss and increase overall system efficiency. This efficiency is achieved through a technique known as soft switching. Soft switching is a technique that introduces an intentional overlap or delay during the transistor's switching transitions. This section aims to provide a detailed examination on the functionality of a switch network and the precise mechanisms of it.

A common switch network is constructed with two parallel transistors, typically MOSFETS, that are on the opposite polarities of the voltage or current source. This configuration, shown below in figure 9, allows the switch network to serve as a square wave generator for the resonant circuit. This wave is produced through alternating switches Q1 and Q2 at a specified switching frequency. This control of the specified switching frequency is the main advantage of resonant converters, as it enables them to achieve soft switching. This technique introduces an intentional overlap or delay during the transistor's switching transitions, designed to minimize the abrupt changes in voltage and current during the switching process. Given the significance soft switching has on the system's operation, it is important to have a sufficient understanding of the concept and the conditions for achieving it (Huang, 2010).

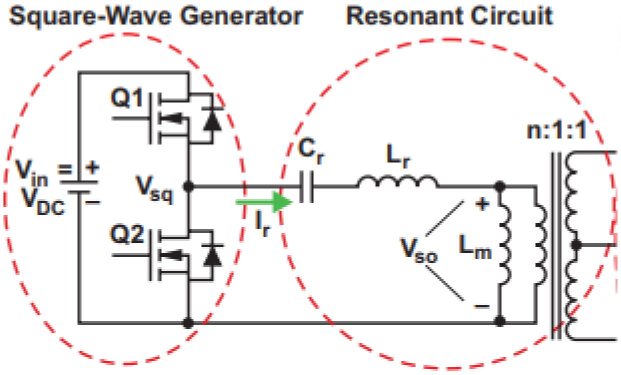


Figure 9:A dual switch network, serving as a square wave generator.

Soft switching can be more precisely described as *zero-voltage switching* (ZVS). ZVS, as the name implies, means that before a transistor turns on it must reach zero voltage. Implementing ZVS allows a system to operate more efficiently and avoid undesirable effects. Switching a device while the voltage across it is zero minimizes the energy dissipated during the switching transitions. If a switch turns on under non-zero conditions, there is potential for significant power losses across the device. ZVS also minimizes the stress applied to the switch itself and the overall system, as switching under non-zero conditions can harm the device leading to reduced reliability and potentially break the device (Yu, 2018). Through minimizing switching losses and maintaining system reliability, ZVS provides improved system performance and control over the voltage flow. For a switch network to achieve ZVS, there must be a current present to completely discharge MOSFET's output capacitor before it is turned on. There are three different conditions that must be met: inductive input impedance, there is sufficient energy stored in the resonant tank, and there is sufficient dead-time between the two switches.

One condition of ZVS is inductive input impedance. As discussed, the device must be at zero voltage and there must be a current present when the device is switching on. Therefore, current is lagging the voltage. This means having an inductive resonant tank within the desired frequency range will ensure the current does not drop to zero during the turn on transition. In addition to inductor impedance, the second condition that must be met is that sufficient energy is stored in the resonant tank. This concept allows the tank to maintain a constant current flow between the turn-on and turn-off phases, which prevent/minimize abrupt spikes that will cause undesirable effects on the transmitted waveform. To ensure this condition is met, there must be more energy stored in the resonant tank than the energy stored in the MOSFET (C_{OSS}). Referencing figure 6, the equation below is, “the worst case-equation for this LLC-SRC to achieve ZVS,” (Yu, 2018).

$$L_M I_{LM(Peak)}^2 > C_{oss} V_{DS(Q1)}^2$$

(Yu, 2018)

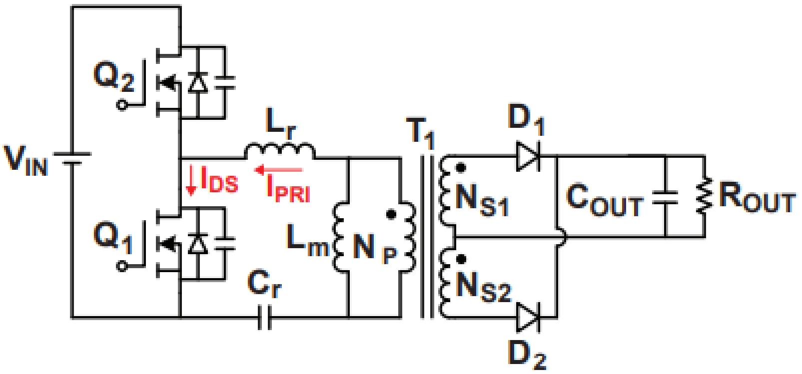


Figure 10:Half Bridge LLC Example Schematic (Yu, 2018)

Now that the system can fully charge and discharge the MOSFET’s output capacitors, the final condition is if there is sufficient dead time between the two switching transitions. For a system to achieve ZVS, the dead time between the switches Q1 and Q2 must be enough time for the output capacitors to fully charge or discharge. If a capacitor is unable to fully discharge when a switching transition occurs, the residual charge will cause a voltage difference across the device. Thereby nullifying the ZVS condition. The minimum required dead time, for the configuration shown in figure 10, can be calculated through the following process.

If a constant current I_{DS} is used to discharge the output capacitance of Q1, Q1-C_{OSS}, from the voltage V_{IN} to zero and charge Q2-C_{OSS} from zero to V_{IN} with the assumption that $C_{OSS(Q1)} = C_{OSS(Q2)} = C_{oss}$, then the time to fully charge or discharge can be expressed as:

$$t_{d(\min \square)} = \frac{2C_{oss}V_{IN}}{I_{DC}}$$

(Yu, 2018)

Resonant Tank

Resonance is a state that occurs when the frequency of an applied signal matches the system’s desired frequency. Resonant frequency is the frequency at which the reactive components in the circuit exchange energy with minimal loss. Operating near this frequency improves efficiency and reduces switching loss. Resonant tanks are made of capacitors and inductors in different configurations. Its role is to filter out the square wave's harmonics, outputting a sine wave of the fundamental switching frequency to the input of the transformer. A configuration is shown in figure 11 below.

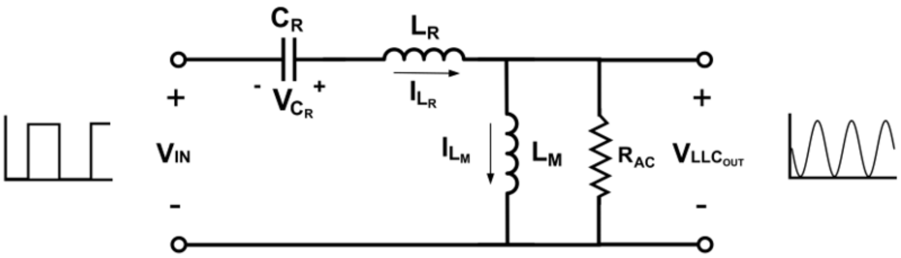


Figure 11:Schematic of an LLC Tank with a Primary-Referenced Load (Hudson, 2022).

The LLC converter has a wide operation range and high efficiency due to the resonant tank's dual inductors. In order to understand how this works we take a look at 2 different resonant tanks under heavy and light loads represented in figure 12 below.

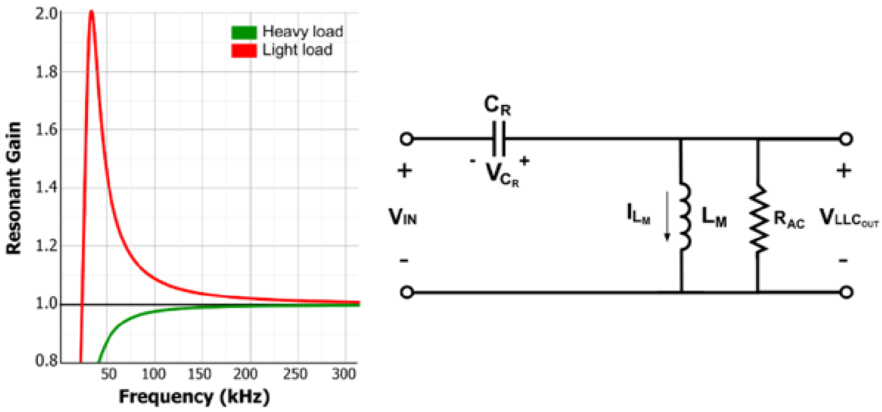


Figure 12:Gain Response and Schematic for an LC Tank with Parallel Inductor (Hudson, 2022).

If the resonant tank is only made up of the resonant inductor (L_R) in series with the resonant capacitor, the behavior is different. The gain does not exceed 1, but when the load is heaviest, the tank reaches unity gain much more quickly than it would with the parallel inductor.

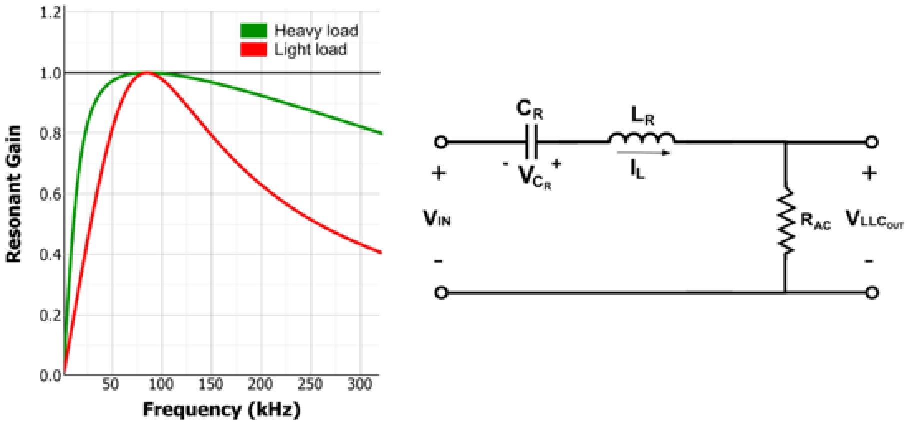


Figure 13:ain Response and Schematic for an LC Tank with a Series Inductor (Hudson, 2022).

The bandwidth of the tank circuit, also known as the resonance width, is related to the sharpness of the resonance peak. A narrower bandwidth corresponds to a sharper resonance. Quality factor Q is calculated as the ratio of the resonant frequency to the bandwidth. The system transfers the energy more efficiently when it is in resonance.

Charging Methodology

Charging a battery must be a regulated and systematic process to ensure the battery's lifespan is not reduced through any undesirable damage. The importance of the charging system led to a standard charging methodology that consists of three phases: pre-charge mode, constant current (CC) regulation, and constant voltage (CV) regulation. This section discusses the three different modes of charging and outlines the CC-CV charging profile

The modes of charging are dependent on feedback the system controller receives that is provided by voltage and current sensors about the load. The sensors communicate what state the battery is presently in. If the battery is measured to be extremely discharged and is below a specified threshold, then the charger will enter pre-charge mode. This mode is a unique mode, as many instances of charging will skip this entirely and start with constant current mode. Pre-charge mode is a crucial step for heavily discharged batteries to avoid damage from inrush current. This is an instance of high input current that may exceed a system's normal operating conditions. The reactive components of a system (Inductors and capacitors) can contribute to inrush current, as when power is first applied these components demand high initial currents as they charge up or magnetize. This sudden surge of current can potentially damage the system and is why a pre-charge feature is necessary for any charger. Constant current (CC) mode is the start of the full charge cycle when the battery is not at full capacity, and it can accept a higher current without any issues like overheating or anything. In this mode the supplied current is constant, and the battery voltage gradually climbs. Constant voltage (CV) is the final stage of the charging process when the battery is at or near its desired voltage. Now the current voltage will be maintained at a stable level while the current gradually decreases. This mode is to prevent overcharging and prevent any undesirable effects that it may have. The charging profile of this charging standard is shown in figure 14 below.

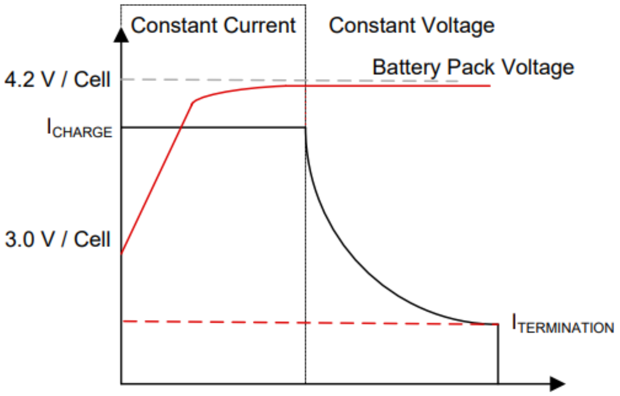


Figure 14:Charging Profile of Li-Ion Battery (TI-Designs 2014).

Sensors

Current sensors

A current sensor is a device designed to measure the electric current flowing through a conductor. It plays a crucial role in various applications where monitoring and controlling current levels are essential. Current sensors come in different types, but their fundamental purpose is to provide information about the current in a circuit. Below are some types of sensors and how they work.

Hall Effect Sensors:

Hall effect sensors are commonly used in current sensors. They operate based on the Hall effect, which is the generation of a voltage perpendicular to the flow of electric current in a conductor in the presence of a magnetic field. The current-carrying conductor produces a magnetic field, and the Hall sensor detects the voltage generated perpendicular to the current flow. Below is shown an HMS Series Open Loop Hall-Effect Transducer produced by LEM USA inc.

Figure 15:HMS Series Open Loop Hall-Effect Transducer (Mathas, 2012).

In the other picture is represented an LTS 25-NP Closed-loop Current Sensor produced by LEM USA inc.

Figure 16:The LEM LTS 25-NP Closed-loop Current Sensor (Mathas, 2012).

Current Transformers (CT):

Current transformers operate on the principle of electromagnetic induction. They consist of a primary winding through which the current to be measured passes, and a secondary winding connected to the measuring instrument. The secondary current is proportional to the primary current and is used for measurement.

Shunt Resistors:

Shunt resistors are placed in series with the current-carrying conductor. According to Ohm's law, the voltage drop across the resistor is proportional to the current. By measuring this voltage drop, the current can be determined.

Rogowski Coils:

Rogowski coils are flexible coils that surround the conductor. When the current changes, it induces a voltage in the coil, and the rate of change of this voltage is proportional to the current magnitude.

Voltage sensors

Voltage sensors, also known as voltage detectors or voltage transducers, are devices designed to measure the electric potential difference (voltage) between two points in an electrical circuit. These sensors play a crucial role in various applications where monitoring and controlling voltage levels are essential. Voltage sensors come in different types, but their primary function is to provide information about the voltage in a circuit. Below are listed some types of voltage sensors and an explanation of how they work.

Voltage Divider Principle:

One common method for voltage sensing is based on the voltage divider principle. A resistive divider network is created using two resistors connected in series. The voltage to be measured is applied across the network, and the voltage at the junction between the resistors is proportional to the input voltage. This scaled-down voltage can then be measured and used to determine the actual voltage.

Zener Diode Voltage Sensors:

Zener diodes exhibit a constant voltage drop across their terminals when operated in the reverse-biased breakdown region. Voltage sensors using Zener diodes leverage this property to create a reference voltage. By comparing the input voltage with the reference voltage, the sensor can determine the voltage level.

Capacitive Voltage Sensors:

Capacitive voltage sensors use the capacitance change in response to the applied voltage. When the voltage changes, it affects the capacitance of the sensor, and this change can be measured to determine the voltage level.

Optical Voltage Sensors:

Optical voltage sensors utilize the electro-optic effect, where the refractive index of a material changes with the applied electric field. By passing light through such a material and measuring the resulting optical changes, the voltage level can be determined.

Piezoelectric Voltage Sensors:

Piezoelectric materials generate an electric charge in response to mechanical stress. In voltage sensors, piezoelectric elements are subjected to the voltage-induced stress, resulting in a charge that can be measured to determine the voltage.

Voltage Regulator

Battery voltage is an essential aspect of understanding how batteries work. When the battery is being charged, chemical reactions are replenished within the battery, which increases the electric potential difference between the battery terminals. The charging voltage required for the battery depends on its chemistry and capacity. It’s important to note that the charging voltage should be within the recommended range specified by the battery manufacturer. Charging a battery with too high a voltage can lead to overcharging and damage the battery, while charging with too low a voltage may not fully charge the battery. It’s essential to use a charger with the correct voltage output to avoid damaging the battery or compromising its performance. This is where the voltage regulator comes out as a crucial component to our design.

The primary job of a voltage regulator is to drop a larger voltage to a smaller one and keep it stable, since that regulated voltage is being used to power (sensitive) electronics. A voltage regulator is basically a beefed-up emitter follower, a transistor connected to a stable reference that spits out a constant voltage, dropping the rest. This is often used to protect electronic equipment from power fluctuations and to maintain a consistent voltage level for various devices. The most common series of voltage regulators is the 78XX series. The two digits after the 78 represent the output voltage of the regulator, for example the 7805 is a 5V regulator and the 7812 is a 12V regulator. The output voltages available with fixed regulators covers a large range from 3.3V to 24V with nice values like 5V, 6V, 9V, 15V and 18V available. Figure 15 shows a 78XX series Voltage Regulator IC.

Figure 17:Voltage Regulator IC.

Electronic devices are designed to use DC supply. These devices are modeled to have a predefined power rating i.e. current and voltage. The DC supply can be provided using a battery or cell, which can be expensive. Instead, AC supply is converted into DC supply. The current utilization is dynamic and dependent on the load, which affects the output voltage or the power rating. Hence, voltage regulation is required for the proper functioning of the devices for maintaining the power rating in any conditions.

DC output from an AC line overview

Voltage regulation gives us the ability to feed a fixed DC voltage independent of the AC line variation or other parameters. Below in Figure 16 we show a block diagram to explain how AC supply is converted to constant DC.

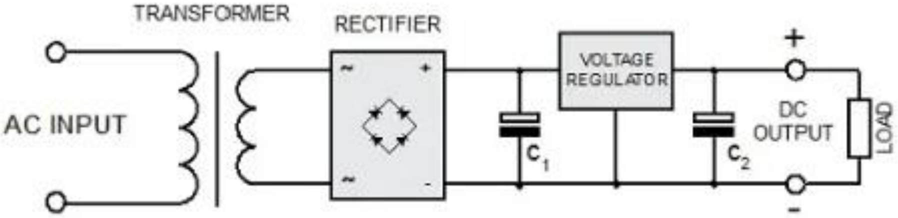


Figure 18: Power Supply Diagram.

Transformer steps up or down the AC voltage utilizing the magnetic field between the primary and secondary windings. Then the rectifier converts the AC voltage to DC pulsating voltage. The filter will reduce the fluctuations of the rectifier output but will still have some minimum ripple voltage. Voltage regulator gives a fixed voltage value to the load, regardless of the input of the voltage value.

Voltage regulator circuit

Voltage regulator circuits are installed between the supply voltage and the electrical load. Due to several factors, the input voltage may either increase or decrease. Figure 17 shows a voltage regulator circuit with unregulated input from power supply filter. There are two cases where the regulator comes into play.

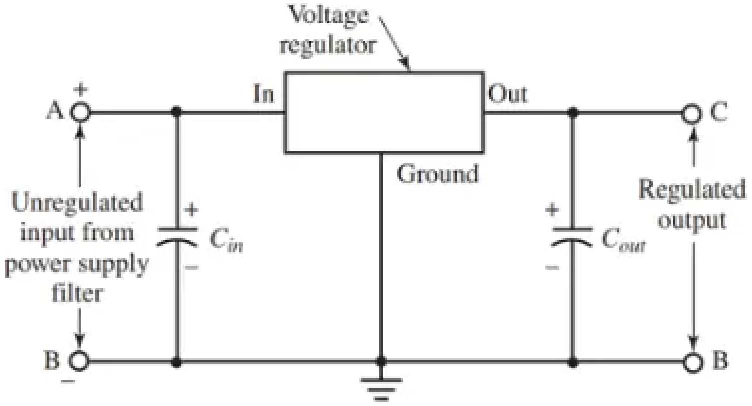


Figure 19:Voltage regulator circuit.

Case 1: Output voltage exceeds rated voltage.

In this case, the control elements inside the voltage regulator will increase the voltage drop across it, resulting in reducing the voltage magnitude in the output.

Case 2: Output voltage drops below rated voltage.

In this case the voltage drop across the regulator gets reduced, hence the voltage is again obtained at the output terminal.

Proposal

EMI Filter

Compared to the fundamental frequency of AC power supplies, electromagnetic noises are high-frequency signals. To suppress high-frequency noises from entering a sensitive load, low-pass filters are used as EMI filters for AC power supplies.

Low-pass EMI filters for power supplies can be either active or passive filters, and they divert noise from the sensitive load to the ground. Active filters are systems that analyze the noise present in the waveform of interest and inject the anti-noise generated to the voltage or current waveform so that noise gets canceled and noise-free outputs are achieved. In passive EMI filters, inductors and capacitors are arranged in different fashions according to filter requirements. The internal configuration of passive EMI filters determines up to what frequency they can suppress high-frequency noise.

Design compatibility

After consideration of both types of EMI filters, we have decided to use a passive EMI filter for our design. One of the main reasons is the reliability that comes with these types of filters, compared to active ones. Passive filters have fewer components which mean less sources of error and failure. The cost of both filters was considered too. Passive filters are less expensive due to having fewer components. Another disadvantage of active filters was power consumption. Active filters require op-amps, which need additional power to function. However, active filters can provide dynamic compensation to varying loads. Considering we will have only one type of load, which in our case is one type of battery, this fact did not come into play. Figure 20 shows different types of EMI filter configurations that we might implement in our design.

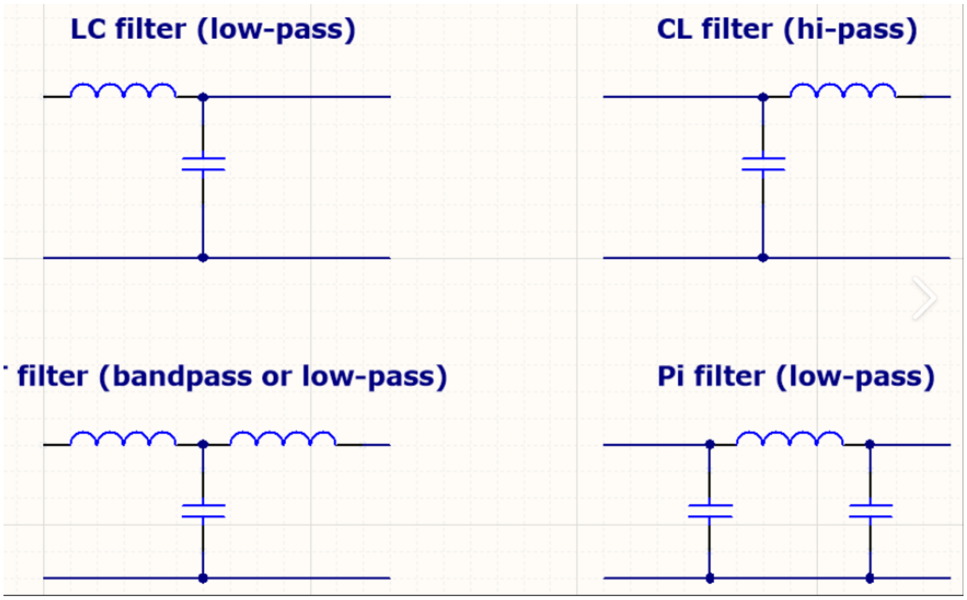


Figure 20:Resulting Power Input (Red) and Output (Grey) from resonant converter.

Evaluating DC-DC Converters

In the field of battery chargers, DC-DC converters are a crucial element in the energy conversion process. At its core, a DC-DC converter facilitates the adjustment of voltage levels to ensure compatibility between the source and the load. DC-DC converters maximize the system efficiently through stepping down voltage levels to the desired load input. Given that a primary focus on this project is power efficiency, DC-DC converters play a significant role in our product. Thus, when finalizing the topology that will be used, the different DC-DC converters must be analyzed for what is most ideal for our purposes, and there are several key qualities that must be considered. As previously discussed, the primary consideration is the power efficiency each converter offers. Furthermore, reliability and stability are paramount for our system, ensuring continuous performance allows for optimal regulation and protection in various conditions. Additionally, factors regarding the converter’s construction weighed heavily in our decision making, such as size, cost, and ease of implementation will contribute to making an ideal project. The two primary converters that were considered are the buck converter and resonant converter. Buck converters offer a simple design but fall short when compared to other DC-DC converter topologies. On the other hand, resonant converters offer the potential for high power efficiency but introduce many complications when constructing them due to their intricate operating principles. This section will investigate the characteristics, advantages, and disadvantages of both converter topologies, culminating in a final selection on the optimal topology for our charger.

Resonant converters

Resonant converters are commonly used in modern DC-DC conversion systems. Comprising a switch network, resonant tank, and rectifying network, these DC-DC converters excel at optimizing power efficiency by minimizing losses. The switch network, the initial stage of the conversion process, filters and manipulates an incoming pulsating-DC signal. While other converters often utilize hard switching, the resonant converter's use of soft switching allows them to greatly enhance efficiency when compared to other converters. The resonant tank, constructed with capacitors and inductors, filters the harmonics from the switch network by operating near resonant frequency, which ensures minimal loss when stepping down the voltage Finally, the rectifying network transforms the stepped down AC signal into a constant DC voltage that can be fed into the load. This section will explore the functionalities of each component to detail their characteristics that will be considered in the selection for our projects DC-DC converter.

The switch network is the initial stage of energy conversion in resonant converters. Its primary function is to receive an incoming pulsating DC signal and transform it into a high-frequency square wave suitable for further processing in the resonant tank. This network is configured with dual transistors, typically MOSFETs, that are parallel to one another. This configuration enables the system to use the soft switching technique to reduce power loss and enhance overall efficiency. Soft switching, also referred to as zero-voltage switching, is a technique where before a switching transition, the transistor reaches zero voltage. By doing so, the system minimizes loss by dissipating any power that would be in the transistor if it were to switch earlier. This also reduces any stress that could be done to a component if it were to be subjected to high power loss, protecting the components and improving reliability. However, switch networks found in resonant converters do introduce some slight complications for our project. The most prominent issue being their design and implementation complexity. This complexity arises from the need of precise control over the switching frequency, which if not implemented properly, will severely decrease the system's overall efficiency.

The resonant tank receives the pulsating DC signal output by the switch network. This element is responsible for adjusting the frequency of that power signal to modulate the gain amplitude to the desired voltage levels. These act as low-pass filters, allowing desired frequencies to pass through while blocking frequencies higher than the specified frequency cutoff. The tank allows for the voltage to step down before being fed into the rectifier, as well as smoothing the square wave to facilitate processing. While the resonant tank can produce highly efficient energy transfers between transformer coils, they also introduce further complexities in design and implementation. The resonant tank's impedance is dependent on the received signal frequency, which leads to there always being a difference between input and output frequencies. This ultimately means there will *always* be some energy loss in the circuit. This loss can be described by the dimensionless parameter referred to as the Q-factor. The resonant tank's Q factor measures the ratio of energy stored in the tank circuit to the energy dissipated per cycle, which means a high Q factor indicates low energy loss. So, it is desirable to achieve the system's maximum Q factor, which is referred to as achieving resonance. To achieve resonance, the circuit components must be tuned to achieve a certain frequency where the impedance from the inductors and capacitors cancel each other out, resulting in a purely resistive impedance. This ideal frequency is referred to as resonant frequency. Achieving this frequency is complex as it requires intricate design and precise implementation. Failing to reach this frequency may result in increased heat generation and therefore more stress on the components. Any slight deviations from the resonant frequency may also cause severe decreases in energy transfer, which means the design demands thorough preparation and precise implementation.

Buck Converters

When selecting a topology for our battery charger, the most important consideration was efficiency. Using a dc-dc converter would be a good idea to step down the voltage to reach the required recommendations of our battery choice. In front of the design decision we had two options, first is the linear power supply dc-dc converter (PSU) and the second option is to use a high frequency pulse width modulation switching regulator.

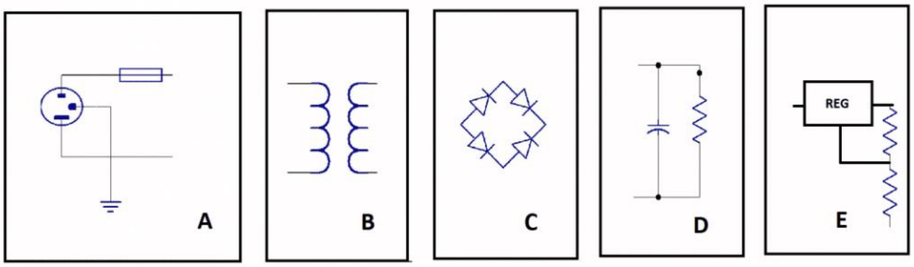


Figure 21:Power supply unit main blocks (linear power supply dc-dc converter, picture from circuit basics).

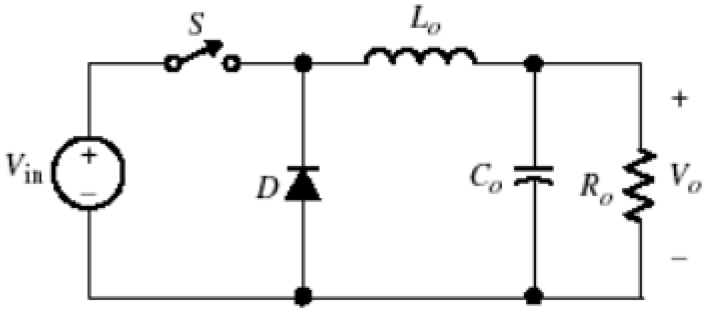


Figure 22:Buck converter circuit (source EEL6246 Power Electronics II Dr. Sam Abdel-Rahman)

The linear power supply has an advantage that it is easier to design, and it has very low EMI noise and ripple when compared to the high frequency pulse width switching regulator design. However, their disadvantage is that they are larger and heavier. They also produce a lot of heat and require a heat sink. They are also limited to only one output. Their efficiency is low when compared to the second type, so it would be self-explanatory on why we would choose the dc-dc high frequency pulse width modulation switching regulator design. The second design's challenge is that it has a greater circuit complexity and produces high electromagnetic interference (EMI) and ripple. The main advantages are that they are more efficient and are not limited to only one output.

Selecting between the linear power dc-dc converter and the frequency pulse width modulation switching regulator converter was obvious. In the following, there will be listed advantages and drawbacks of this topology.

In general, high frequency pulse width modulation switching regulator buck converters can offer high efficiency and different output voltage range. It also is translated into less power lost as heat and this reduces the need for cooling. They can be regulated by the duty cycle of the switching transistor to produce different types of charging modes. The general disadvantages are the generation of the ripple current and voltage at the output, due to its switching. This may cause harm to sensitive components, such as the battery or the load. In order to reduce the ripple, additional filtering components may be required, and this increases the size and cost of the circuit. Buck converters also produce electromagnetic interference (EMI) due to the high frequency switching. This EMI might affect the operation of nearby circuits or devices and may require shielding or filtering to comply with regulatory standards.

Feedback loop

From an early perspective, it is visible that for each design a feedback loop will need to be implemented to avoid harming the battery or control the temperature and different charging modes. A feedback loop implementation is represented in the figure below, a switch mode power supply topology.

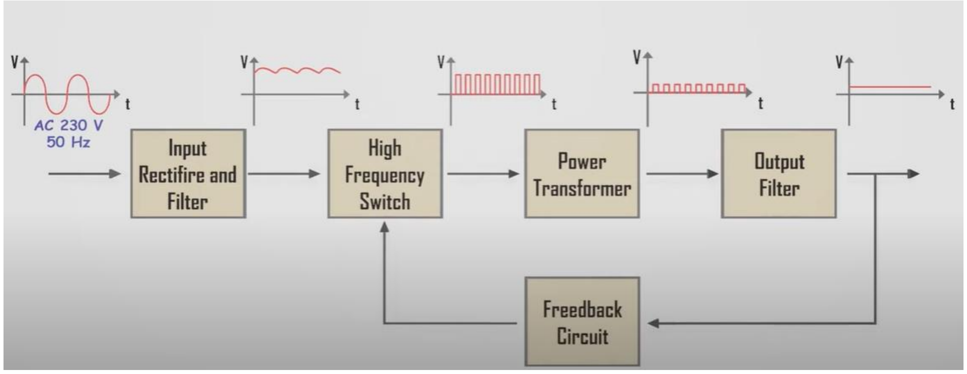


Figure 23:Switch mode power supply (SMPS)

The feedback loop can be constructed by using a Zener diode connected to an optocoupler. When the voltage gets to a certain level the Zener diode will let the current flow to the optocoupler and then go to the circuit to control the transistors.

An opto-isolator (also called an optocoupler, photocoupler, or optical isolator) is an electronic component that transfers electrical signals between two isolated circuits by using light (Graf, p.522) Why use an optocoupler (opto-isolator) in our design. The main reason is that optocouplers provide electrical insulation (galvanic insulation) and we know from our everyday life how important insulation is when using a charger (our cell phone chargers for example).

Opto-isolators also prevent high voltages from affecting the system receiving the signal (Lee et al. p.2). Commercially available opto-isolators withstand input-to-output voltages up to 10 kV (Hasse, p.145)

Below are shown two schematics of an optocoupler.

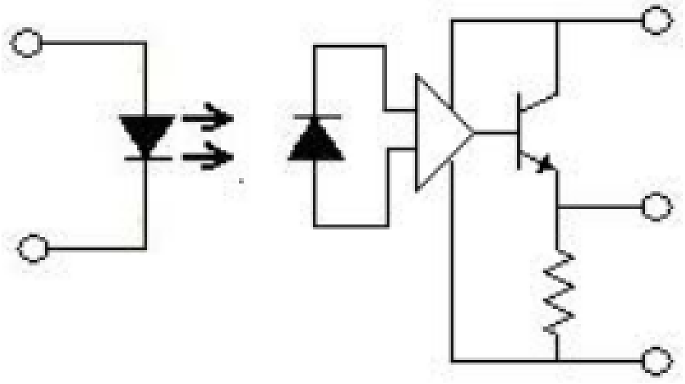


Figure 24:Schematic diagram of an opto-isolator (optocoupler, source Google images).

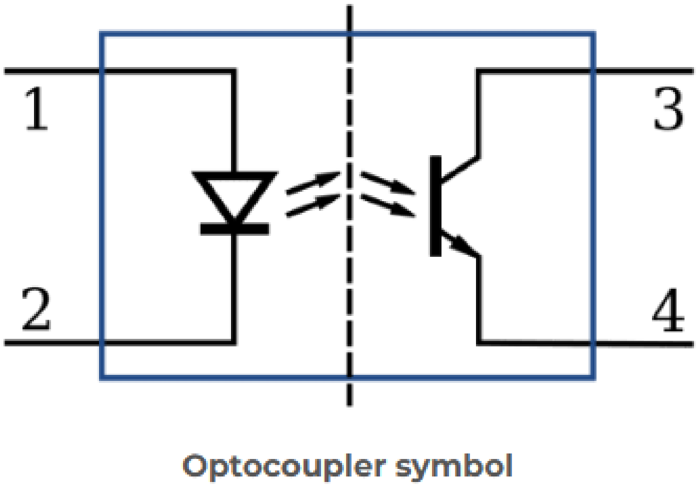


Figure 25:Schematic diagram of an opto-isolator (optocoupler, source Circuit Basics).

The optocoupler is made of two main elements a LED on the left, and a sensor (phototransistor) on the right connected through dielectric barrier in the center.

Conclusion

To make our selection we reviewed different topologies. Based on our requirement on building a high efficiency battery charger our focus was to select the most efficient topology while also focusing on the time of charge. The most efficient out of the designs would be the resonant switching converter.

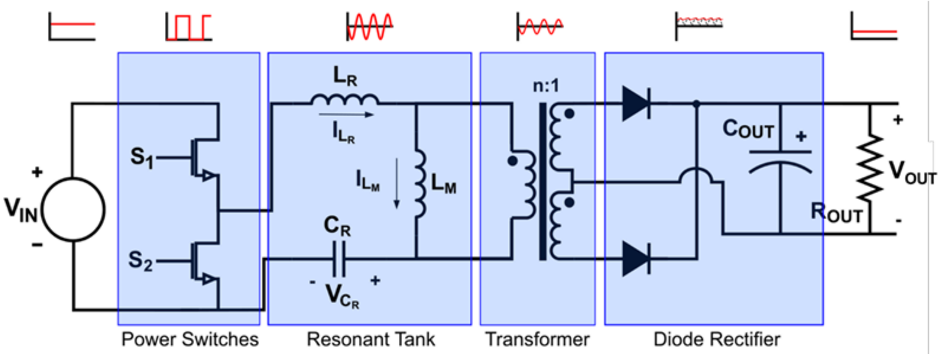
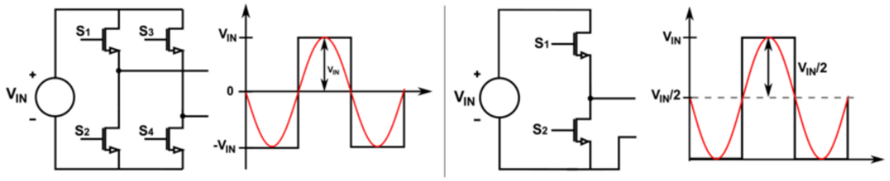


Figure 26:Simplified resonant circuit topology (LLC converter, Hudson MPS).

When deciding on which topology to select for our resonant converter there are 2 main the full bridge and half bridge (represented in the figure below)



a) Full-Bridge Topology

b) Half-Bridge Topology

Figure 27:Full and half bridge topologies (Hudson, MPS).

Based on the study by Hudson, for our implementation it is recommended the half bridge design as the power does not exceed 1kW.

Below is also shown a resonant circuit (Hudson, MPS) which converts the square wave to the sinusoidal of the first harmonic.

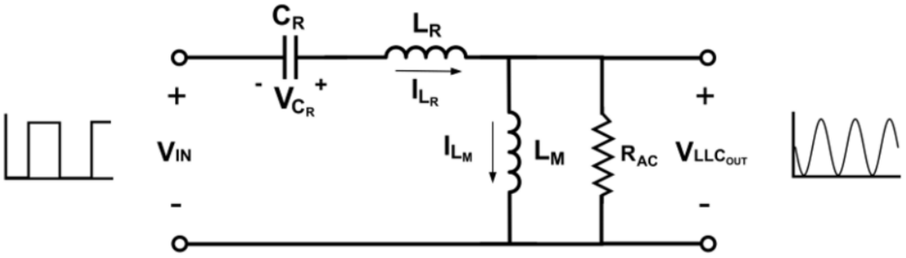


Figure 28:LLC Tank showing the conversion of the input square wave to the sinusoidal output.

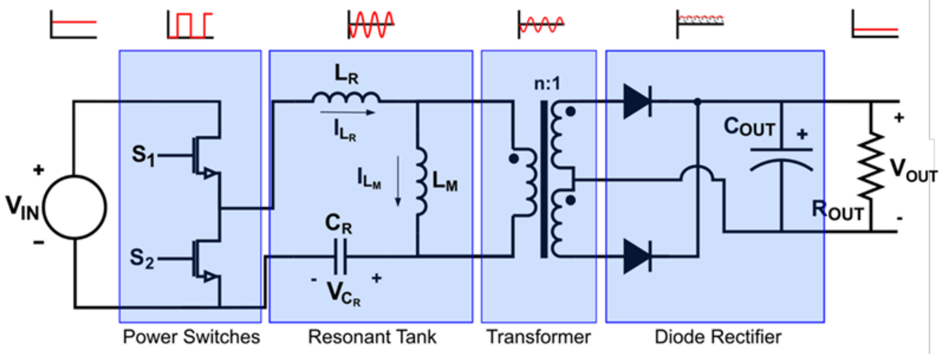


Figure 29:Simplified resonant circuit topology (LLC converter, Hudson MPS)

In general, our proposal will be similar to the one on fig. above taking into consideration that to reach the dc voltage Vin a diode bridge rectifier will be used after the AC source (might be used also a step-down transformer and EMI filter).

Methodology

This section will briefly discuss the project plan we followed and provide a framework for the following implementation and design section. The initial plan to produce this charger consisted of two primary objectives, design our schematic through simulations and then use those findings to optimally construct the charger. However, due to the time constraint we faced, we had to scale down the project objectives and specifications in order to set realistic goals. Now, rather than charging a 400V load at 5A, our final design was a 24Vrms load at 277mA. So, we will not be constructing the system and will focus on completing the simulation process and analysis of the LLC resonant converter. This section will briefly discuss what we would have done if we were constructing it.

Before we can begin the physical construction of our system, we must first complete our design and map out how our system will interconnect. The approach we took when designing our system was to utilize the circuit simulation software LTspice, produced by semiconductor manufacturer analog devices. The resonant converter was the primary focus of our simulation. To most effectively utilize the software, we decided to simulate each of the previously established phases; switch network, resonant tank, and rectifying network; independently and then combine them piece by piece to reach our final design. This approach allows us to verify the design of each phase and facilitates any troubleshooting that we will need to do. Starting with the switch network, we initially intended on utilizing solely a dual MOSFET configuration as our means of implementing soft switching for high efficiency. This was later altered by incorporating an n-channel half bridge driver due to difficulties we faced with our initial design. This quickly resolved the issue, and we were able to verify the intended square wave output. With the switch network completed, we were then able to focus on the key component of the resonant converter, the resonant tank. This posed a more complex design process than the switch network and a more in-depth exploration of the utility provided by LTspice in order to successfully implement it into the software. This consisted of investigating the concepts of spice directives, the various AC sources provided for an AC sweep, generating bode plots to observe the gain and phase of different configurations, and other AC analysis tools LTspice provides the user. Once each individual phase has been constructed and verified through analysis, we were then able to incorporate the designs into a single simulation and finalize our system's design.

As discussed, we were unable to complete the initial construction objective or incorporate a microcontroller to more effectively regulate the system. These will be further discussed in the recommendations section. There was a general plan for what our construction process would have been if we had the time to begin. With the simulations completed, we would be able to start designing a PCB. This would be done by implementing our design into Multisim and then exporting it to PCB design software, Kicad. We would then be able to order the designed PCB and begin physically constructing our system with the desired components. The specific components of our design will be further discussed in the following sections, as well as problems we faced and how we overcame them.

Design and Simulations

As discussed in the methodology section, our design process scope was to design, simulate, and troubleshoot to produce an optimal design that can be implemented in the future. The focus of our design process was on the DC-DC resonant converter. To facilitate the design process and potential troubleshooting, we decided to simulate each of the established phases; switch network, resonant tank; and rectifying network; independently to verify their design and then combine them to reach our final system design. This was seen as a more efficient and practical approach, as simulating the entire system as the first step would make identifying faults in the system more complicated. Through successful simulation and verified analysis, we can develop confidence in our theoretical knowledge and how our design would behave in the real world.

The first phase we chose to design was the switch network. This phase is responsible for converting the DC signal into a pulsating square wave that the resonant tank receives. Our initial design was to use a dual MOSFET configuration that would utilize soft switching. However, when doing the initial configuration, the low MOSFET was not having any influence on the system, and we were not able to determine how to correctly implement this design. We were able to resolve this by altering our design to incorporate a half bridge n-channel MOSFET driver, specifically the LT1158. By doing so, we successfully simulated the switch network and produced the desired results. This driver serves the purpose of efficiently driving the MOSFETs by providing the necessary gate drive voltage and current to rapidly switch them on and off and helps minimize losses. MOSFET drivers also include safety features in the case of system faults, which helps ensure reliability and system safety. The design for this phase of the system and resulting waveforms can be seen in the figure below. As you can see from the results, the two switches are operating at a 50% duty cycle. The output of the switch network (pink) is also at the intended value of the load, 24V. These results verify that the switch network simulation phase is properly working and we can proceed with the resonant tank.

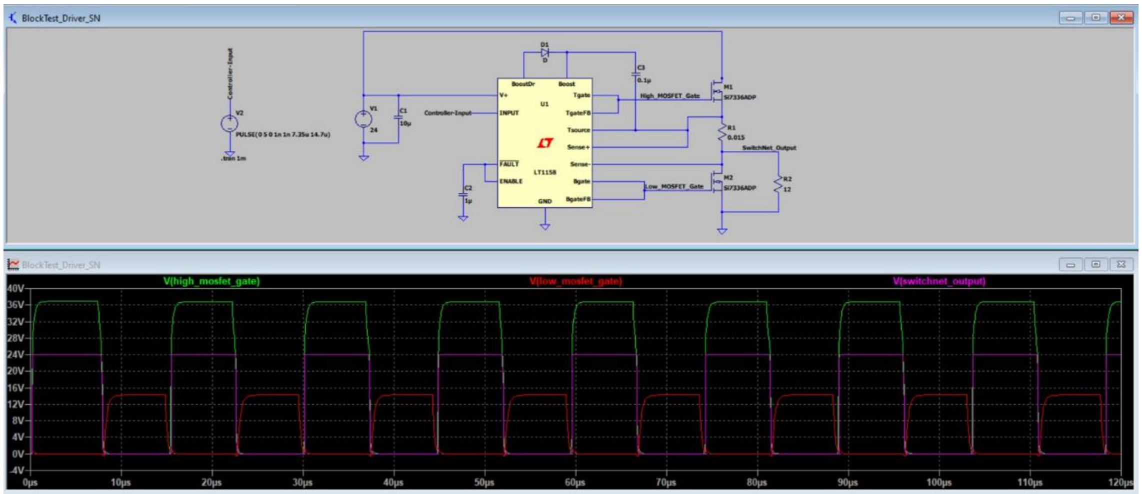


Figure 30:Switch Network schematic and results (Green=high MOSFET gate; Red=low MOSFET gate; Pink=switch onetwork output).

After deciding on how to drive the MOSFETs the next challenge was to design and verify the resonant tank. Our main source on how to design of the resonant tank was a survey by Texas Instruments on resonant inverter topologies. The best configuration for our purpose is the LLC SRC configuration because it is a very useful configuration on most charger applications existing. It also provides the desired gain for our project scope and is easier to configure.

On the simulation tool, we tried to see the behavior of transformers in spice. As we mentioned earlier the battery that needs to be charged is seen as a load of 80 ohms (even after scaling down the current and voltage). So, a good way to start our simulation would be by placing an 80Ω resistor after the secondary stage of the transformer. It is important to notice that for the simulations we used ideal transformers. In order to have a step down of 2:1, the inductor values in the transformer should be 4:1 as we know that the relationship between the inductances and the turns ratio is:

$$\frac{L_1}{L_2} = \left(\frac{N_1}{N_2}\right)^2$$

In the simulation represented below in figure 30 the values used for the inductances are specifically 10mH and 2.5mH which agree to the values of a turn ratio of 2:1. The green trace represents the voltage on the primary side and the red trace represents the voltage in the secondary side of the transformer. In order to have a sanity check we also did use a value of a 320 ohm that represents the reflected load as it is seen on the primary side of the transformer.

$$Z' = \left(\frac{N_1}{N_2}\right)^2 \cdot Z = \left(\frac{2}{1}\right)^2 \cdot 80 = 320\Omega$$

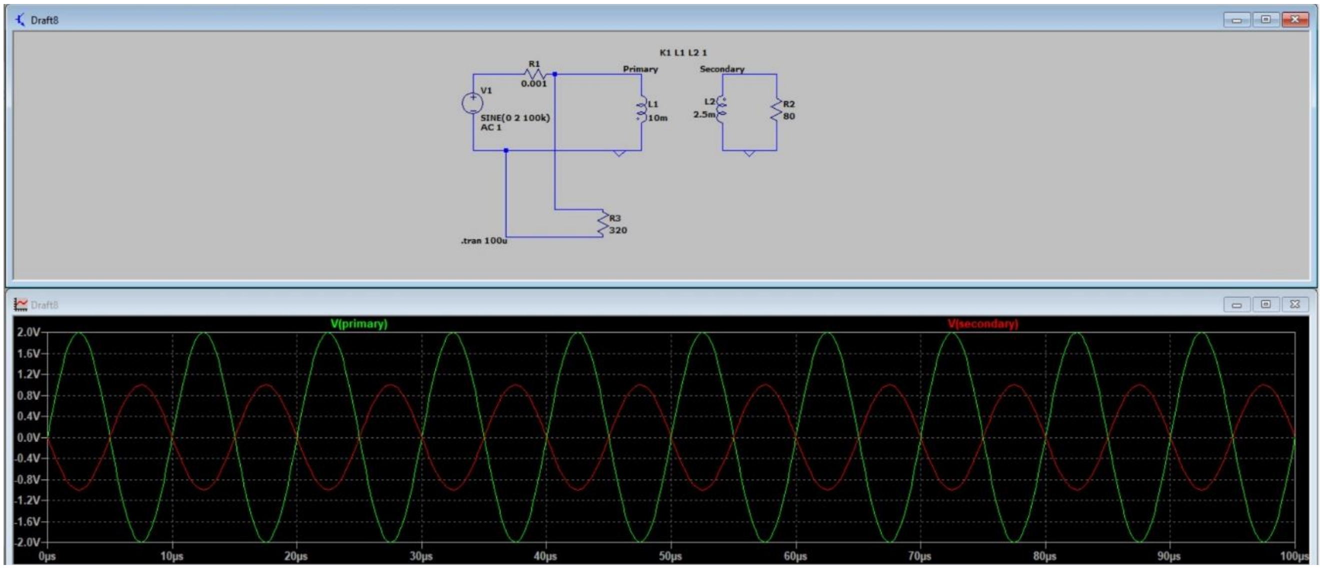


Figure 31: Verifying transformer Spice directives work properly.

One difficulty in simulating our LLC design was making it so the transformer did not interfere with the functionality of our resonant tank. Initially, the inductance from the primary coil was having undesired effects on our gain and therefore our resulting output voltage. To troubleshoot this problem we incorporated a matching LLC tank, but removed the transformer and replaced it with an equivalent resistance to the load on the secondary side. This allowed us to do a transient and frequency response on the LLC to verify the transformer was not interfering with the functionality. The verification was done through observing if the gain of the tank with the transformer was equivalent to the gain of the tank without the transformer. In figure ###, we show the simple configuration of verifying our understanding of spice's transformer directives. As you can see from that, the directive is done properly, and we can step down the voltage from the input to the output. In figure 31 below the design of the LLC and its transient response in different nodes, one when it is connected to the transformer (red), one when it is not connected to the transformer (green), and one when it is connected to the load (pink). You can see in this figure that can verify the functionality of the LLC when connected to the transformer because our green and red traces overlap, displaying that the presence of the transformer does not alter our gain.

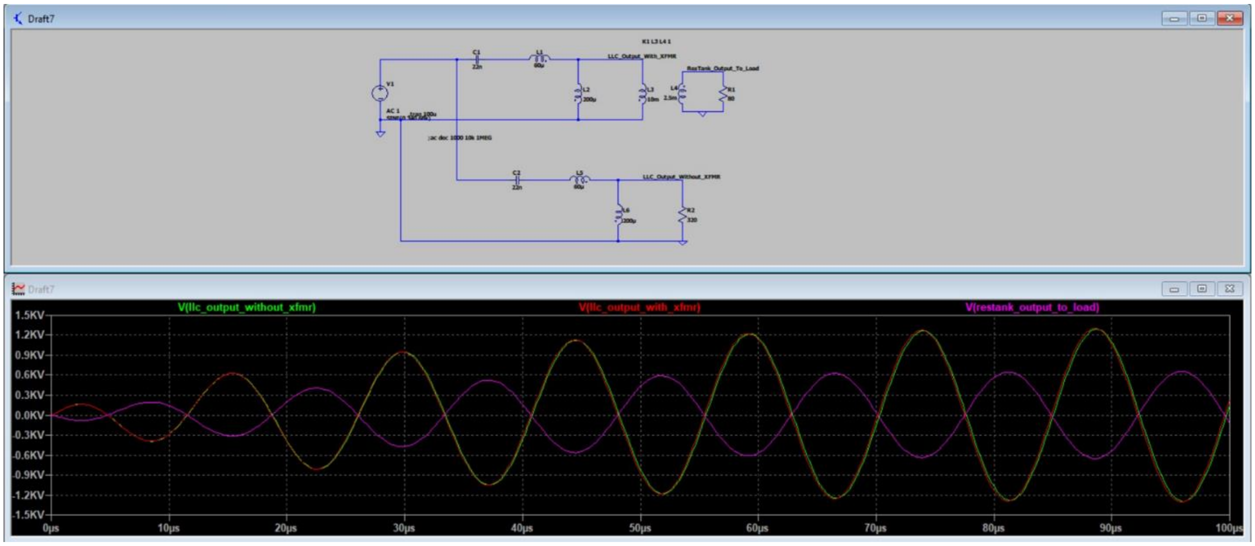


Figure 32:LLC Transient Response (Green=VR2, Red=V at primary xfmr, Pink=Vload).

With the LLC and transformer configuration verified, we will now plot the frequency response of the LLC to observe the relationship between the tank input frequency and the gain. Prior to this simulation we calculated the expected resonant frequency. Doing this before will allow us to see if the simulation is working as expected and if we need to further adapt our design. The resonant frequency calculation is shown here:

$$f_{R2} = \frac{1}{2\pi\sqrt{(Ls + Lp) \cdot Cr}}$$

$$f_{R1} = \frac{1}{2\pi\sqrt{(Ls+Lp)Cr}}$$

We chose the value of Ls=60uH and Lp=200uH and Cr arbitrary, then we calculated the value of the resonant frequency.

Having calculated the resonant frequency to be roughly 68kHz, we can now expect our frequency response to have a peak gain around that frequency. The frequency response we generated can be observed below.

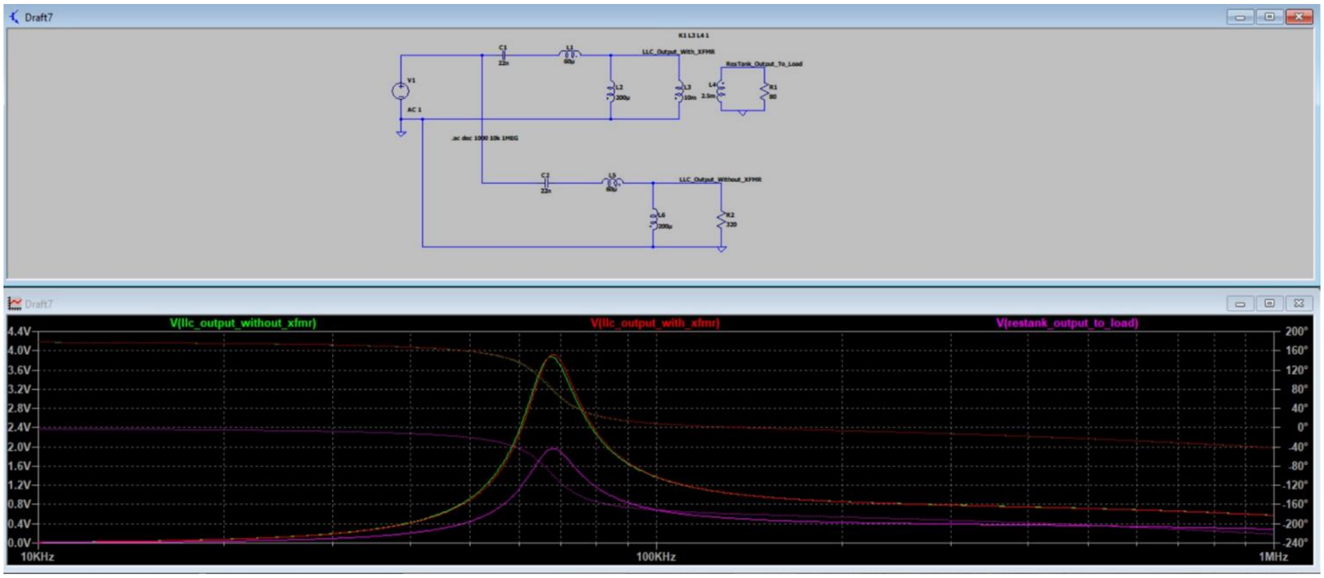


Figure 33:: LLC Frequency Response (67kHz resonant frequency).

The above figure verifies that our calculations are correct, as our peak gain is measured around 67kHz. This adds confidence that both our calculations and simulations are accurate for our intended results.

In order to verify the output that is going to the load (battery) we need to also rectify the output right after the transformer and this would need another simulation as it is shown in the figure 33 below, the constructed circuit in LT Spice and also the transient response.

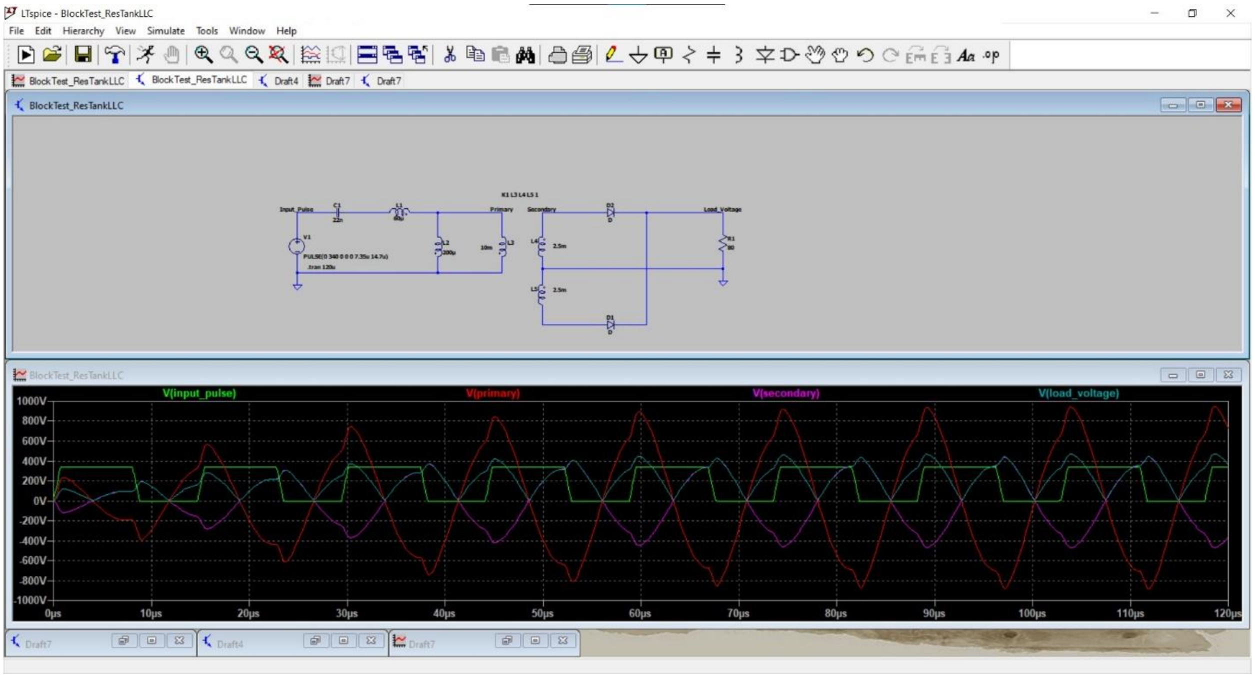


Figure 34:Pulse=green, Vprimary in red, secondary in pink, Vout in blue.

In green is shown the input voltage, in red is the voltage measured at the primary side and in purple is the voltage at the secondary side and in blue is represented the output voltage.

In figure 34 below is the simulation of the battery as a voltage source. The input power is the red trace, and the output power is yellow.

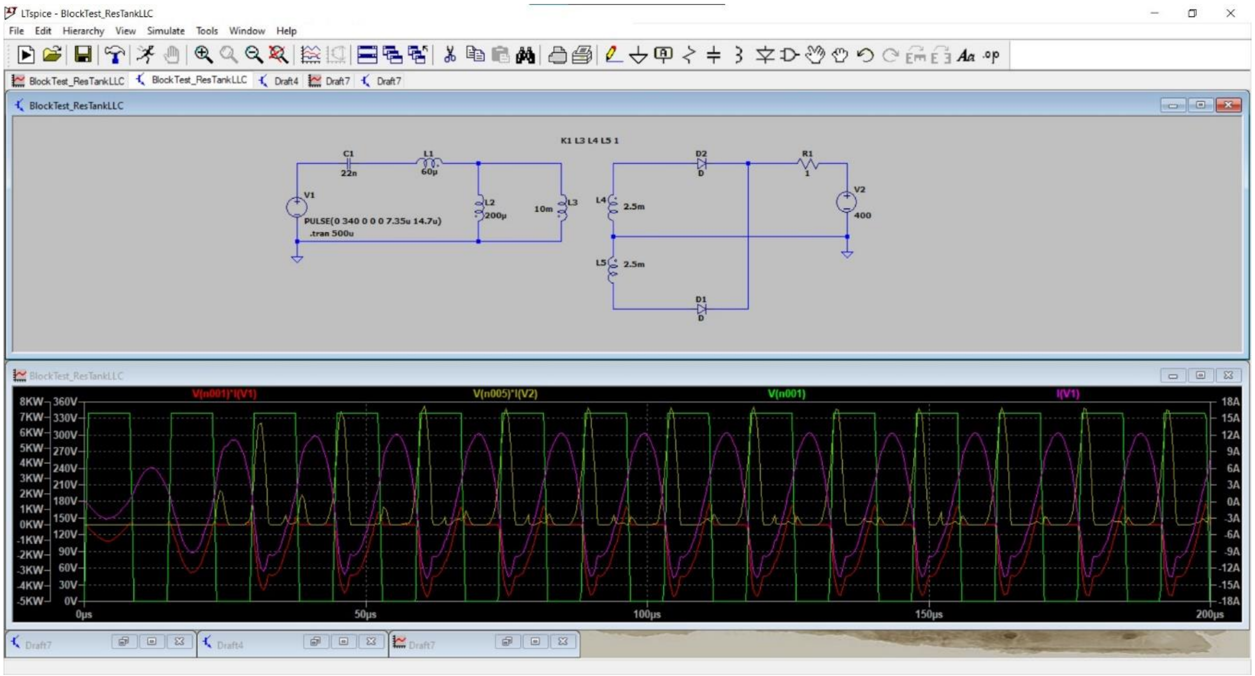


Figure 35:P_in=red and P_out=yellow.

Analysis and Results

Finally, after simulating all the different components of the converter, we will put them all into a single simulation where we will be able to verify they work in a combined system. The resulting schematic and simulation plots are depicted in the figure below.

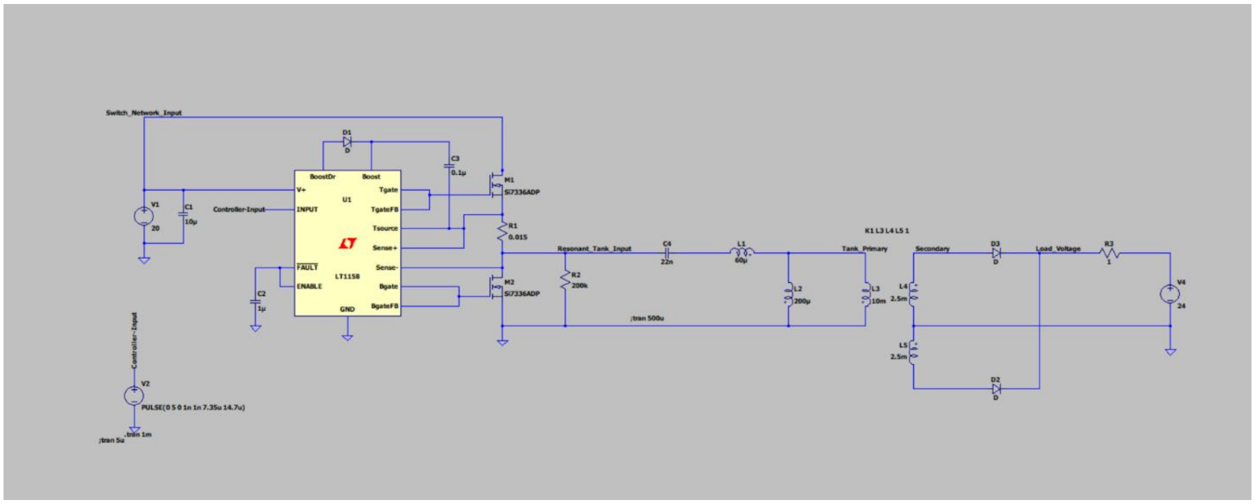


Figure 36:Final design of resonant converter with all phases.

Our final waveform results came out as expected from theory and were aligned with our one-by-one verifications that we mentioned in the previous section. In figure 37 we show 5 different waveforms explained as follows:

Green: V(switch_network_input)= This represents the DC voltage supply of 24V going into the switch network.

Red: V(resonant_tank_input)= This represents the square wave created by the switching network going into the resonant tank.

Light blue: V(tank_primary)= Voltage after the resonant tank. We can clearly see the gain from the resonant tank we are putting a 20V pk square wave and the output of the tank is a 50V pk wave. The gain of the resonant tank was approximately calculated at 2.5.

Yellow: V(secondary)= Voltage at the secondary winding of the transformer. We are using a 2:1 ratio transformer as our inductors are coupled in a 4:1 inductance ratio. The simulation waveforms are accurate as the yellow waveform as a 25V pk , which is half of the resonant tank waveform which was 50V.

Magenta: V(load_voltage): Finally, our final product, load voltage is a constant 24V DC value. This was our main goal since the beginning.

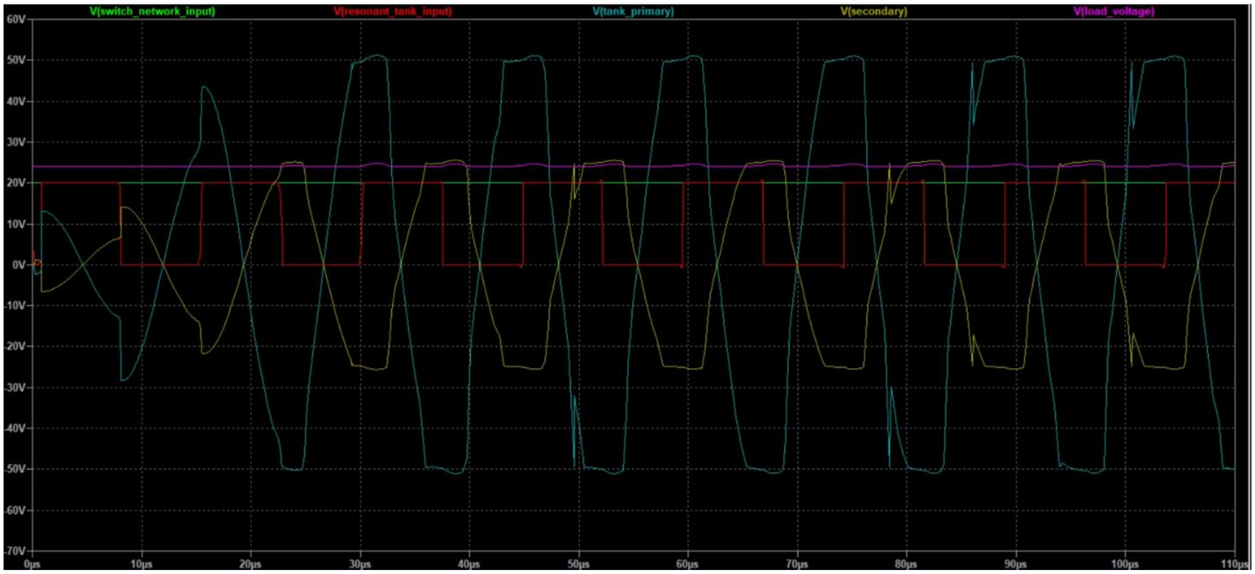


Figure 37: Waveform of critical nodes of design.

After we were sure that our design was performing as expected, we conducted an efficiency analysis. Figure 38 shows power levels for both input and output. We measured the waveforms of input voltage and input current, then we coupled them together to calculate the average input power. The same method was used for the output power level. The average input power was measured as 4.9764W, and the average output power was measured as 4.4267W. This gives us a calculated efficiency of 88.93%. A lot of resonant converters achieve efficiency in the range of 90-95%. Our efficiency level is satisfactory for the scope of this project. Real designs of resonant converters have been optimized frequency input to achieve the highest gain, lowest harmonic distortion and lowest conduction losses.

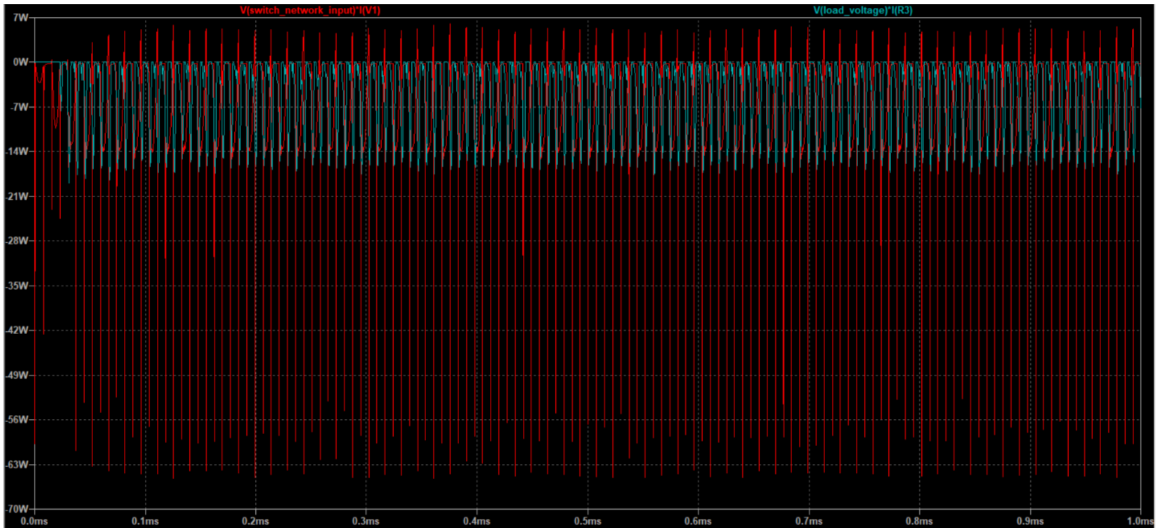


Figure 38:Resulting Power Input (Red) and Output (Grey) from resonant converter.

Recommendations and Future Improvements

Now that our design is finalized and meets the requirements we wanted, it’s time to propose a few improvements to anyone that wants to continue developing our prototype in the future. The initial plan was to implement the design in a PCB using KiCad software. Our findings and schematics can be a valuable resource for any student that wants to complete a power related MQP. Some major recommendations to add to the design are incorporating a feedback loop with an opto-isolator, and using that feedback to communicate to a microcontroller. The feedback loop and microcontroller would work hand in hand to monitor the voltage or current the load is receiving. The microcontroller would then process that information to regulate the switching frequency of the switch network, which in turn allows it to manipulate the gain of the converter and therefore the voltage the load receives.

Every battery charger requires a feedback loop to monitor either current or voltage, enabling the input to be adjusted accordingly. Initially, we intended on utilizing an opto-isolator in our feedback loop. An opto-isolator is an electrical component that transfers electrical signals between two isolated circuits by using light. One significant advantage is that no electrons can pass through this path, as there is no physical connection between the two sides. This is important for improving the safety and reliability of the system, by eliminating the possibility of the high voltage supplied from the AC wall outlet reaching the load and possibly damaging it, thereby providing the user safety. Since there is no physical connection between the primary and secondary sides, if a component were to break and allow for the AC current to not be significantly stepped down it would not be able to overload anything on the secondary side. A common type of opto-isolator consists of an LED and a phototransistor in the same package. Other types of source-sensor combinations include LED-photodiode, LED-LASCR, and lamp-photoresistor pairs. Typically, opto-isolators transfer digital (on-off) signals and can act as an electronic switch, but some techniques allow them to be used with analog signals. In our case, it would serve to transfer analog signals, specifically the voltage level of the load battery. Since voltage levels are a continuously varying signal, it enables the microcontroller to continually regulate the system appropriately.

With the feedback loop providing the analog signal through the opto-isolator, we may now discuss the implementation of the microcontroller and its function in the system. The microcontroller would receive the previously discussed signal and, through an analog-to-digital converter (ADC), would convert this analog voltage level into a digital value the microcontroller can interpret. From interpreting these digital signals, the microcontroller can process the load's voltage levels, i.e. the charge. Based on the controller’s charge measure, it will respond to regulate the system through switching frequency. This regulation is done through sending control signals to the switch network. As discussed, our switch network utilizes an n-channel half-bridge driver to control the MOSFET switching. In our plan for the design, we intended for the controller to send pulse-width modulated (PWM) signals to the half bridge driver. The signals the microcontroller sends determine the duty cycle of the switching waveform. This means that the microcontroller can control the switching frequency, as in the amount of time the MOSFETs are on and off. Since the switching frequency of the switch network regulates the input of the resonant tank and its output, through controlling the switching frequency the microcontroller can control the voltage received by the load. This function can be done by various microcontrollers, but we intended on using an Arduino since it was able to handle our specifications and we had one readily available. Implementing this function would require the students to be familiar with embedded coding and understand ADC and DAC. Another consideration of implementing a controller for system regulation is how the controller will be powered. These microcontrollers typically are powered will a low voltage supply, in our Arduino's case it would be 5V. So, one would have to find a way to reliably power the controller so it can perform its function. It is important to note that the controller is not able to receive the rectified and stepped down voltage on the secondary side, because without the controller initially controlling the driver the system would not be able to output power from the primary side to begin with. One technique we saw to initiate the regulating was powering the controller through leakage inductance from the transformer. This process and other powering options would need to be further investigated by future project groups, as it is crucial for implementing the controller.

The final step to wrap up things would be to construct the circuit in a PCB layout tool such as KiCad. KiCad is a free and open-source software for creating electronic circuit schematics and printed circuit boards. Tools exist within the package to create bill of materials, artwork, Gerber files, and 3D models of the PCB and its components. This tool was suggested by Prof. Bitar and he also provided a 2-hour course on how to get started with building a printed circuit board. Our group liked this software because it uses an integrated environment for all stages of the design process such as schematic capture, PCB layout, Gerber file generalization and library editing. There is no need to export schematics to other software.

Conclusions

We are generally satisfied by the results of our project as most of them were exactly as expected from theory. The learning curve has been comfortable throughout the project. Our background research was very substantial and made us do a deep dive in topics we had not encountered during our ECE classes. The most important thing about our work was the challenges we had in our design and how we overcame those with the help of Prof. Bitar also. This was the first major project for our team members, and it was nice to have some exposure as to what work goes into real electrical designs. We cannot overemphasize how much we have learned from this project and how this will help us in starting our careers as engineers.

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